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Responses of dead forest fuel moisture to climate change

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Abstract

Forest fuel moisture is an important factor for wildland fire behavior. Predicting future wildfire trends and controlled burned conditions is essential to effective natural resource management, but the associated effects of forest fuel moisture remain uncertain. This study investigates the responses of dead forest fuel moisture to climate change in the continental United States, one of the global regions with frequent wildfire and controlled burning activities. Moisture content was calculated for dead fuels with 1- and 1000-hr lags (MC_1 and MC_{1000}) using the algorithms from the U.S. National Fire Danger Rating System. A set of dynamically downscaled regional climate change scenarios provided by the North American Regional Climate Change Assessment Program was used. The present fuel moisture shows large seasonal variations peaked in winter and spatial variability with dominant meridional change in winter and zonal change in summer. Fuel moisture is projected to decrease overwhelmingly across the United States, mainly caused by temperature increases. The largest MC_1 decrease of over 1% mainly occurs in the southwestern United States in spring and southeastern United States in summer, while the largest MC_{1000} decrease of over 1.5% occurs in the southwestern United States in spring and in the southern Plains and eastern United States in summer. The spatial patterns and seasonal variations of future fuel moisture trends, however, vary considerably with regional climate change scenarios. The drying fuel trends suggest that frequency, size, and intensity of wildfires would increase and prescribed burning windows would decrease in the future in the Southwest and the intermountains during spring and the Rocky Mountains during summer if other fuel conditions remain the same. These results highlight the general vulnerability of semiarid forests to drying fuels trends.

KEYWORDS

climate change, CONUS, dead fuel, moisture, wildland fires

1 | INTRODUCTION

Forest fuels such as downed leaves and branches, duff, and litter are part of surface fuels lying on or immediately above the ground (O'Brian, 2004). Surface fuels are surrounded above by canopy fuels (mainly green woods located in the upper forest canopy) and below by ground fuels (primarily duff or soil organic layer lying beneath the surface). Surface fuels, especially dead fuels, receive specific attention in fire management because most wildfires ignite from these fuel sources.

Fuel moisture is the amount of water in fuel. It is one of the most important fuel characteristics for fire occurrence, spread, intensity, and other fire behavior (Rothermel, 1983). The probability of fire ignition is highly dependent on fuel moisture (Wotton & Martell, 2005). Under low fuel moisture, a majority of heat energy will turn into flame rather than evaporation latent heat (Viegas, 1998). Thus, fire is easier to start. For this reason, fuel moisture is a useful indicator for whether a fire ignited by lighting will occur (Dowdy & Mills, 2012). Furthermore, ignited fire spreads faster and more intensely with dry fuel (Baeza, Raventos, De, & Escarre, 2002; Rothermel, 1972; Taylor, Woolford, Dean, & Martell, 2013). Fuel moisture is an essential factor used in various fire danger rating systems such as the U.S. National Fire Danger Rating System (NFDRS) (Burgan, 1988; Deeming, Burgan, & Cohen, 1977), the Canadian Forest Fire Weather Index System (Stocks *et al.*, 1989), and the Australia McArthur Forest Fire Danger Index (Dowdy, Finkele, Mills, & De Groot, 2009).

Fuel moisture is also an important parameter for prescribing a controlled burn. Safety is a primary consideration when land managers prepare a burn prescription. When fuels are dry, controlled fires are more intense, spread faster, and therefore are more difficult to control.

As a result, a controlled fire could go beyond the planned burning area, turning into a spot fire or even a wildfire.

Weather is a major controller of fuel moisture. Water within fuels can change through many mechanisms related to atmospheric conditions. Fuel moisture increases mainly through collecting and storing precipitating water. On the other hand, water within fuels decreases through evaporation on the fuel surface, which is determined in part by air temperature, humidity, wind speed, and radiation. Many empirical (statistical relationships between fuel moisture and weather conditions) and process-based (water, energy, and other conservation relationships among fuels, atmosphere, and soil) models have been developed to predict fuel moisture (Matthews, 2014; Viney & Catchpole, 1991).

A new and urgent issue with fuel moisture is the potential future trends under climate change. Climate models have projected that the greenhouse effect will result in significant climate change by the end of this century (IPCC, 2013), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude areas. A few recent studies indicated large responses of fuel moisture to future climate change. Future fuel moisture was projected to decrease in Australia and impact adversely prescribed burning implementation (Matthews, Nguyen, & McGregor, 2011; Matthews, Sullivan, Watson, & Williams, 2012). Fuel moisture in Canada is very sensitive to future changes in temperature as well as precipitation (Flannigan *et al.*, 2015) and the implications under a future climate. The future trends in temperature and precipitation under climate change, however, have large spatial and temporary variability, suggesting large geographic and seasonal dependence of future change in fuel moisture. In addition, climate change predictions have large variability among climate models, especially at the regional scale, which leads to uncertainty in future fuel moisture trend projections.

The purpose of this study is to project the future trends of dead forest fuel moisture in the continental United States, one of the global regions similar to Australia and Canada with frequent wildfires. Wildfires have increased in recent decades in this region (e.g., Dennison, Brewer, Arnold, & Moritz, 2014; Westerling, Hidalgo, Cayan, & Swetnam, 2006). This trend is likely to continue this century (Balshi et al., 2008; Barbero, Abatzoglou, Larkin, Kolden, & Stocks, 2015Brown, Hall, & Westerling, 2004; Liu, Goodrick, & Heilman, 2013; Spracklen *et al.*, 2009; Yue, Mickley, Logan, & Kaplan, 2013). Also, prescribed burning is extensively used in this region as a forest management tool to maintain forest health and reduce wildfire risk with an annual burned area comparable with those by wildfires. The objectives of this study include calculating and analyzing the magnitude of possible future fuel moisture changes, the spatial and seasonal variability of these changes, major meteorological contributing factors, and climate change scenario dependence. The results from this study are expected to provide useful information for understanding and projecting future wildfire trends and the impacts of climate change on prescribed burning in the continental United States.

2 | METHODOLOGY

2.1 | Estimates of fuel moisture

The empirical fuel moisture models in the NFDRS (Cohen & Deeming, 1985) were used in this study. The models were developed and extensively evaluated against field measurements in the United States. In comparison with the canopy level, surface dead fuel moisture varies much faster in response to the atmospheric change. The response rate is measured by time lag, the time necessary for a departure (the difference between actual and equilibrium fuel moisture) to be reduced by about two-thirds in magnitude. The NFDRS models calculate fuel moisture with four time lags of 1, 10, 100, and 1000 hr (denoted as 1-, 10-, 100-, and 1000-hr, respectively), which represent fuels with diameters of less than 1/4 in. (0.635 cm), 1/4 to 1 in. (2.54 cm), 1 to 3 in. (7.62 cm), and greater than 3 in. The NFDRS also includes a process-based model (Carlson, Bradshaw, Nelson, Bensch, & Jabrzemski, 2007; Nelson, 2000). This process-based model was not used because it includes complex processes with a large number of fuel and soil parameters not available for this study. In addition, the process-based model is primarily for 10-hr fuels, while this study calculated moisture for both fine fuels (1 hr) and very coarse fuels (1000 hr).

Fuel moisture was characterized by moisture content (*MC*), the ratio of water to dry weight of the fuel. Fuel moisture content, MC_i (i = 1 and 10 for 1- and 10-hr fuel moisture, respectively), was calculated using the following:

$$MC_i = C_i \times MC_e, \tag{1}$$

$$MC_e = \begin{cases} a_1 + (a_2 - a_3 T)RH, & RH < 10\% \\ a_4 + a_5 RH - a_6 T, 10\% & 10\% \le RH < 50\% \\ a_7 + (a_8 RH - a_9 T - a_{10})RH, & RH \ge 50\%, \end{cases} \tag{2}$$

where MC_e is equilibrium moisture content and RH and T are air relative humidity and air temperature, respectively. C_1 = 1.03, and C_2 = 1.28. a_i (i = 1,2,…,10) are positive empirical constants. The role of precipitation (P) is taken into account indirectly by adjusting T and RH based on cloudiness. Moisture content of 1000-hr fuels, MC_{1000}, was calculated using the following:

$$MC_{1000} = MC_{1000,w} + \left(\overline{DBY} - MC_{1000,w}\right) \times \left(1 - 0.82e^{-0.168}\right), \tag{3}$$

where $MC_{1000,w}$ is MC_{1000} a week ago (the seventh previous day); $\overline{DBY}$ is the average of the daily precipitation property factor, P_f, over 7 days:

$$P_f = \left[(24 - P_{dur}) \times \overline{MC_e} + P_{dur} \times (2.7 \times P_{dur} + 76)\right]/24, \tag{4}$$

where P_{dur} is a precipitation duration indicator depending on rainfall amount and climate class, and $\overline{MC_e}$ is a weighting average of day and night MC_e, which was approximated with daily MC_e in this study. The formula for 100-hr fuel moisture is the same as Equations 3–4 except with 1-day average and different empirical constants. The calculated fuel moisture using the NFDRS empirical models was found to be systematically lower than the measured one (e.g., Estes, Knapp, Skinner, & Uzoh, 2012). The impact of the bias is minimal for this study because the focus of this study is on the future trends measured by the differences between the present and future fuel moisture.

Because of the similarity in fuel moisture calculations between 1 and 10 hr and between 100 and 1000 hr, fuel moisture was analyzed only for 1- and 1000-hr fuels in this study.

2.2 | Regional climate change scenarios

The regional climate scenarios generated by the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns *et al*., 2012) were used. The NARCCAP conducted high-resolution climate change simulations to investigate uncertainties in regional projections of future climate and to generate climate change scenarios for use in climate change impact research. Regional climate change scenarios were obtained by running a set of regional climate models (RCMs) driven by a set of global general circulation models (GCMs) over North America. The global GCMs used included the Community Climate System Model (CCSM) (Collins *et al*., 2006), the Canadian Coupled Global Climate Model, version 3 (CGCM3) (Flato, 2005), the Geophysical Fluid Dynamics Laboratory (GFDL) climate model (GFDL GAMDT, The GFDL Global Model Development Team, 2004), and the Hadley Centre Climate Model, version 3 (HadCM3) (Gordon *et al*., 2000; Pope, Gallani, Rowntree, & Stratton, 2000).

The RCMs used included the Canadian Regional Climate Model (CRCM) (Caya *et al*., 1995), the Regional Spectral Model (Juang, Hong, & Kanamitsu, 1997), the High-resolution Regional Model (HRM) (Jones *et al*., 2004), the mesoscale Meteorological Model, version 5 (MM5) (Grell, Dudhia, & Stauffer, 1993), the Regional Climate Model, version 3 (RCM3) (Pal *et al*., 2007), and the Weather Research and Forecasting model (Skamarock *et al*., 2008). A total of 10 GCM–RCM scenarios were used in this study.

Simulations were conducted for the present period of 1971–2000 and the future period of 2041–2070 at a spatial (horizontal) resolution of 50 km. The downscaling of future climate projections was made only for the IPCC Special Report on Emission Scenarios A2 emissions scenario (Nakicenovic *et al*., 2000). The A2 emission scenario together with three other scenarios combines two sets of divergent tendencies: One set varies between strong economic values and strong environmental values, while the other set varies between increasing globalization and increasing regionalization. In comparison with the A1 scenario that describes a future of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, the A2 scenario describes a very heterogeneous world with slower growth and greater regional disparity.

The two-tailed *t*-test was conducted to determine whether the difference between the present and future means of any fuel moisture or meteorological variable is statistically significant.

3 | RESULTS

3.1 | Present conditions

The spatial pattern of MC_1 shifts from mostly zonal in winter to mostly meridional in summer (Figure 1). The winter MC_1 is about 10–12% near the Mexican border and increases to 22–24% near the Canadian border. The spatial variation is much more substantial in the south–north than the west–east direction. The zonal pattern is disturbed by topography, leading to larger values in the northern Rocky Mountains and lower values in the Great Plains. The zonal pattern rotates

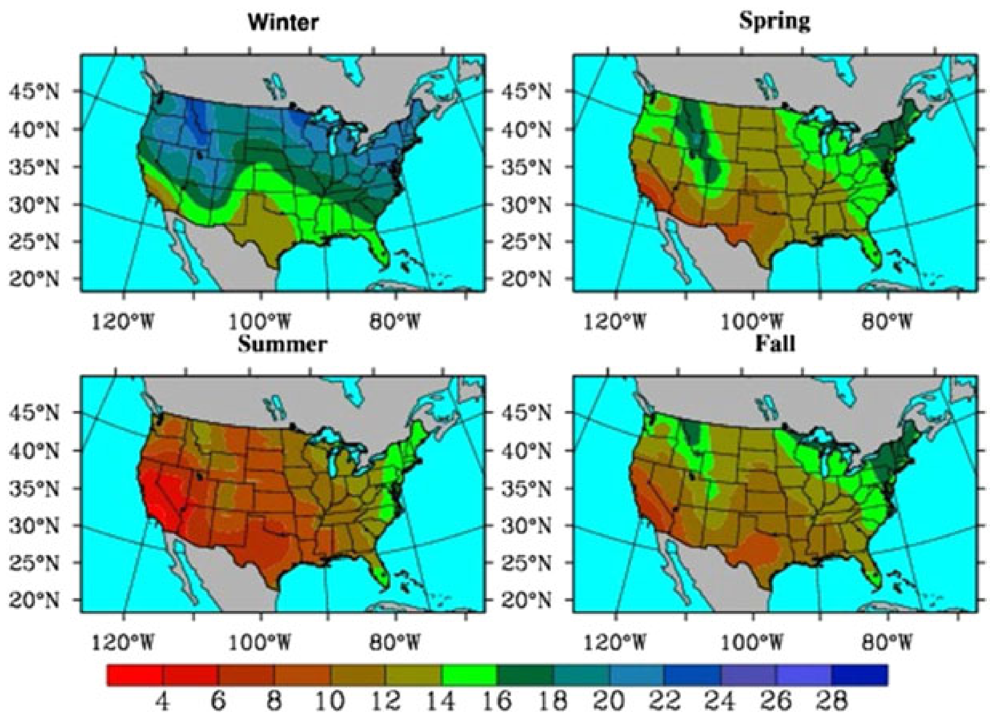

FIGURE 1 Spatial distribution of present (1971–2000) seasonal 1-hr fuel moisture (%) based on an ensemble average of 10 general circulation model–regional climate model scenarios

clockwise in spring with decreasing MC_1 by about 6% in the north, 4% along the Mexican border, and 2% in the Gulf coast region. The pattern during the summer becomes mostly meridional, featured by MC_1 changes mainly in the west–east direction from about 2% in southwestern California to about 16% in the Northeast. The MC_1 spatial pattern in fall is similar to that in spring except for slightly smaller magnitudes.

The seasonal shift in spatial patterns also can be seen in the regional averages (Figure 2). Large differences are found between the northern and southern regions in winter (20.41% in NW vs. 14.54% in SC) and between the eastern and western regions in summer (16.03% in NE vs. 9.76% in PS).

The magnitude of fuel moisture has a clear seasonal cycle. MC_1 averaged over the continental United States (CONUS) is the largest in the winter (17.79%), the smallest in the summer (10.32%), and intermediate in the spring (13.68%) and fall (12.92%).

The spatial pattern and seasonal shift of the present MC_{1000} (Figure 3) are similar to those of MC_1. MC_{1000} is larger than MC_1 in most areas (10–28% with MC_{1000} vs. 10–24% with MC_1 in winter, and 2–22% vs. 2–16% in summer). Similarly, there is a clear seasonal cycle with the MC_{1000} magnitude (Figure 4). Its CONUS averages are 19.74%, 17.84%, 14.35%, and 14.19% from winter to fall. Note that the lowest average occurs in fall instead of summer.

3.2 | Future trends

For the future projections, the MC_1 averaged over the 10 GCM–RCM scenarios decreases substantially except over some small Midwest areas in the winter and spring (Figure 5). The substantial decreases occur over the western and eastern coast regions and in Texas. The largest decrease of 1% or more occurs mainly in the southwestern United States in spring and the southeastern United States in summer. Small decreases or even increases occur in the northern Plains.

The CONUS-averaged future MC_1 decreases are slightly larger in summer (−0.61%) than winter, spring, and fall (−0.43%, −0.43, and −0.45%) (Figure 2). Regionally, larger decreases are found mainly in the southern regions, including PS, SW, and SC in winter (−0.57%, −0.63%, and −0.66%), PS and SW in spring (−0.74% and −1.11%), SW, SC, and SE in summer (−0.72%, −0.83%, and −0.80%), and SW in fall (−0.72%). The only case in the northern region with a larger decrease is the NE in summer (−0.74%). Among the 32 values of the future changes in fuel moisture (eight regions by four seasons), 5, 10, and 8 values are statistically significant at the confidence intervals of 99%, 95%, and 90%, respectively.

The spatial patterns of future MC_{1000} trends (Figure 6) are similar to those of MC_1, but with larger decreases, which are more than 1.5% in some areas. The CONUS averages are −0.93% in summer

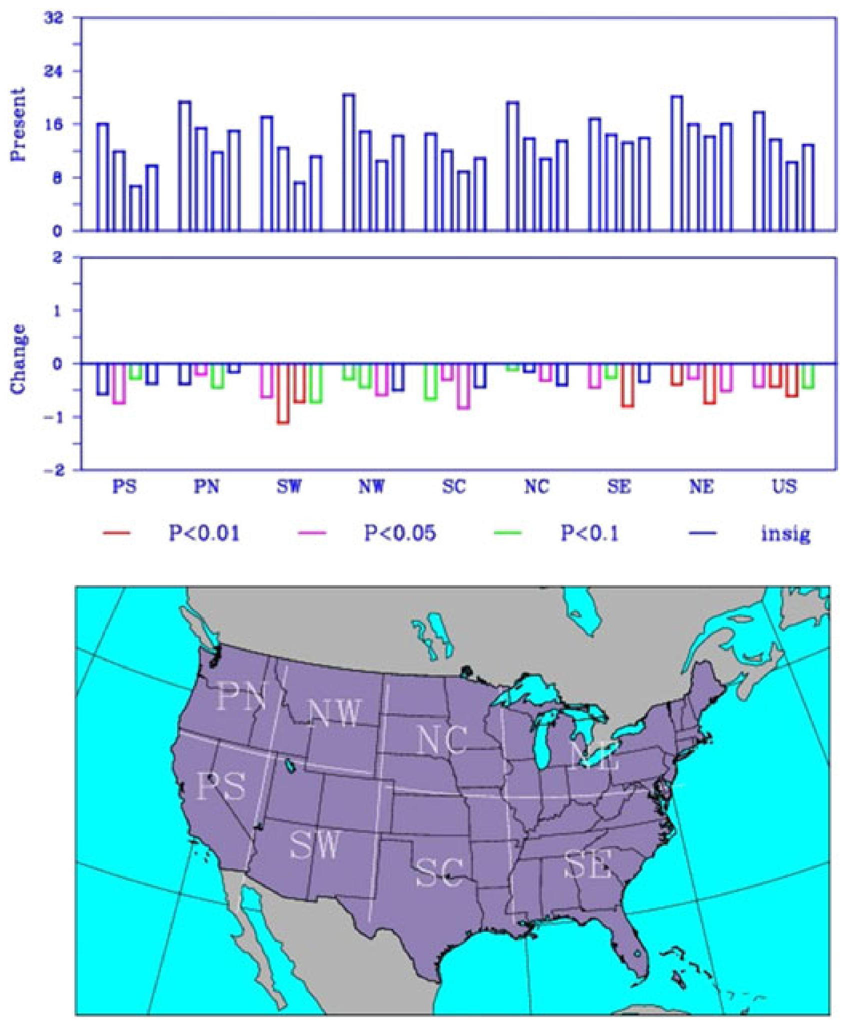

FIGURE 2 Regional 1-hr fuel moisture (%) based on an ensemble average of 10 general circulation model–regional climate model scenarios. The upper and middle panels are present period (1971–2000) and future change between 1971–2000 and 2041–2070. The four bars for each region are winter, spring, summer, and fall. The colors indicate different significance levels. Bottom panel shows regions of Pacific South (PS), Pacific North (PN), Southwest (SW), Northwest (NW), South Central (SC), North Central (NC), Southeast (SE), and Northeast (NE)

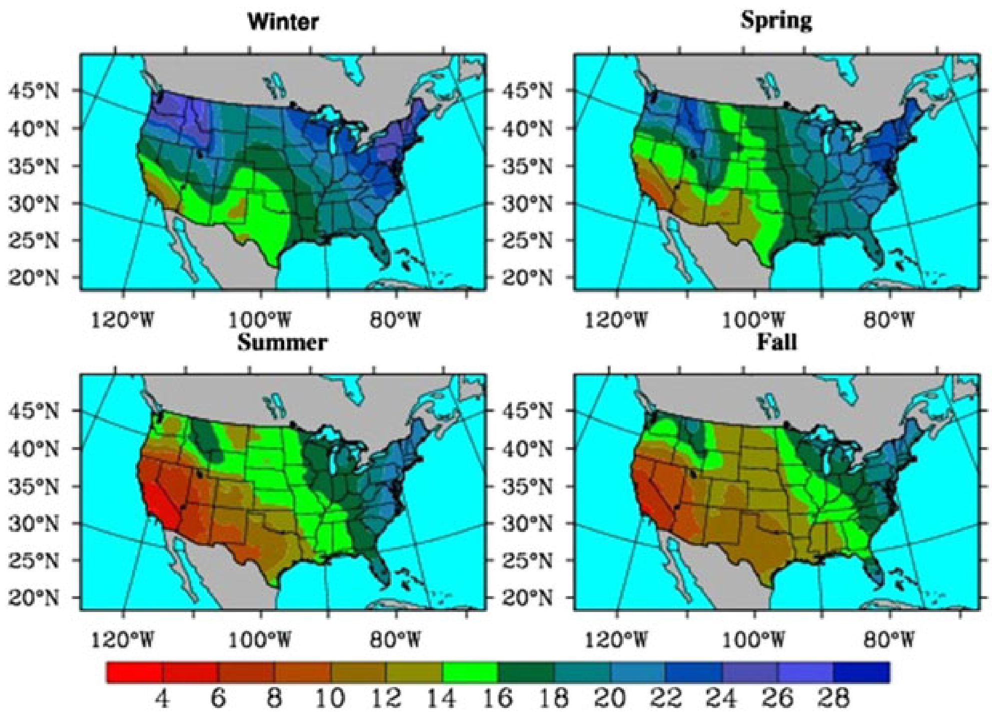

FIGURE 3 Same as Figure 1 except for 1000-hr fuel moisture (%)

and −0.70% in other seasons (Figure 4), which are about 0.3% larger than the corresponding MC_1 decreases. Regionally, decreases are −1% or more in the PS and SW regions in spring and the SC, SE, and NE regions in summer. The statistical significance of the 1000-hr fuel moisture changes is much smaller than that of 1-hr fuel moisture. Only 2, 5, and 12 values of the 1000-hr fuel moisture changes are statistically significant at the confidence intervals of 99%, 95%, and 90%, respectively, meaning that the future decreases in the 1000-hr fuel moisture are less certain than those in the 1-hr fuel moisture.

3.3 | Climate change scenario dependence

The spatial pattern and magnitude of the future moisture trends vary substantially with the GCM–RCM scenarios. The future MC_1 changes under the GFDL–HRM scenario, for example, are considerably different from the changes averaged over the 10 scenarios. The decreases are barely seen in spring and even absent in other seasons in the western and eastern coast regions. The spatial patterns also vary remarkably from one season to another. The future decreases in winter are very small, and future fuel moisture even increases slightly in the western United States. In contrast, large decreases of more than 4% occur in summer in the central Great Plains and Mississippi River Valley. For the CCSM–MM5 scenario, on the other hand, the future fuel moisture increases in the central United States all seasons with an increase of about 2% in the northern Great Plains in summer.

Future regional 1-hr fuel moisture changes vary across climate change scenario and season (Table 1). For the winter and spring, scenarios with HadCM–HRM, HadCM_MM5, GFDL–HRM, and CCSM–MM5 project large fuel moisture decreases around 1% in most regions, while CGCM–CRCM and CCSM–CRCM for both seasons and CGCM–

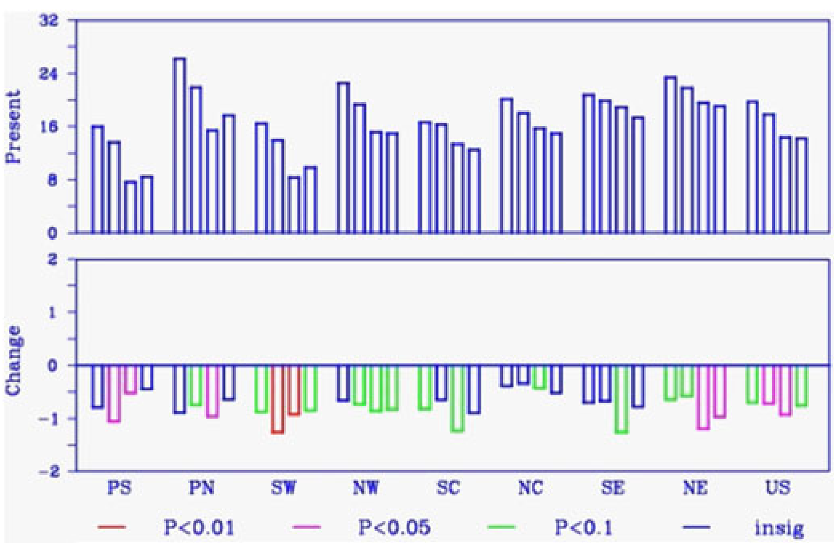

FIGURE 4 Same as the top and middle panels in Figure 2 except for 1000-hr fuel moisture (%)

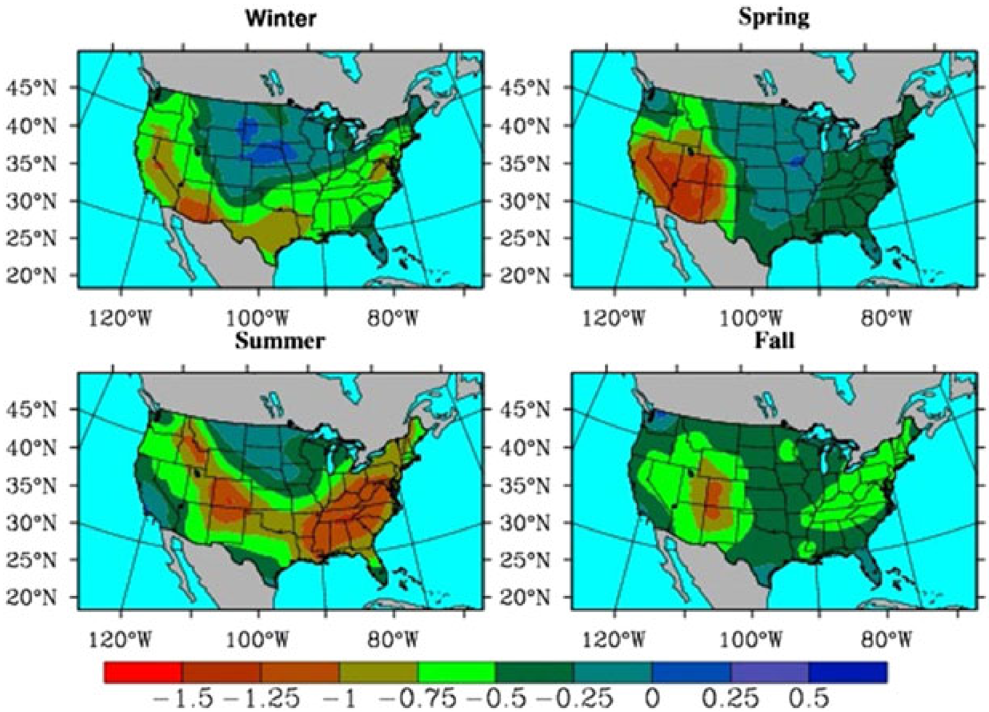

FIGURE 5 Spatial distributions of projected future changes in seasonal 1-hr fuel moisture (%) between the 1971–2000 and the 2041–2070 periods based on an ensemble average of 10 circulation model–regional climate model scenarios

Weather Research and Forecasting for spring project small decreases or even increases in many regions. For summer, the scenarios with HadCM–HRM, GFDL–HRM, and CGCM–CRCM project much larger decreases than other scenarios. The scenario dependence is less substantial in fall than in other seasons. Thus, the magnitudes of the future fuel moisture decreases in winter, spring, and summer vary across the scenarios. Two or three scenarios even project increases in many regions.

3.4 | Meteorological factors

Moisture content of 1-hr fuel is proportional to *RH* and inversely proportional to *T* (Equations 1–2). The present *T* is the lowest in winter and highest in summer, while *RH* is the largest in winter and smallest in summer for the CONUS average and for each of the eight regions (except the SE where *RH* is slightly larger in summer than fall). The seasonal variations of *T* and *RH* are consistent with the seasonal cycle

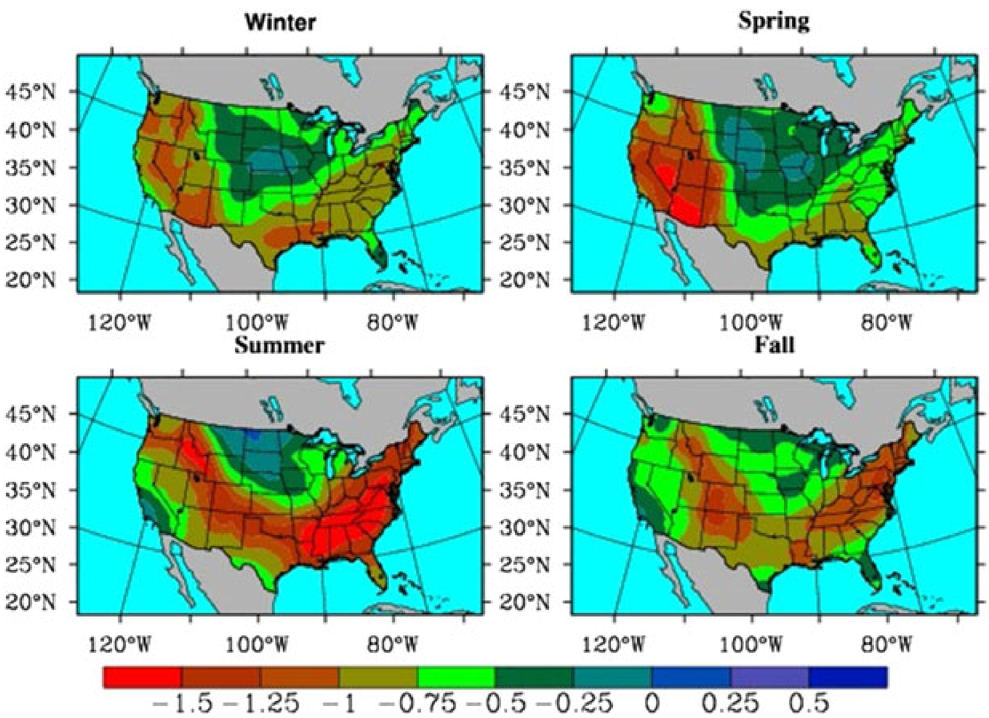

FIGURE 6 Same as Figure 5 except for 1000-hr fuel moisture (%)

TABLE 1 Future regional 1-hr fuel moisture changes (%) under various climate change scenarios (see Figure 2 for definition and locations of regional abbreviations)

		HadCM		GFDL		CGCM			CCSM		
Season	Region	HRM	MM5	HRM	RCM	RCM	WRF	CRCM	WRF	CRCM	MM5
Winter	PS	−1.0	−0.7	−0.5	0.1	−0.6	−0.7	0.1	−1.0	−0.1	−1.3
	PN	−0.7	−0.1	−0.8	−0.2	−0.2	−0.2	−0.2	−0.4	0.0	−1.0
	SW	−1.1	−1.1	−0.6	−0.1	−0.5	−0.4	0.2	−1.1	0.3	−1.9
	NW	−0.8	−0.4	−0.7	−0.5	−0.2	0.1	−0.4	0.3	0.4	−0.7
	SC	−1.1	−1.4	−1.2	−0.2	−0.4	−0.1	0.0	−1.3	−0.1	−0.7
	NC	−1.0	−0.5	−1.0	−0.4	0.0	0.8	0.2	0.2	0.6	0.1
	SE	−0.7	−1.3	−0.9	−0.2	−0.3	−0.3	−0.2	−0.5	0.2	−0.6
	NE	−0.8	−0.6	−1.3	−0.3	−0.4	−0.3	0.4	−0.4	0.8	−1.0
Spring	PS	−0.9	−0.8	−1.9	−1.0	−0.5	0.0	−0.3	−0.9	−0.3	−0.7
	PN	−0.7	−0.4	−1.3	0.1	0.4	0.3	0.8	−0.7	0.2	−0.7
	SW	−1.2	−2.0	−2.2	−1.3	−1.1	−0.3	−0.3	−0.8	0.1	−1.8
	NW	−0.7	−1.3	−1.2	0.0	0.0	0.2	0.5	−0.3	0.1	−1.7
	SC	−0.7	−0.8	−1.8	−0.6	−0.2	0.2	−0.4	0.8	0.1	0.3
	NC	−1.1	−0.8	−1.0	0.0	0.2	0.7	0.0	0.5	−0.1	0.1
	SE	−0.5	−0.6	−0.8	−0.2	0.0	0.4	−0.3	0.0	−0.3	−0.1
	NE	−0.9	−0.8	−1.2	0.0	0.1	0.5	0.1	−0.2	−0.2	−0.2
Summer	PS	−0.2	0.2	−0.8	−1.1	−0.5	−0.1	−0.5	−0.2	0.1	0.2
	PN	−0.5	−0.2	−1.4	−1.2	−0.5	0.0	−0.5	−0.2	0.0	0.0
	SW	−1.2	0.1	−2.0	−1.3	−0.9	−0.3	−0.8	−0.1	0.1	−0.8
	NW	−0.9	−0.1	−2.0	−1.3	−0.6	0.1	−0.8	0.4	0.0	−0.6
	SC	−1.1	−0.3	−2.8	−1.3	−1.1	−0.1	−0.6	−0.5	−0.5	0.0
	NC	−1.4	−0.2	−2.2	−0.5	−0.4	0.8	−0.7	0.6	0.0	0.8
	SE	−0.7	−0.4	−1.4	−0.6	−0.8	−0.1	−1.0	−1.2	−1.1	−0.5
	NE	−0.9	−0.2	−1.8	−0.8	−0.7	−0.1	−1.2	−0.6	−0.9	−0.1
Fall	PS	0.0	−0.1	−0.7	−0.9	−0.4	−0.1	0.0	−0.4	−0.5	−0.5
	PN	0.0	0.0	−1.3	−0.8	0.3	0.3	0.1	−0.1	0.2	−0.3
	SW	−0.6	−0.5	−1.1	−0.3	−1.1	−0.4	−0.5	−0.9	−0.3	−1.5
	NW	−0.9	−0.6	−1.1	−0.3	−0.2	−0.1	−0.5	−0.4	0.2	−1.1
	SC	−0.7	−0.5	−0.8	−0.2	−0.6	0.2	−0.2	−0.4	−0.6	−0.8
	NC	−0.8	−1.0	−1.2	0.1	−0.5	−0.2	−0.7	0.0	0.4	−0.1
	SE	−0.5	−0.5	−0.6	−0.2	0.1	0.3	−0.5	−0.5	−0.5	−0.5
	NE	−0.6	−0.8	−1.1	−0.6	−0.2	−0.5	−0.5	−0.4	−0.4	0.1

HadCM, Hadley Centre Climate Model; GFDL, Geophysical Fluid Dynamics Laboratory; CGCM, Canadian Coupled Global Climate Model; CCSM, Community Climate System Model; HRM, High-resolution Regional Model; MM5, Meteorological Model, version 5; RCM, regional climate model; WRF, Weather Research and Forecasting; CRCM, Canadian Regional Climate Model.

of MC_1 described earlier, that is, the largest in winter and smallest or next to smallest in summer.

T and *RH* have the same impacts on $MC_{1000.}$ Because *P* is much larger in the eastern regions in summer, the differences in the present MC_{1000} between winter and summer are smaller in the eastern than the western regions. Furthermore, because *P* is larger in summer than fall in the eastern regions, MC_{1000} is larger in summer than fall in these regions. The seasonal cycle of the present *P* depends on region. In the PS and PN regions where the Mediterranean climate prevails, *P* is larger in winter than summer. This seasonal variation is consistent with the seasonal cycle of MC_{1000}. In other regions, actual *P* is larger in summer than winter. However, this seasonal difference is not clearly seen in the NARCCAP downscaling in many eastern regions. The seasonal MC_{1000} cycle (as shown in Figure 4) suggests that this bias might modify the magnitude but would not change the MC_{1000} seasonal cycle because of the consistent variations and dominant roles of *T* and *RH*.

In the future projections, *T* increases (Figure 7a), and the warming signal is strong, indicated by the statistical significance at the 99% confidence interval for all seasons at both national and regional levels. Meanwhile, *RH* decreases (Figure 7c) in all regions, with 8, 8, and 6 values statistically significant at the confidence intervals of 99%, 95%, and 90%, respectively. The national changes are significant at 99% in winter, spring, and summer, and at 90% in fall. The warming and drying trends explain why fuel moisture would decrease in the continental United States. This trend is the same as that for Canada in the summer (Flannigan *et al*., 2015). The future decreases in the continental United States are generally largest in the summer. Because the present fuel moisture is the lowest in summer, the relative decrease

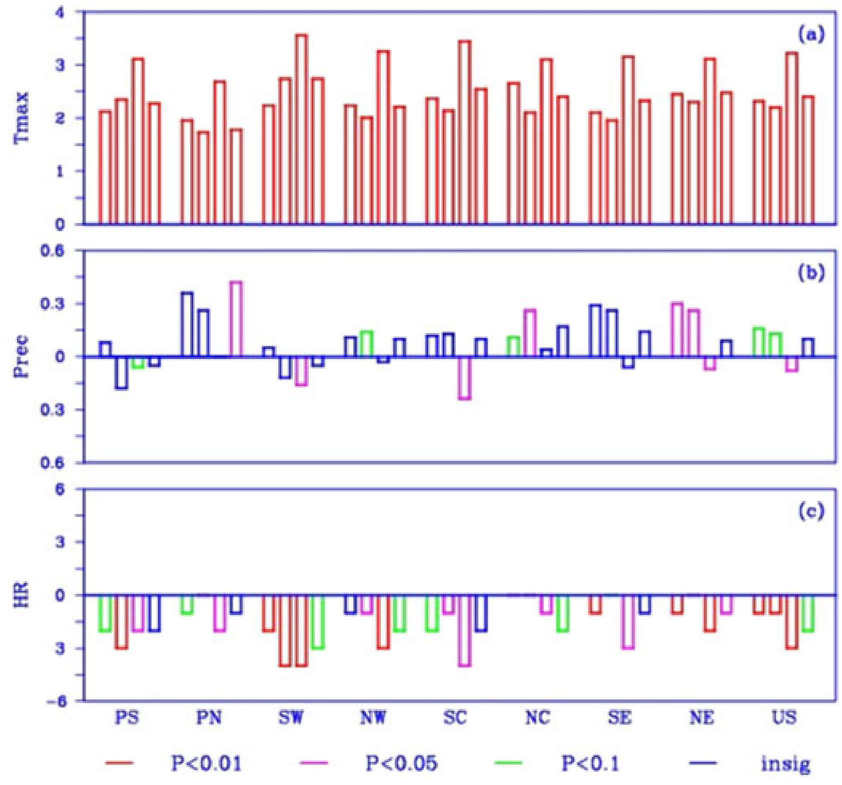

FIGURE 7 Regional changes in maximum temperature (°C) (a), precipitation (mm/day) (b), and relative humidity (%) (c) based on an ensemble average of 10 circulation model–regional climate model scenarios. The four bars for each region are winter, spring, summer, and fall. The colors indicate different significance levels

rate therefore is even larger in this season. This is especially true for the eastern regions.

Flannigan *et al*. (2015) further found that summer fuel moisture change in Canada is more sensitive to the change in temperature than precipitation; precipitation has to increase by more than 15% for dead surface fuels, about 10% for loosely compacted organic material on the forest floor and about 5% for deep, compact organic soil layers (drought code) to compensate for the drying caused by every degree of warmer temperature. In this study, regional temperature increases by 2–2.75°C in winter and spring, 2.75–3.5°C in summer, and 1.75–2.75°C in fall. Thus, precipitation has to increase by at least 10–13.75% in winter and spring, 13.75–17.5% in summer, and 8.75–13.75% in fall to offset the drying caused by the temperature increases. However, the projected precipitation change rates, as estimated from Figure 7b, only increase by 10% or less in winter and spring, 7.5% or less (except PN) in fall, and even decrease in summer. This suggests that the change of temperature overwhelms that of precipitation and leads to the future decreasing MC_{1000} trend. Regional precipitation changes are much less certain than temperature and humidity changes, with only 7 and 3 values statistically significant at the confidence intervals of 95% and 90%, respectively. This explains why the regional 1000-hr fuel moisture decreases are not significant in many seasons and regions. Precipitation is a more important contributor to variation of 1000-hr than 1-hr fuel moisture. National 1000-hr fuel moisture is significant at 95% in summer and 90% in winter and spring and insignificant in fall.

4 | CONCLUSION AND DISCUSSION

A drying trend is expected in the future for all types of dead fuels from 1 to 1000 hr in the continental United States because of climate change, mainly rising temperature. The trend is most substantial in the southern United States in the summer and spring. The statistical significance is much greater for the decreases of 1-hr than 1000-hr fuel moisture.

The drying fuel trends would increase the possibility of more frequent and intense wildfires in the Southwest and the inter-mountains in spring and the Rocky Mountains in summer. It would also increase the safety risks for prescribed burns accordingly. The Southeast has the most extensive prescribed burning across the U.S. regions (Melvin, 2016). While the major burning time is from late winter to early spring, burning in some parts of the region is year-round. The changes in fuel moisture are expected to increase burning safety risks and reduce burning windows during summer in this region.

Wildfire danger in the NFDRS is assessed by several indexes, including ignition component, spread component, and energy release component, which measure the probability of fire occurrence, fire spread rate, and fire intensity, respectively. MC_1 is a primary factor for the ignition component and also a major contributor to the spread component, while MC_{1000} is a major contributor to the energy release component. The projected drying of fuels obtained in this study suggests that future wildfires in the southern United States would increase in frequency, burned area, and intensity if other fuel conditions remain the same.

Land managers use empirical thresholds of meteorological and fuel parameters to determine the preferable weather conditions for controlled fires. One of the extensively used parameters is fuel moisture. For example, when MC_1 is smaller than 10% in the Southeast, fire would move quickly and be difficult to control (Wade, 2013). A controlled burn under these conditions is therefore unsafe and usually not implemented. There are only a certain number of days during a year (burning windows) when controlled burns can be implemented without substantial safety or other concerns. The projected decreases in MC_1 suggest an increasing possibility of unsafe conditions for controlled burning and therefore narrower burning windows. Most controlled forest burns in the United States are implemented in the Southeast in winter and spring. The largest impacts of future fuel moisture change on controlled burning would occur in winter in this region.

This study investigated the possible future changes in dead forest fuel moisture under changing climate and their impacts on wildfire and prescribed burning. These changes may also have implications for other ecohydrological processes. Water exchange between ecosystem and the soil and atmosphere is one of core issues for ecohydrology. Similar to vegetation and soil, dead fuels can store water. Also the fuels, especially those in the duff layer, can prevent soil water from excessive evaporation, which would affect water transfer from roots to plants and therefore affect transpiration. The projected future drying trends in dead fuels suggest that this capacity would be weakened, leading to increasing water stress to plants. Furthermore, forest fuels are a bed for insect multiplication. The projected future drying trends in dead fuel moisture would be unfavorable for insect multiplication and therefore favorable for forest health.

Large variability in fuel moisture trends was found among the different regional climate change scenarios. These scenarios were generated through dynamic downscaling, which has the advantages of physical consistency with GCMs, less dependence on historical data, and better representation of complex topography in comparison with statistical downscaling. However, only a few sets of scenarios are available because of dramatically large computational resources needed for running regional climate models. Statistical downscaling has an advantage in this regard. An ensemble study of future fuel moisture trends using a larger set of climate change scenarios provided by statistical downscaling would help reduce the uncertainty due to the scenario-induced variability.

The NARCCAP climate change scenarios used in this study were downscaled from the Coupled Model Intercomparison Project Phase 3 (CMIP3) global climate projections. The CMIP5 global climate projections are available now (IPCC, 2013). CMIP5 used new emission scenarios, and their projections have been downscaled using statistical approaches, but not yet with a systematic dynamic downscaling project such as NARCCAP. When they become available, the new dynamic scenarios need to be used for fuel moisture projections to understand the possible differences due to the new IPCC emission scenarios.

Thus, climate change would lead to drier dead forest fuels, more frequent and intense wildfires, narrower prescribed burning windows, and larger water stress, especially in the Southwest and the intermountains. These results highlight the general vulnerability of semiarid forests to drying fuels trends.

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