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Assessing Climate Change Impacts on Live Fuel Moisture and Wildfire Risk Using a Hydrodynamic Vegetation Model

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Abstract: Live fuel moisture content (LFMC) plays a critical role in wildfire dynamics, but little is known about responses of LFMC to multivariate climate change, e.g., warming temperature, CO_2 fertilization and altered precipitation patterns, leading to a limited prediction ability of future wildfire risks. Here, we use a hydrodynamic vegetation model to estimate LFMC dynamics of chaparral shrubs, a dominant vegetation type in fire-prone southern California. We parameterize the model based on observed shrub allometry and hydraulic traits, and evaluate the model's accuracy through comparisons between simulated and observed LFMC of three plant functional types (PFTs) under current climate conditions. Moreover, we estimate the number of days per year of LFMC below 79% (which is a critical threshold for wildfire danger rating) from 1950 to 2099 for each PFT, and compare the number of days below the threshold for medium and high greenhouse gas emission scenarios (RCP4.5 and 8.5). We find that climate change could lead to more days per year (5.5-15.2% increase) with LFMC below 79% from historical period 1950-1999 to future period 2075-2099, and therefore cause an increase in wildlife danger for chaparral shrubs in southern California. Under the high greenhouse gas emission scenario during the dry season, we find that the future LFMC reductions mainly result from a warming temperature, which leads to 9.5-19.1% reduction in LFMC. Lower precipitation in the spring leads to a 6.6-8.3% reduction in LFMC. The combined impacts of warming and precipitation change on fire season length are equal to the additive impacts of warming and precipitation change individually. Our results show that the CO_2 fertilization will mitigate fire risk by causing a 3.7-5.1% increase in LFMC. Our results suggest that multivariate climate change could cause a significant net reduction in LFMC and thus exacerbate future wildfire danger in chaparral shrub systems.

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Keywords: FATES-HYDRO, chaparral shrubs, plant functional types, southern California, CO_2 enrichment, climate change

1. Introduction

Historical warming and changes in precipitation have already impacted wildfire at a global scale (e.g. Stocks et al. 1998; Gillett et al. 2004; Westerling et al. 2003, 2006) and it is expected that accelerating future warming will continue to significantly influence global wildfire regimes (e.g. Flannigan et al. 2009; Liu et al. 2010; Moritz et al. 2012). So far, prior studies have mainly focused on impacts of dead fuel moisture and weather conditions on wildfire. For example, dead fuel moisture is found to be related to fire ignition and fire spread potential (or potential area burnt) (Aguado et al. 2007; Caccamo et al. 2012a), and specific weather conditions such as increased vapor pressure deficit (Williams et al. 2019) can lead to a vast increase in fire activity (Goss et al. 2020). While previous studies provide great insights into fire risks with changes in climate and dead fuel moisture, there is still limited understanding of how climate change influences live fuel moisture content (LFMC) and the consequent wildfire risks. This is particularly true for the combined impacts of warming temperature, altered precipitation, and increasing CO_2 fertilization (Chuvieco et al. 2004; Pellizzaro 2007; Caccamo et al. 2012b; Williams et al. 2019; Goss et al. 2020).

A measure of water content within living leaves and fine branches in relation to their dry weight, LFMC has been found to be one of the most critical factors influencing combustion, fire spread, and fire consumption (e.g. Agee et al. 2002; Zarco-Tejada et al. 2003; Bilgili & Saglam 2003; Yebra et al. 2008; Dennison et al. 2008; Anderson & Anderson 2010; Keeley et al. 2011). This is because a low fuel moisture content leads to increased flammability and a higher likelihood of ignition (Dimitrakopoulos & Papaioannou 2001). For instance, LFMC was found to

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be a significant factor contributing to the occurrence of wildfires in Australia (Plucinski 2003), Spain (Chuvieco et al. 2009) and California (Santa Monica Mountains; Dennison et al. 2008; Dennison & Moritz 2009; Pivovaroff et al. 2019). Dennison & Moritz (2009) found strong evidence of a LFMC threshold, but near 79%, which may determine when large fires can occur.

Vegetation moisture content is dependent on both ecophysiological characteristics of the species and environmental conditions, including both climatic variables and soil water availability (Rothermel 1972; Castro et al. 2003; Castro et al. 2003; Pellizzaro 2007; Pivovaroff et al. 2019; Nolan et al. 2020). So far, little is known about the relative importance of different climate variables to future LFMC. On the one hand, warming could contribute to a higher atmospheric demand and higher evapotranspiration (Rind et al. 1990) and thus lead to a lower LFMC. On the other hand, higher CO_2 concentration will decrease stomatal conductance (Wullschleger et al. 2002) and plant water loss, and thus lead to a higher LFMC. The impacts of CO_2 and warming could be complicated by local changes in precipitation patterns and humidity (Mikkelsen et al. 2008).

The sensitivity of LFMC to climate change is likely to be affected by plant hydraulic traits (PFT, the plant properties that regulate water transport and storage within plant tissues), which affect plant water regulation (Wu et al. 2020). Hydraulic traits determine contrasting plant drought adaptation strategies when responding to dry conditions: 1) water stress avoiders and 2) water stress tolerators (Tobin et al. 1999; Wei et al. 2019). The “avoiders” generally have a more conservative hydraulic strategy under water stress by either closing stomata early, dropping leaves or accessing deep water to avoid more negative water potentials and therefore xylem cavitation. Meanwhile, the “tolerators” generally have a more aggressive hydraulic strategy by building xylem and leaves that are more resistant to cavitation so that they can tolerate more

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negative water potential and continue to conduct photosynthesis under water stress. Therefore, compared with the tolerators, the avoiders normally have a lower sapwood density and higher plant water storage capacity in their tissues to avoid cavitation (Meinzer et al. 2003, 2009; Pineda-Garcia et al. 2013). Because the avoiders rely on water storage capacity as one way to avoid cavitation thereby maintaining a relatively high LFMC, and water loss from storage should increase with warming, LFMC should be more sensitive to climate change in avoiders relative to tolerators.

While over half of terrestrial landscapes on Earth are considered fire-prone (Krawchuk et al. 2009), Mediterranean-type climate regions are routinely impacted by fire, often on an annual basis. This is partly because Mediterranean climate regions are characterized by winter rains followed by annual summer drought, when no rainfall occurs for several months. Multiday periods of extreme temperatures, as well as katabatic hot, dry, and intense winds, often punctuate the annual drought, leading to some of the worst fire weather in the world (Schroeder et al. 1964). This can result in wildfires that are large, high-intensity, and stand-replacing (Keeley 1995; Keeley & Zedler 2009; Balch et al. 2017). Globally, Mediterranean climate regions are characterized by evergreen sclerophyllous-leaved shrublands. The Mediterranean climate region in California is dominated by chaparral, which is adapted to the periodic fire regime in California (Venturas et al. 2016). Previous studies have proposed a variety of relationships between chaparral LFMC and fire danger in southern California (Dennison et al. 2008; Dennison & Moritz 2009), but less is known about how climate changes could alter LFMC and fire danger. In chaparral, LFMC is usually high during the winter and spring (wet season) and then gradually declines during the dry season (summer and fall), which leads to a typical fire season approximately six months long in southern California (Pivovaroff et al. 2019). One key risk is that severe drought conditions are becoming exacerbated under climate change, which might lead to the occurrence of larger and higher-intensity fires in chaparral (Dennison et al. 2008; Dennison & Moritz 2009).

There has been a long history of wildfire modeling, with three types of models: 1) fine-scale fire behavior models (e.g. FIRETEC by Linn et al. 2002); 2) landscape-scale fire disturbance models (e.g. LANDIS-II by Sturtevant et al. 2009); and 3) global-scale fire dynamics models (e.g. SPITFIRE by Thonicke et al. 2010). While these models focus on simulation at different scales, their fire danger indices are mainly calculated from climate and dead fuel moisture and currently lack dynamic prediction of LFMC. One key limitation is that most previous models have not yet considered plant hydrodynamics (Holm et al. 2012; Xu et al. 2013; Seiler et al. 2014), which is integral to LFMC prediction. Recently, there have been important improvements to global dynamic vegetation models by incorporating plant hydrodynamics (Fisher et al. 2018). These models have been used to study the interaction between elevated CO_2 and drought (Duursma & Medlyn, 2012), the impact of hydraulic traits on plant drought response (Christofferson et al. 2016), the role of hydraulic diversity in vegetation response to drought (Xu et al. 2016) and hydroclimate change (Powell et al. 2018), and vegetation water stress and root water uptake (Kennedy et al. 2019). While the main purpose of the new hydraulic components is to improve the vegetation response to drought, the fact that hydrodynamic models consider tissue water content as a prognostic variable provides an opportunity to assess the climate impacts on LFMC.

The objective of this study is to quantify LFMC dynamics and associated changes in fire season duration for a chaparral ecosystem in southern California under climate change using a vegetation demographic model that incorporates plant hydraulics. We test one overarching

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hypothesis: future climate change will decrease LFMC and result in a longer fire season as determined by a critical threshold of LFMC (H_0). Specifically, we test the following four sub-hypotheses: 1) warming has a stronger impact on LFMC than CO_2 fertilization (H_1); 2) seasonal changes in precipitation lead to a longer fire season as determined by LFMC (H_2); 3) the combined impacts of warming and precipitation on fire season length are equal to the additive impacts of warming and precipitation change individually (H_3); and 4) plants with more conservative hydraulic strategies ("avoiders") will be more sensitive to warming because their higher water storage capacity could be more vulnerable to warming (H_4).

2. Materials and Methods

To understand climate change impacts on LFMC for the chaparral ecosystem, we applied the Functionally Assembled Terrestrial Simulator (FATES; Fisher et al. 2015; Massoud et al. 2019; Koven et al. 2020) coupled with a hydrodynamic vegetation module (FATES-HYDRO; Christoffersen et al. 2016) in the Santa Monica Mountains in California. We validated the model using the observed LFMC for three chaparral shrub PFTs. Then, we applied FATES-HYDRO to estimate long-term dynamics of LFMC during 1950-2099 for each PFT using downscaled Earth System Model (ESM) climate scenarios. Based on the simulated LFMC, we evaluated wildfire danger based on the number of days per year of LFMC below the critical value of 79% from 1950 to 2099 for each PFT under RCP 4.5 and 8.5. Finally, we assessed the relative importance of changes in individual and combined climate variables including CO_2, temperature, precipitation, and relative humidity and tested the corresponding hypotheses.

2.1 Study site

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The study site is located at the Stunt Ranch Santa Monica Mountains Reserve, in the Santa Monica Mountains in California, USA (N 34° 05', W 118° 39'). Stunt Ranch is dominated by chaparral vegetation, with an elevation of approximately 350 m and a Mediterranean-type climate. The average maximum temperature is 31.5 °C and the average minimum temperature is 4.6 °C. Mean annual precipitation is 478 mm, occurring mostly during the wet season (i.e. November-March) with almost no rainfall during the dry season (i.e. April-October). Soil texture information for Stunt Ranch is based on a national soil survey database (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx; Table S1). We focused on PFTs representing 11 study species, including chamise (*Adenostoma fasciculatum* - Af), red shank (*Adenostoma sparsifolium* - As), big berry manzanita (*Arctostaphylos glauca* - Ag), buck brush (*Ceanothus cuneatus* - Cc), greenbark ceanothus (*Ceanothus spinosus* - Cs), mountain mahogany (*Cercocarpus betuloides* - Cb), toyon (*Heteromeles arbutifolia* - Ha), laurel sumac (*Malosma laurina* - Ml), scrub oak (*Quercus berberidifolia* - Qb), hollyleaf redberry (*Rhamnus ilicifolia* - Ri), and sugar bush (*Rhus ovata* - Ro). Detailed information about the study site and species characterizations found at Stunt Ranch can be found in Venturas et al. (2016) and Pivovaroff et al. (2019).

2.2 FATES-HYDRO model

FATES is a vegetation demographic model (Fisher et al. 2015), which uses a size-structured group of plants (cohorts) and successional trajectory-based patches using the ecosystem demography approach (Moorcroft et al. 2001; Massoud et al. 2019). FATES simulates growth in part by integrating photosynthesis across different leaf layers for each cohort. FATES allocates photosynthetic carbon to storage and leaf, root, and stem tissues based on the allometry of different plant species (Koven et al. 2020). Mortality within FATES is mainly simulated by

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carbon starvation caused by depletion of carbon storage and hydraulic function failure caused by embolism via the hydrodynamic model (Christoffersen et al. 2016). FATES is coupled with the Exascale Energy Earth System Model (E3SM, Caldwell et al., 2019) land model (ELM).

A key component of FATES, the plant hydrodynamic model (HYDRO; Christoffersen et al. 2016), simulates the water flow from soil through root, stem and leaf to the atmosphere. In this model, water flow is calculated based on water pressure gradients across different plant compartments (leaf, stem, transporting roots, absorbing roots and rhizosphere). Specifically, flow between compartment i and i + 1 (Q_i) is given by

$$Q_i = -K_i \Delta h_i \qquad (1)$$

where K_i is the total conductance (kg MPa^{-1} s^{-1}) at the boundary of compartments i and $i+1$ and Δh_i is the total water potential difference between the compartments:

$$\Delta h_i = \rho_w g(z_i - z_{i+1}) + (\psi_i - \psi_{i+1}) \qquad (2)$$

where z_i is compartment distance above (+) or below (-) the soil surface (m), ρ_w is the density of water (10^3 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), and ψ_i is tissue or soil matric water potential (MPa). K_i is treated here as the product of a maximum boundary conductance between compartments i and $i+1$ ($K_{max,i}$), and the fractional maximum hydraulic conductance of the adjacent compartments (FMC_i or FMC_{i+1}), which is a function of the tissue water content. A key parameter that controls FMC is the critical water potential (P_{50}) that leads to 50% loss of hydraulic conductivity. The tissue water potential is calculated based on pressure-volume (PV) theory (Tyree & Hammel, 1972; Tyree & Yang, 1990; Bartlett et al., 2012). For leaves, it is described by three phases: 1) capillary water phase with full turgor, 2) elastic drainage phase before reaching turgor loss point; and 3) post-turgor loss phase. For other tissues, it only has phases 2 and 3. Compared to a non-hydrodynamic model, this formulation allows the simulation

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of plant water transport limitation on transpiration. For the non-hydrodynamic version of FATES, the water limitation factor for transpiration (B_{tran}) is calculated based on the soil moisture potential (Fisher et al. 2015). For the hydrodynamic version, B_{tran} is calculated based on the leaf water potential (ψ_l) (Christoffersen et al. 2016) as follows,

$$B_{tran} = [1 + (\frac{\psi_l}{P_{50\_gs}})^{a_l}]^{-1}, \quad (3)$$

where P_{50_gs} is the leaf water potential that leads to 50% loss of stomatal conductance and a_l is the shape parameter. Please refer to Christoffersen, et al. 2016 for details of formulations of FMC for different plant tissues.

Because the main purpose here is to assess LFMC, we controlled for variation in size structure that could arise from hydrodynamic trait or climate differences between model runs by using a reduced-complexity configuration of the model where growth and mortality are turned off and ecosystem structure is held constant. The plant sizes and number density are set based on a vegetation inventory from Venturas et al. (2016).

2.3 Allometry and trait data for model parameterization

FATES-HYDRO has a large number of parameters (>80; see Massoud et al. 2019 for a complete list except for hydraulic parameters). Based on a previous sensitivity analysis study (Massoud et al. 2019), we focused on estimating the most influential parameters for allometry, leaf and wood traits, and hydraulic traits from observations of 11 chaparral shrub species (see Supplementary, Table S2), collected from Jacobsen et al. (2008) and Venturas et al. (2016). Based on a hierarchical cluster analysis of allometry and trait data, the chaparral shrub species were classified into three PFTs (Fig. 1 and Table S3): a low productivity, aggressive hydraulic strategy PFT (PFT_LPAH) with a relative low $V_{c,max25}$ (the maximum carboxylation rate at 25

^{o}C) and a very negative P_{50} (the leaf water potential leading to 50% loss of hydraulic conductivity); a medium productivity, conservative hydraulic strategy PFT (PFT_MPCH) represented by a medium $V_{c,max25}$ and a less negative P_{50}, turgor loss point and water potential at full turgor; and a high productivity, aggressive hydraulic strategy PFT (PFT_HPAH) with a relatively high $V_{c,max25}$ and a very negative P_{50}. The mean of species-level trait data weighted by species abundance at the site were used to parameterize FATES-HYDRO.

2.4 Live Fuel Moisture Content for model evaluation

In this study, we used measured LFMC to validate the FATES-HYDRO predictions. LFMC (%) is the ratio of water weight to dry weight of living plant tissue (Burgan 1979). LFMC was measured approximately every three weeks, concurrently with plant water potentials in 2015 and 2016 (Pivovaroff et al. 2019). For comparison with our model outputs, we calculated the mean LFMC within leaves for each PFT weighted by the species abundance (Venturas et al. 2016).

2.5 Climate drivers

We forced the FATES-HYDRO model with temperature, relative humidity, precipitation, downward solar radiation, wind components, and specific humidity. Historical climate data during 2012-2019, which were used for FATES-HYDRO calibration, were extracted from a local weather station (https://stuntranch.ucnrs.org/weather-date/). Historical and future climate data during 1950-2099, which were used for simulations of LFMC by FATES-HYDRO model, were downloaded from the Multivariate Adaptive Constructed Analogs (MACA) datasets (Abatzoglou & Brown 2011; http://maca.northwestknowledge.net). The MACA datasets (1/24-degree or approximately 4-km; Abatzoglou & Brown 2011) include 20 ESMs with historical forcings during 1950-2005 and future Representative Concentration Pathways (RCPs) RCP 4.5 and RCP8.5 scenarios during 2006-2099 from the native resolution of the ESMs. As training data for MACAv1/v2-METDATA, the gridded surface meteorological dataset METDATA (Abatzoglou, 2013) were used with high spatial resolution (1/24-degree) and daily timescales for near-surface minimum/maximum temperature, minimum/maximum relative humidity, precipitation, downward solar radiation, wind components, and specific humidity.

2.6 Hypothesis testing

To test H_0, we compared the simulated LFMC under the climate projections from 20 ESMs under RCP 4.5 and 8.5. We then tested if the LFMC during the April-October dry season in the historic period of 1950-1999 is significantly higher than that in the future period of 2075-2099. For the fire season duration, we estimated the number of days per year below a critical threshold of LFMC (79%). Similarly, we tested if the number of days per year below the critical threshold of LFMC during the historical period are significantly different from that during the future period.

To test H_1, we compared model outputs of mean LFMC and fire season length for three PFTs with/without CO_2 changes (fixed CO_2 at 367 ppm vs dynamic CO_2 concentrations from RCP 4.5 or RCP 8.5) and warming. To remove the future warming trend, future temperature was replaced with historical (1986-2005) temperature data for every 20 year period. Similarly, to test H_2, we compared the model outputs of LFMC and fire season length for three PFTs with/without precipitation changes. To test H_3, we compared model outputs of LFMC and fire season length for three PFTs under three scenarios: 1) without warming; 2) without precipitation changes; and 3) without warming and precipitation changes. Finally, to test H_4, we compared model outputs of LFMC and fire season length across the three different PFTs with different hydraulic strategies.

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3. Results

3.1 Comparison between simulated and measured LFMC

Our results showed that FATES-HYDRO was able to capture variation in the LFMC for different PFTs (Fig. 2). Specifically, the model was able to capture 93%, 88%, and 82% of the variance in observed LFMC for the period of 2015-2016 for three PFTs, respectively (Fig. 2 b, d, f). The model was also able to capture the seasonal dynamics of LFMC in comparison to observed data (Fig. 2 a, c, e).

3.2 Changes in the LFMC and fire season length from historical to future periods

Using the validated model driven by climate projections from 20 ESMs under greenhouse gas emission scenarios RCP4.5 and RCP 8.5, we found that the daily mean LFMC during the future period of 2075-2099 was projected to become significantly lower than that during the historical period of 1950-1999 for all three PFTs (Fig 3, $P<0.0001$). Specifically, the histogram of daily mean LFMC during the April-October dry season showed that there was a higher probability of low LFMC under future climate conditions (Fig. S1). The daily mean LFMC decreased from 84.9%, 101.5%, and 78.6% during the historical period of 1950-1999 to 81.3-83.1%, 96.6-99.2%, and 75.1-76.9% during the future period of 2075-2099 under both climate scenarios for PFT_LPAH, PFT_MPCH, PFT_HPAH, respectively (Fig 3).

Based on the projected LFMC, there was a significant increase in the fire season length with the critical threshold of LFMC from the historical period of 1950-1999 to the future period of 2075-2099 for three PFTs. With the critical threshold of 79% LFMC, the fire season length was projected to increase by 21, 23, 20 days under RCP 8.5 (Fig. 4 and Table S4), and to increase by 10, 12, 9 days under RCP 4.5 (Fig. 4 and Table S4). The above results for mean

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LFMC and fire season length support hypothesis H_0 that future climate change will decrease LFMC and result in a longer fire season, as determined by critical thresholds for LFMC, for all three PFTs.

3.3 Relative effects of individual climate changes on the length of the fire season

In order to better understand the relative contribution to fire season length of different climate variables, we ran FATES-HYDRO for three PFTs using meteorological forcings that isolated and removed changes in individual specific variables. Our results showed that the increase in fire season length mainly resulted from warming, which led to 17-24 days (9.5-19.1%) per year increase in fire season length for the critical threshold of 79% LFMC under RCP 8.5 (Fig. 5). For RCP 4.5, the warming contributed to 6-7 days (4.1-4.7%) per year increase in fire season length (Fig. 5). We also found that elevated CO_2 concentrations decreased fire season length with 7-8 days (3.7-5.1%) per year decrease in fire season length under RCP 8.5 (Fig. 5). Under RCP 4.5, CO_2 increases led to 2-3 days (1.7-2.4%) per year decrease in fire season length (Fig. 5). Because the impact of warming on fire season length was stronger than the mitigation from CO_2 enrichment, our results support hypothesis H_1.

Even though total precipitation was projected to increase in the future, lower precipitation in the spring and autumn (Fig. S2 a, b) led to 9-11 days (6.6-8.3%) per year increase in fire season length with the critical threshold of 79% LFMC under RCP 8.5 (Fig. 5). Under RCP 4.5, the precipitation changes contributed to 1-3 days (0.9-1.7%) increase in fire season length (Fig. 5). This result supported hypothesis H_2 that seasonal changes in precipitation lead to a longer fire season as determined by LFMC.

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Our results showed that the combined impacts of warming and precipitation on fire season length were equal to the additive impacts of warming and precipitation change individually. This supported hypothesis H_3. Specifically, the combined changes in temperature and precipitation caused 26-35 days per year (16.1-27.4%) increase in fire season length with the critical threshold of 79% LFMC under RCP 8.5 (Fig. 5). Under RCP 4.5, the combined changes in temperature and precipitation caused a 7-10 days per year (5.0-6.4%) change in fire season length.

3.4 Comparison of changes in fire season length among three PFTs under climate change

Regarding three PFTs under both climate scenarios, fire season length of PFT_HPAH was the longest (165-176 days per year), while fire season length of PFT_MPCH was the shortest (113-124 per year) during 2075-2099 (Fig. 4). However, the response of fire season length to warming was strongest for PFT_MPCH. Specifically, for PFT_MPCH, warming under RCP 8.5 led to an increase of 23 days in fire season length (Fig. 5 b) and warming under RCP 4.5 led to an increase of 12 days in fire season length. For PFT_LPAH, warming under RCP 8.5 led to an increase of 21 days in fire season length (Fig. 5 a) while warming under RCP 4.5 led to an increase of 10 days in fire season length. Finally, for PFT_HPAH, warming under RCP 8.5 led to an increase of 19 days in fire season length (Fig. 5 c) and 9 days in fire season length with under RCP 4.5. Because PFT_MPCH has a more conservative hydraulic strategy with less negative P_{50}, turgor loss point and water potential at full turgor, this result supported hypothesis H_4 that the more conservative hydraulic strategy will be more sensitive to warming.

4. Discussion

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Low LFMC within shrub leaves and small branches increases the flammability and likelihood of combustion, making it vitally important to monitor temporal variations in LFMC, especially during the dry season (Dennison et al, 2008). The strong relationships between observed and simulated LFMC of all PFTs suggested that the plant hydrodynamic model, FATES-HYDRO, could accurately estimate LFMC seasonal dynamics, and consequently be useful to predict fire risks in Mediterranean-type climate regions. During the future period (2075-2099) and the historical period (1950-1999), both periods displayed lower values in the dry season (April - October), which is consistent with lower LFMC during the summer-fall dry season, rather than the winter-spring wet season (Chuvieco et al, 2004; Pellizzaro et al, 2007; Pivovaroff et al. 2019). Extremely low daily LFMC was more likely to occur during the future period, which had higher temperature than the historical period. From the historical to the future period, fire season length could increase by 5.5-15.2% as determined by the critical threshold of LFMC of 79% under climate change for chaparral shrub ecosystems (H_0).

Quantifying influences of climatic variables on LFMC is crucial to predicting future fire risks (Dennison & Moritz, 2009). Our results showed that future warming was the most important driver of LFMC. This finding suggested that higher temperature would substantially decrease LFMC and strongly increase the fire season length, which may greatly increase fire risks in the future (e.g. Dennison et al, 2008; Chuvieco et al, 2009; Pimont et al, 2019). CO_2 fertilization is expected to reduce stomatal conductance (Pataki et al. 2000; Tognetti et al. 2000) and thus could mitigate the impacts of warming on LFMC. Our results displayed that, even though the CO_2 impact did cause a 3.7-5.1% reduction in fire season length, the impact of warming on fire season length is about 5.8-14% larger than the CO_2 effect (H_1). This result suggests that CO_2 fertilization cannot offset the LFMC impacts from warming. The FATES-HYDRO model assumes a consistent stomatal sensitivity to CO_2 concentration across Mediterranean shrub species. While Mediterranean shrub species in arid and semi-arid systems would vary in their stomatal response in the real world (Pataki et al. 2000). Therefore, our model may overestimate the CO_2 effect on stomatal conductance and its mitigating influence might be smaller in reality for some species.

Previous studies implied that the timing of precipitation may have a strong impact on subsequent LFMC (e.g. Veblen et al. 2000; Westerling et al. 2006; Dennison & Moritz 2009). In this study, precipitation was also the key driver of LFMC under future climate conditions. Our results showed that, even though total precipitation was projected to increase, the reduction in spring and autumn precipitation was projected to cause a longer fire season length (H_2; Fig. 5). This result was in agreement with a prior study indicating that spring precipitation, particularly in the month of March, was found to be the primary driver of timing of LFMC changes (Dennison & Moritz 2009). We also found that the combined impacts of warming and precipitation on fire season length were equal to the linearly additive impacts of warming and precipitation change individually (H_3). Our results suggested that, when evaluating future fire risks, it is critical that we considered the seasonal changes in precipitation and its interaction with the warming impact.

Modeled vegetation responses to environmental changes could be determined by variations in traits (Koven et al, 2020). For three PFTs co-occurred in the simulations, even though they grew together and showed similar patterns in LFMC in response to climate change during 1950-2099, we did see some critical differences. Specifically, the plant functional type (PFT_MPCH) with more conservative hydraulic strategy had the strongest responses to climate change (Fig. 5). This could be related to the fact that the PFT_MPCH is more conservative in

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terms of hydraulic strategy with less negative P_{50}, turgor loss point, and water potential at full turgor. The PFT_MPCH plants had a relatively high saturated water content based on observed data (Fig 2) and the water within plant tissues could change more quickly in response to the environmental condition changes (H_4).

5. Conclusions

A hydrodynamic vegetation model, FATES-HYDRO, was used to estimate historical and future LFMC dynamics of chaparral shrub species in southern California under climate change. FATES-HYDRO model was validated using monthly mean LFMC for three PFTs. The fire season length was projected to substantially increase under both climate scenarios from 1950-1999 to 2075-2099. This could increase wildlife risk over time for chaparral shrubs in southern California. Our results showed that temperature was the most important driver of LFMC and relative humidity was the least important among four climatic variables including CO_2, temperature, precipitation, and relative humidity. The LFMC estimated by the FATES-HYDRO model offered a baseline of predicting plant hydraulic dynamics subjected to climate change and provided a critical foundation that reductions in LFMC from climate warming may exacerbate future wildfire risk.

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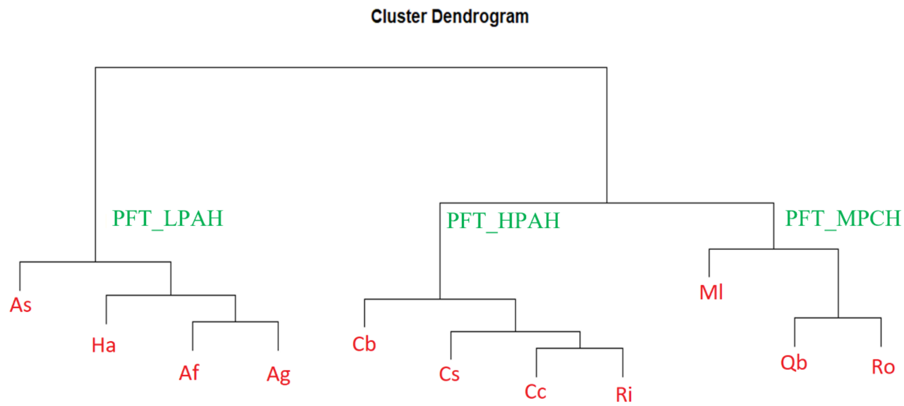
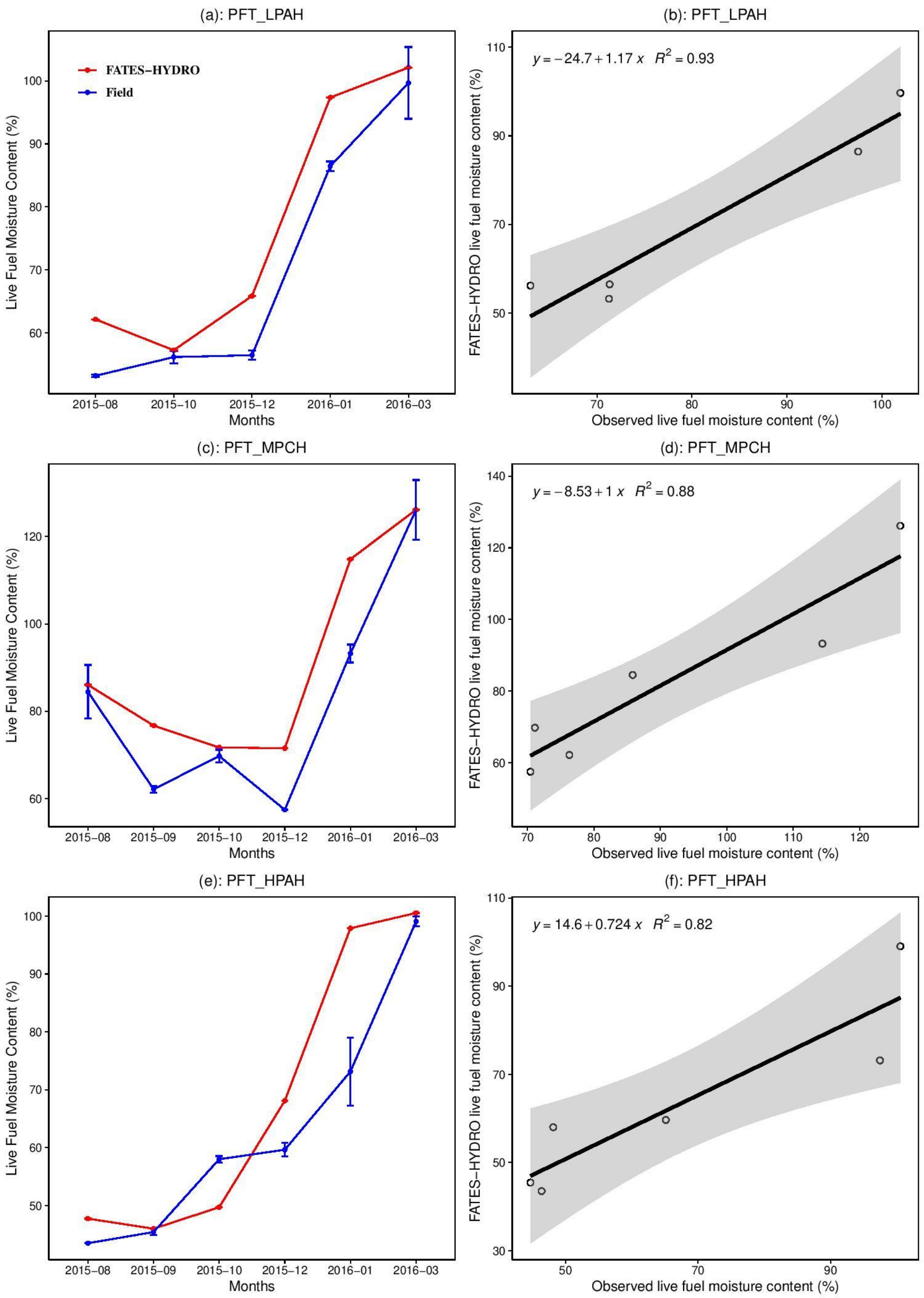


Fig 1. Hierarchical cluster analysis of allometry and hydraulic traits for eleven chaparral shrub species used to define three plant functional types at Stunt Ranch. The plant functional types with a Low Productivity and an Aggressive Hydraulic strategy (PFT_LPAH) was defined based on traits of red shank (Adenostoma sparsifolium - As), toyon (Heteromeles arbutifolia - Ha), Chamise (Adenostoma fasciculatum - Af), big berry manzanita (Arctostaphylos glauca - Ag); the plant functional types with a High Productivity and an Aggressive Hydraulic strategy (PFT_HPAH) was defined based on traits of mountain mahogany (Cercocarpus betuloides - Cb), greenbark ceanothus (Ceanothus spinosus - Cs), buck brush (Ceanothus cuneatus - Cc), hollyleaf redberry (Rhamnus ilicifolia - Ri); the plant functional types with a Medium Productivity and an Conservative Hydraulic strategy (PFT_MPCH) was defined based on traits of laurel sumac (Malosma laurina - Ml), scrub oak (Quercus berberidifolia - Qb), sugar bush (Rhus ovata - Ro).



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667 **Fig.2** Simulated and observed monthly live fuel moisture content and related R^2 for three PFTs
668 (refer to Figure 1 for explanation of the PFTs).

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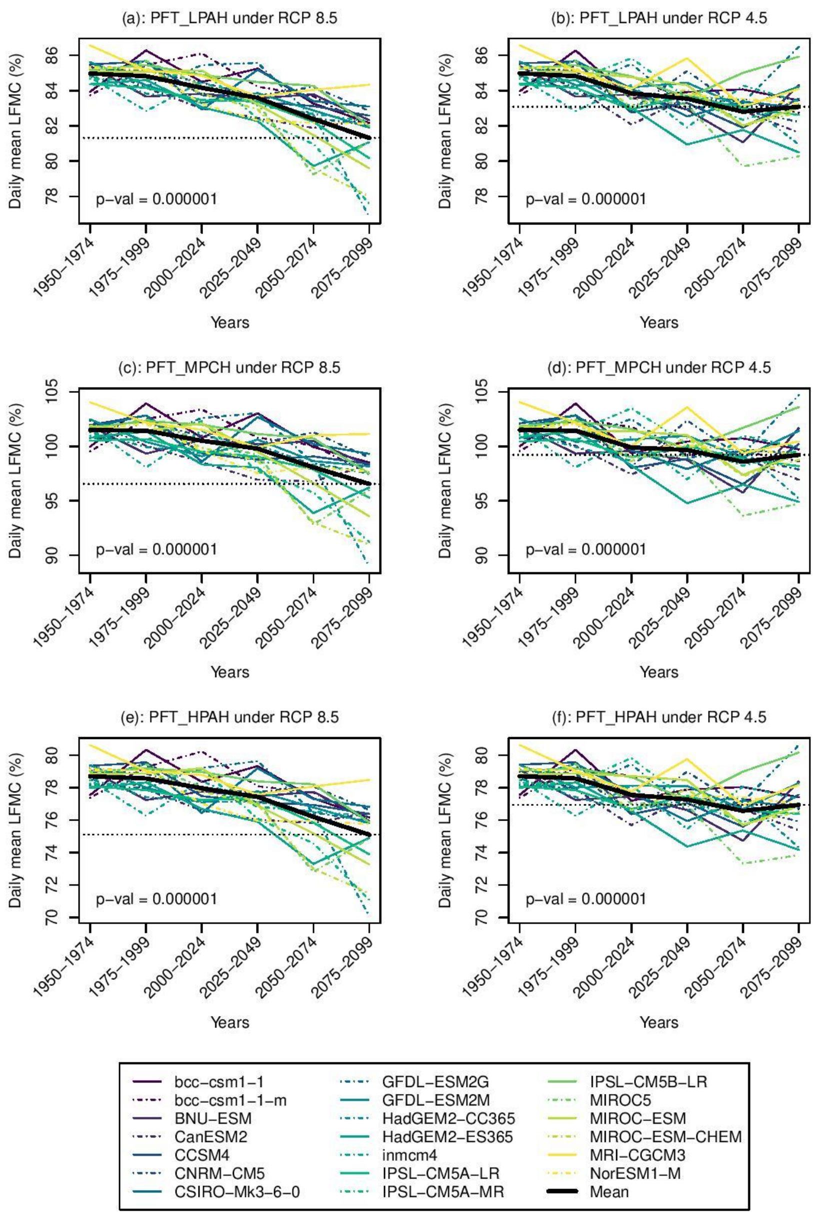

Fig.3 Temporal changes in daily mean live fuel moisture content from 1950 to 2099 for three PFTs (refer to Figure 1 for explanation of the PFTs) under climate scenario RCP 4.5 and 8.5 considering all climatic variables changes. The P values were calculated using bootstrap sampling to test whether the daily mean live fuel moisture content across different models during the future period (2075–2099) was significantly lower than that during the historical period (1950-1999). The grey horizontal dotted line represents the ensemble mean for 2075–2099.

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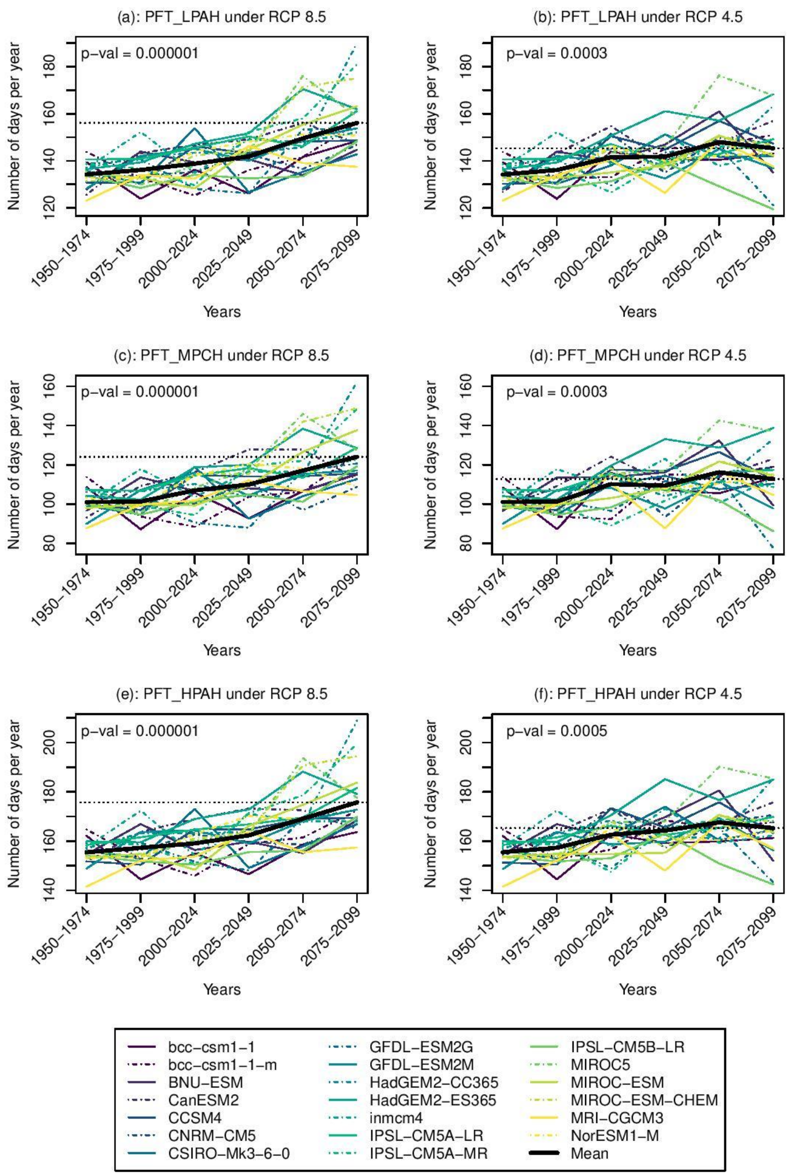

Fig.4 Temporal changes in number of days per year of live fuel moisture content below 79% from 1950 to 2099 for three PFTs (refer to Figure 1 for explanation of the PFTs) under climate scenario RCP 4.5 and 8.5 considering all climatic variables changes. The P values were calculated using bootstrap sampling to test whether the number of days across different models during the future period (2075–2099) was significantly higher than that during the historical period (1950-1999). The grey horizontal dotted line represents the ensemble mean for 2075–2099.

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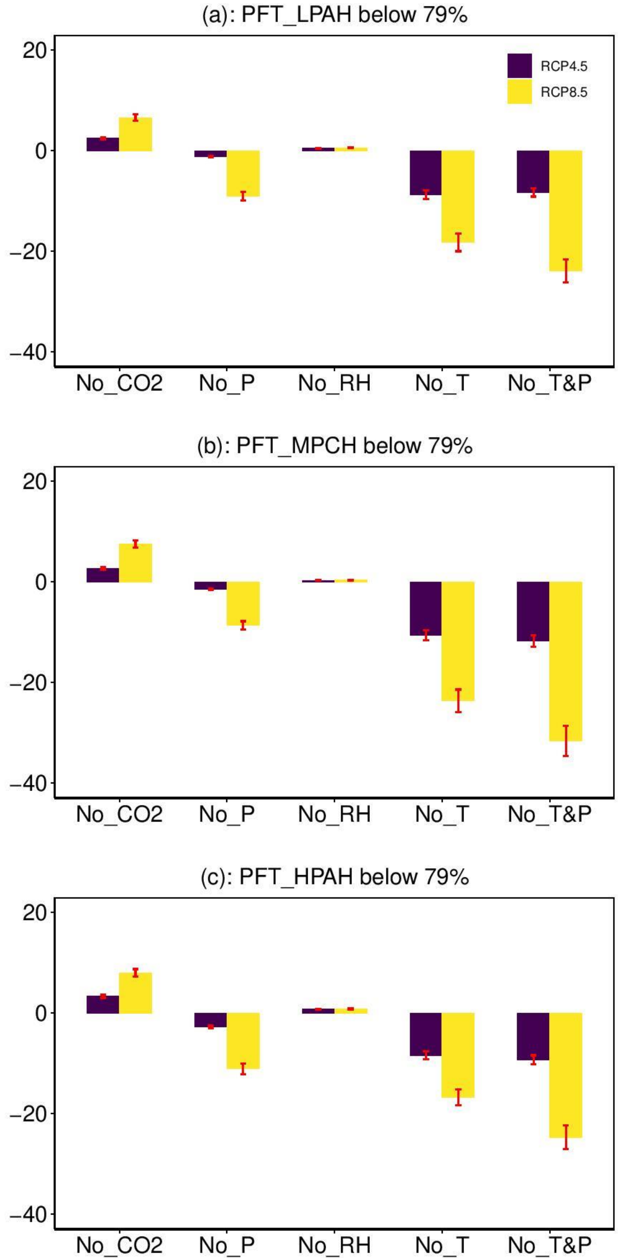

Fig.5 Differences on number of days per year of live fuel moisture content below 79% from 2075 to 2099 for three PFTs (refer to Figure 1 for explanation of the PFTs) under climate scenario RCP 4.5 and 8.5 between considering all climatic variables changes and without considering CO_2, precipitation, temperature, precipitation & temperature, relative humidity changes.