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Future changes in fire weather, spring droughts, and false springs across U.S. National Forests and Grasslands

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Abstract. Public lands provide many ecosystem services and support diverse plant and animal communities. In order to provide these benefits in the future, land managers and policy makers need information about future climate change and its potential effects. In particular, weather extremes are key drivers of wildfires, droughts, and false springs, which in turn can have large impacts on ecosystems. However, information on future changes in weather extremes on public lands is lacking. Our goal was to compare historical (1950–2005) and projected mid-century (2041–2070) changes in weather extremes (fire weather, spring droughts, and false springs) on public lands. This case study looked at the lands managed by the U.S. Forest Service across the conterminous United States including 501 ranger district units. We analyzed downscaled projections of daily records from 19 Coupled Model Intercomparison Project 5 General Circulation Models for two climate scenarios, with either medium-low or high CO_2- equivalent concentration (RCPs 4.5 and 8.5). For each ranger district, we estimated: (1) fire potential, using the Keetch-Byram Drought Index; (2) frequency of spring droughts, using the Standardized Precipitation Index; and (3) frequency of false springs, using the extended Spring Indices. We found that future climates could substantially alter weather conditions across Forest Service lands. Under the two climate scenarios, increases in wildfire potential, spring droughts, and false springs were projected in 32–72%, 28–29%, and 13–16% of all ranger districts, respectively. Moreover, a substantial number of ranger districts (17–30%), especially in the Southwestern, Pacific Southwest, and Rocky Mountain regions, were projected to see increases in more than one type of weather extreme, which may require special management attention. We suggest that future changes in weather extremes could threaten the ability of public lands to provide ecosystem services and ecological benefits to society. Overall, our results highlight the value of spatially-explicit weather projections to assess future changes in key weather extremes for land managers and policy makers.

Key words: climate change; conservation planning; disturbances; droughts; extreme weather; fires; forest management; National Forests and Grasslands; public lands.

Introduction

Public lands provide numerous benefits to people as well as biodiversity and often contain the only remaining large continuous patches of native vegetation in a region. Public lands provide clean water, regulate floods and climate, provide outdoor recreation opportunities, provide habitat for wildlife, and are major assets held for the benefit of citizens by federal, state, and local governments (Fausold and Lilieholm 1999, Dudley and Stolton 2003, Hand et al. 2008, Geldmann et al. 2013, Bebber and Butt 2017). However, climate change is expected to affect ecosystem processes in ways that could substantially alter the amount and mix of ecosystem services that public lands provide (Schroter et al. 2005, Bellard et al. 2012, Sun et al. 2015).

In particular, weather extremes are important drivers of disturbances and stress that can affect the structure and function of ecosystems (Parmesan et al. 2000, Smith 2011) and mediate the provisioning of services that benefit society (Anderegg et al. 2013, Hurteau et al. 2014, Orwin et al. 2015). For example, events such as wildfires, which are influenced by weather conditions, can

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dramatically change the soil, water, and vegetation components of ecosystems and are also a major threat to homes and communities (DeBano et al. 1998, Spracklen et al. 2009, Pechony and Shindell 2010). Similarly, droughts can have negative consequences for overall floral and faunal productivity, increase plant stress, cause tree mortality, and reduce species persistence (Easterling 2000, Parmesan et al. 2000, Ji and Peters 2003, Adams et al. 2009). For temperate regions such as the United States, monitoring droughts that occur during the growing season (i.e., spring droughts) is particularly important, because of the importance of the spring season to overall floral (Ivits et al. 2016) and faunal (Bolger et al. 2005) productivity.

In addition to affecting the incidence of events such as wildfires and droughts, climate change is also expected to affect the timing, or phenology, of important ecological events. The occurrence of a hard freeze after the plant growing season has begun, hereafter referred to as a “false spring,” can cause vegetation damage that reduces plant productivity, survival, and growth (Gu et al. 2008, Hufkens et al. 2012). Furthermore, the direct effects of false springs on vegetation can cascade through food webs as flowers, fruits, and seeds are important to many primary consumers (Thomas et al. 1996, Inouye 2008, Augspurger 2011).

While numerous studies have evaluated the effects of fires and droughts on the structure and function of vegetation, including the effects of disturbance interactions (i.e., droughts, insects, fires; see McKenzie et al. 2009, Keane et al. 2015, Seidl et al. 2017), spatially explicit information on future changes in weather extremes (fire weather, droughts, false spring) on public lands because of changes in climate, is lacking (Redford and Adams 2009, Martinuzzi et al. 2016). Studies evaluating the incidence of weather extremes under changing climates have shown that the length of the fire weather season has increased globally by 18.7% between 1979 and 2013 (Jolly et al. 2015). Projections of wildfire potential under future climate change in places such as the United States suggest widespread increased wildfire potential in the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific Coast regions (Liu et al. 2013). Similarly, droughts are projected to increase in the southwestern United States, raising concerns about increasing tree mortality (Breshears et al. 2005, Adams et al. 2009, Williams et al. 2013), changes in forest structure and composition (Kelly and Goulden 2008, Williams et al. 2010), and decreased reproduction and abundance among native faunal communities in both terrestrial (McCreedy and van Riper 2015) and aquatic (Ruhí et al. 2015) systems. In contrast, the picture for future false springs is mixed. The incidence of false springs is projected to remain the same or decline across most of the United States, but may increase throughout the 21st century in some areas, such as the central Great Plains (Allstadt et al. 2015).

Quantifying future changes in fire weather, droughts, and false springs on public lands provides valuable information to land managers seeking to identify areas vulnerable to future climates, prioritize the allocation of limited management dollars, geographically tailor management actions, or identify areas where interventions may be too expensive to change the system’s trajectory (Millar et al. 2007). Furthermore, this information allows us to identify areas likely to see an increase in multiple types of weather extremes (e.g., fire weather and droughts, false springs and droughts, etc.). Increases in multiple types of weather extremes in an area, in turn could exacerbate the effects on ecosystems (McKenzie et al. 2009, Seidl et al. 2017), and may require more complex management strategies (*cf.* Lawler et al. 2002) to mitigate those effects. Yet previous studies forecasting changes in weather extremes under future climates typically looked at one variable at a time (fire weather or drought).

Our goal was to evaluate changes in fire weather, spring droughts, and false springs under future climates on the National Forests and Grasslands (hereafter “national forests”) administered by the U.S. Forest Service within the conterminous United States (Fig. 1). Our specific objectives were to (1) quantify future changes in fire weather, spring droughts, and false springs at both the ranger district (fine scale) and the regional (coarse scale) levels; (2) identify which Forest Service lands are projected to see increased incidence of multiple types of weather extremes as an indicator of threat complexity; and (3) evaluate the sensitivity of our projected future changes in fire weather, spring drought, and false springs by varying the thresholds for defining notable shifts from historical conditions.

METHODS

Data

Forest service lands.—We focused on the conterminous United States and on two administrative levels within the Forest Service organization: ranger districts ($n = 501$) and administrative regions ($n = 8$) (Fig. 1). The ranger district is the smallest management unit; national forests are typically composed of several ranger districts. National forests, in turn, aggregate into eight broad administrative regions. We obtained the boundaries for Forest Service management units from the agency’s geodata clearinghouse (USDA Forest Service 2015). The median size of a Ranger District is ~154,000 ha.

Weather extremes.—We derived three types of weather extremes (fire weather, spring drought, and false springs) using daily records from the Coupled Model Intercomparison Project 5 (CMIP5) multi-model ensemble General Circulation Models (GCM) spatial data set. We

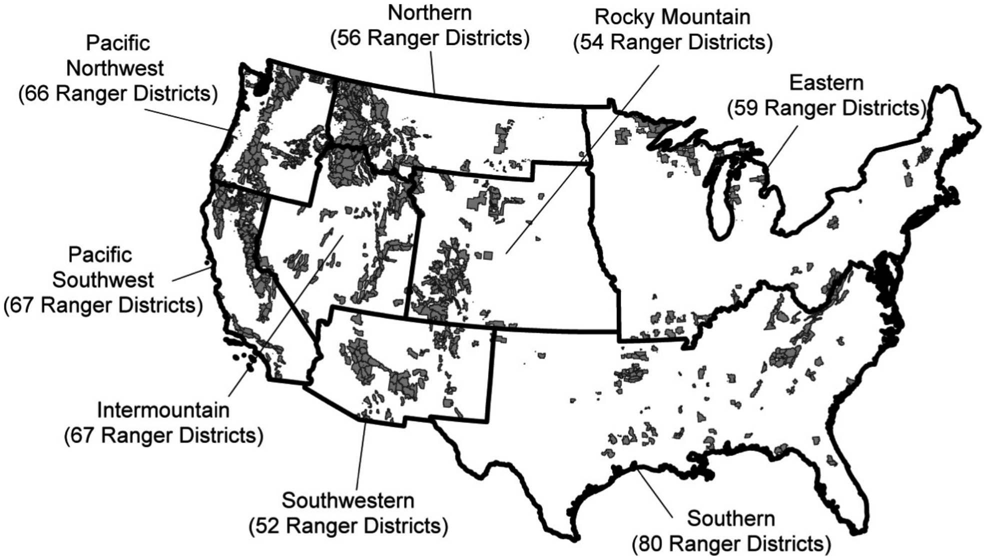

FIG. 1. Distribution of Forest Service lands in the conterminous United States. The thick black lines are the boundaries of the administrative regions (n = 8), and the gray polygons correspond to the ranger districts (n = 501). The number of ranger districts in each administrative region is shown between parentheses.

acquired data for 19 different GCMs (Appendix S1: Table S1) that had been statistically downscaled to ~12-km resolution using the Bias-Corrected Constructed Analog (BCCA) technique (Maurer et al. 2007, Bureau of Reclamation 2014). We compared modeled historical (1950–2005) climate with projected mid-century (2041–2070) climate derived from two climate scenarios referenced as Representative Concentration Pathways (RCPs).One scenario reflected a medium-low concentration and emission pathway (RCP4.5); the other reflected a high concentration and emission pathway (RCP8.5) (Moss et al. 2010). We had previously calculated spring drought and false springs for the conterminous United States in Martinuzzi et al. (2016) and Allstadt et al. (2015) and calculated wildfire potential for this study; these are explained in the following subsections.

1. Fire weather.—We quantified fire weather using the Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968), which is a measure of wildfire potential commonly used in the United States (Burgan 1988, Melton 1989, Liu et al. 2013). The KBDI estimates daily soil moisture based on a formula that includes precipitation, temperature, day length, and previous day conditions, and it is essentially an indicator of soil moisture deficit that does not make any assumptions about vegetation growth or buildup (Keetch and Byram 1968). The KBDI values range from 0 (saturated soil, low fire risk) to 800 (no soil moisture, extreme fire risk; Keetch and Byram 1968, Melton 1989).

We calculated KBDI for each 12-km grid cell based on the daily weather data. The KBDI was set to 0 at the beginning of the study period. Typically, the KBDI is reset to 0 again during an annual period of saturated soil, for example after snowmelt or a rainy season (Dolling et al. 2005). However, due to the range of climates that we considered here, we did not initialize KBDI other than at the first time step and instead left it to actual precipitation events to reduce fire risk. While initialization does affect KBDI values, the effects diminish rapidly over time with warm spells (temperatures >10°C) and particularly precipitation, for which a single event can remove any difference in initial KBDI values (Fujioka 1994).

To describe changes in wildfire potential, KBDI is typically classified into fire risk categories using fixed thresholds. For example, Melton (1989) broadly describes the effect of forest fires using KBDI thresholds of <150–300, 300–500, 500–700, and 700+, where increasing values correspond to increasing flammability of soil materials. However, given our large geographic coverage, we found that high KBDI values were never reached in more northerly areas, despite the fact that fires do occur there. Therefore, we quantified relative changes in KBDI at each grid cell, as recommended when quantifying future changes in KBDI (Liu et al. 2013). For this, we calculated the 95th quantile of daily KBDI values during the historical period (1950–2005), hereafter called KBDI 95th. By definition, approximately 18 d per year will be above this value during the historical period (i.e.; 365 d * 0.05 = 18). For the future time period (2041–2070), we calculated the average number of days per year above KBDI 95th in each grid cell. Our assumption was that an increase in the number of days above KBDI 95th would be an indicator of an increase in wildfire potential, and vice versa.

2. Spring droughts.—We identified drought conditions using the Standardized Precipitation Index (SPI; McKee et al. 1993). Although there are a number of drought indices, we selected SPI because of its designation by the World Meteorological Organization as the reference index for meteorological drought (Hayes et al. 2011), and its recent use in other studies, including a historical analysis of drought effects on U.S. National Forests and Grasslands (Sun et al. 2015), and an examination of changes in drought frequencies in U.S. National Wildlife Refuges (Martinuzzi et al. 2016). We characterized drought stress using the 3-month index centered on spring months (March, April, May) given their importance to overall floral (Ivits et al. 2016) and faunal (Bolger et al. 2005) productivity across the warm temperate and cool temperate life zones (Vicente-Serrano et al. 2013) that dominate the conterminous United States (see Fig. 4a in Lugo et al. 1999).

To quantify changes in spring droughts, we defined droughts as those occurring every 20 yr in the historical period (referred to as a "20-yr drought"), and compared them with the frequency of droughts of a similar magnitude in the mid-century climate projections. For example, the equivalent of a 20-yr drought in the historical period might occur every 10 yr by mid-century, which means that the frequency has doubled. We chose 20-yr droughts because they represent a weather event that is extreme enough to act as a disturbance agent, yet frequent enough that it would be expected to occur at least once over a land manager's career.

The SPI is a probabilistic measure, calculated independently for each grid cell and for each of the 19 GCMs. In each cell, we calculated the total precipitation in the spring months (March, April, May) for each year during the historical time period (1950–2005). We fit a Pearson-III distribution to annual spring precipitation totals and converted percentiles from this distribution to the standard normal distribution of the SPI (Guttman 1999). By definition of a standard normal distribution, a 20-yr drought has an annual probability of 0.05, which corresponds to an SPI value of ≤ -1.64 during the historical period. However, the frequency of SPI ≤ -1.64 may occur more or less often in the future given changes in projected precipitation patterns, so that what was a 20-yr drought during the historical period may occur at a different frequency in the future. Therefore, we were able to compare changes in drought frequency by mid-century (2041–2070) for each 12-km pixel in each of the 19 GCMs and two RCP scenarios.

3. False springs.—A false spring is defined as a hard freeze, a daily minimum temperature below −2.2°C, after spring plant growth has begun (Schwartz 1993, Marino et al. 2011). Vegetation damage from false springs can affect buds, flowers, leaves, and shoots; flowers are generally more sensitive to freeze damage than leaves (Sakai and Larcher 1987). This matters because flowers and the resulting seeds are often important food sources for animals (Nixon and McClain 1969) in addition to being key for plant reproduction. Therefore, we focused on false springs that occur after flowers have bloomed. For this, we calculated flower emergence date using the extended Spring Indices (Schwartz et al. 2013), and assumed that a hard freeze after the emergence date constituted a potentially damaging false spring event. We extracted the mean annual probability (from 0 to 1) of false springs in the historical period and in the mid-century scenarios (Allstadt et al. 2015). The data for flower emergence date and the last hard freeze are *available online*.[6]

Data preparation

We extracted (1) the number of days above KBDI 95th, (2) the mean annual probability of historical 20-yr spring droughts, and (3) the mean annual probability of observing false springs for each Forest Service ranger district using the mean value among pixels intersecting ranger district polygons. We repeated this for each GCM (n = 19) and each climate future (RCP4.5 and RCP8.5) for a total of 38 historical vs. mid-century comparisons. We also converted the units of frequency for droughts and false springs from mean annual probability values (from 0 to 1) into return intervals (in years) by dividing 1 by the annual probability. Return interval, i.e., the average time between occurrences of an event, is an intuitive unit for communicating our results to land managers.

Ranger district summaries

We created nationwide categorical maps at the ranger district level (n = 501) describing patterns of change across the three types of weather extremes. To map changes in fire weather, we categorized each ranger district based on the number of days above KBDI 95th projected by mid-century, using 30-d intervals (i.e., 30–60, 60–90 d, etc.). To quantify changes in the frequency of droughts and false springs, we used rates of change. Those ranger districts projected as having a >20% reduction in the return interval of droughts, or false springs, relative to the historical period were categorized as having "more frequent" events. Ranger districts projected to see a >20% increase in the return period of droughts or false springs were categorized as having "less frequent" events. The remaining ranger districts were categorized as "no change." Ranger districts with a very low return interval (>30 yr) of false springs during the historical and future periods were placed in the "no change" category, because false springs are expected to be rare in those ranger districts regardless of the estimated rate of change. We chose a rate of change of 20% because it depicts spatial patterns in our data well, and because 20% can be considered a substantial change. We created

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[6] http://silvis.forest.wisc.edu/climate-averages-and-extremes

separate maps of categorical change for wildfire potential, spring droughts, and false springs for the RCP 4.5 and 8.5 scenarios, for a total of six change maps. The change class for each ranger district was estimated from the median value of the 19 GCMs.

Regional summaries

We aggregated the ranger districts into the eight Forest Service administrative regions, and calculated the median value for each weather extreme index within each region. We used the regional median value, rather than the mean, due to skewness of the data. This aggregation process was repeated for each of the 19 different GCMs.

For each administrative region, we reported the number of days above KBDI 95th, the return interval (in years) of spring droughts, and the return interval of false springs using the median, 25th, and 75th percentile values across the 19 GCMs. The 25th and 75th percentile values were chosen to indicate index variability across GCMs in each region. We presented the results for the historical period and mid-century RCP 4.5 and RCP 8.5 scenarios.

Increase in multiple types of weather extremes

To identify which ranger districts may be under increasing threat from multiple types of weather extremes, we calculated the number of indices projected to increase in each ranger district. For this, we overlaid maps of the ranger districts projected to see increases in wildfire potential (using a threshold of >60 d above KBDI 95th), with maps of those districts projected to see “more frequent” spring droughts, and those projected to see “more frequent” false springs. This resulted in two new maps with the number (0, 1, 2, or 3) of types of weather extremes projected to increase in each ranger district under the RCP 4.5 and RCP 8.5 scenarios. For the results, we focused on ranger districts projected to see increases in two to three types of weather extremes, our indicator of higher threat and management complexity.

Sensitivity analysis

In the previous step, we used thresholds of rates of change >20% above the historical rate for spring droughts and false springs, and >60 d above KBDI 95th for increases in wildfire potential. To assess the effect of those thresholds, we calculated the number of ranger districts projected to see increases in 2–3 weather extremes using higher rates of change for spring droughts and false springs (>20%, >30%, >40%), and >60, >75, and >90 for days above KBDI 95th (i.e., nine combinations total).

RESULTS

Projected changes at the ranger district level

Projected changes in weather extremes between ranger districts ($n = 501$; Fig. 2) showed strong spatial patterns across the conterminous United States. Fire weather, as measured by the number of days above the historic KBDI 95th, was projected to increase across all ranger districts from 18 d in the historic period to a minimum of 30 d, up to a maximum of 98–158 d (depending on the climate scenario; Fig. 2a). Indeed, 32% and 72% of ranger districts were projected to see >60 d above KBDI 95th under the RCP4.5 scenario and RCP8.5, respectively. These ranger districts were largely located along the eastern front of the Rocky Mountains and into the Great Plains, the inland Northwest, and the semiarid regions of the Southwest (Fig. 2a). Under the RCP 8.5 scenario, ranger districts with >60 d above KBDI 95th occurred throughout much of the West and North.

Spring droughts, on the other hand, were projected to decrease in frequency in more than half (59% and 63% for RCP 4.5 and 8.5, respectively) of the ranger districts and to increase in frequency in about one-third (29% and 28%, respectively). Ranger districts projected to see more frequent spring droughts were located in the Southwest and California (Fig. 2b). Contrary to wildfire potential, the differences between RCP 4.5 and 8.5 scenarios were less pronounced.

Finally, the projected future pattern of the frequency of false springs was dampened relative to the past, with “no change” being the most frequent mid-century projection for ranger districts under both RCP4.5 (61%) and RCP8.5 (47%). Only 13% and 16% of the ranger districts were projected to see notable increases in the frequency of false springs, mostly in the central plains and the Southwest (Fig. 2c). The complete set of weather extreme indices by ranger district is available online in the supporting information (Data S1).

Projected changes at the administrative region level

Projected changes in weather extremes on Forest Service lands aggregated to the eight administrative regions (i.e., regional medians, Fig. 3) provide additional details on the magnitude and geography of the expected changes. Fire weather was expected to increase substantially across all regions ($n = 8$). The number of days above the historic KBDI 95th increased from 18 to 53 d and 82 d by mid-century under RCP4.5 and RCP8.5, respectively, in seven of the eight regions (Fig. 3a). Only the Southern Region showed notably lower values compared to the other regions, yet the estimated number of days of high wildfire potential in the mid-century period more than doubled relative to historical conditions. Increases in wildfire potential were substantially higher

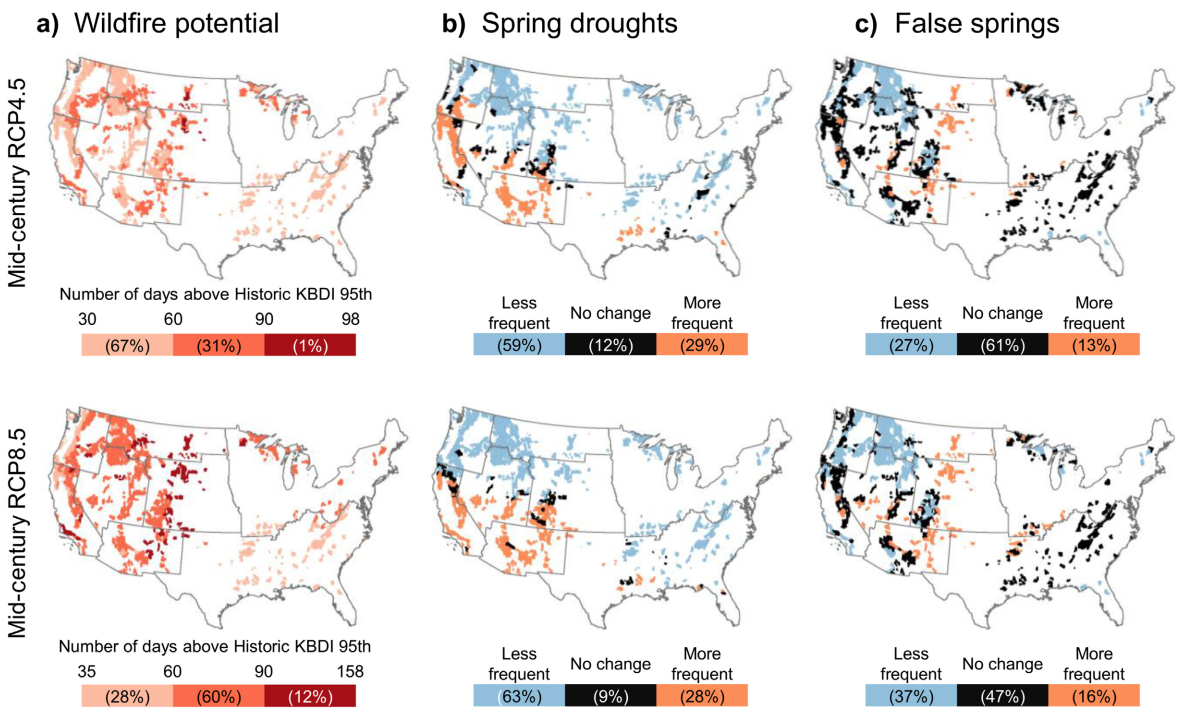

FIG. 2. Projected changes in (a) wildfire potential, (b) spring droughts, and (c) false springs across ranger districts. The maps display the ranger districts (*n* = 501) categorized into simple classes of change (e.g., less frequent, more frequent, etc.). The number of ranger districts in each class is included between parentheses. Mid-century RCP 4.5 and 8.5 correspond to medium-low and high emission scenarios, respectively.

under RCP 8.5 compared to RCP 4.5 (Fig. 3a), and there was relatively little variation among GCMs, as reflected by narrow interquartile ranges.

The return interval of 20-yr spring droughts was projected to become longer (i.e., less frequent) in six of the eight regions making up the conterminous United States, and become notably less frequent in the Northern and Eastern administrative regions (Fig. 3b). However, in the Southwestern and Pacific Southwest regions, the return interval for spring droughts was projected to shorten (i.e., become more frequent), with estimated return intervals declining from ~20-yr in the historical period to 12 and 16 yr by mid-century (Fig. 3b). Differences between RCP 4.5 and 8.5 scenarios were less pronounced than for wildfire potential, and there was substantial variation among GCMs as reflected by the relatively wide 25th and 75th percentile values (Fig. 3b). In particular, the Eastern and Southern regions had more variation among GCMs than the Pacific Southwest or Southwestern regions (Fig. 3b).

False spring frequencies at the regional level, on the other hand, exhibited relatively little change between the historic and the mid-century scenarios (Fig. 3c). Historically, false springs occur more frequently in the Southern, Intermountain, and Southwestern regions (3 yr return period) than in the Pacific Northwest, Rocky Mountain, and Eastern regions (6–7 yr return period). Only the Pacific Northwest showed an increase in the return interval of false springs, from a 7 yr return period in the historic period to a 9 or 11 yr return period (RCP 4.5 vs. 8.5) by mid-century (Fig. 3c). Between 13% and 16% of the ranger districts were projected to see increases in the frequency of false springs (Fig. 2c), but these increases averaged out at the region level. Differences between the RCP 4.5 and RCP 8.5 scenarios were small, as were variations among GCMs, with the exception of the Pacific Northwest and Eastern regions (Fig. 3c).

Increases in multiple types of weather extremes

Knowing which ranger districts are expected to see increases in multiple types of weather extremes is particularly important for land managers. Our maps showing the number of indices projected to increase within ranger districts highlight the ubiquity of potential future threats from climate (Fig. 4). By mid-century, 17% or 30% (RCP 4.5 vs. 85) of all ranger districts were projected to see increases in two or more weather extremes, and 55% or 79% were projected to see increases in at least one. The higher proportions were always under the RCP 8.5 scenario (compare Fig. 4a with Fig. 4b).

At the same time, regional variation in the number of ranger districts with projected increases in two or more weather extremes was pronounced (Fig. 4c). The Southwestern Region had the greatest proportion of ranger

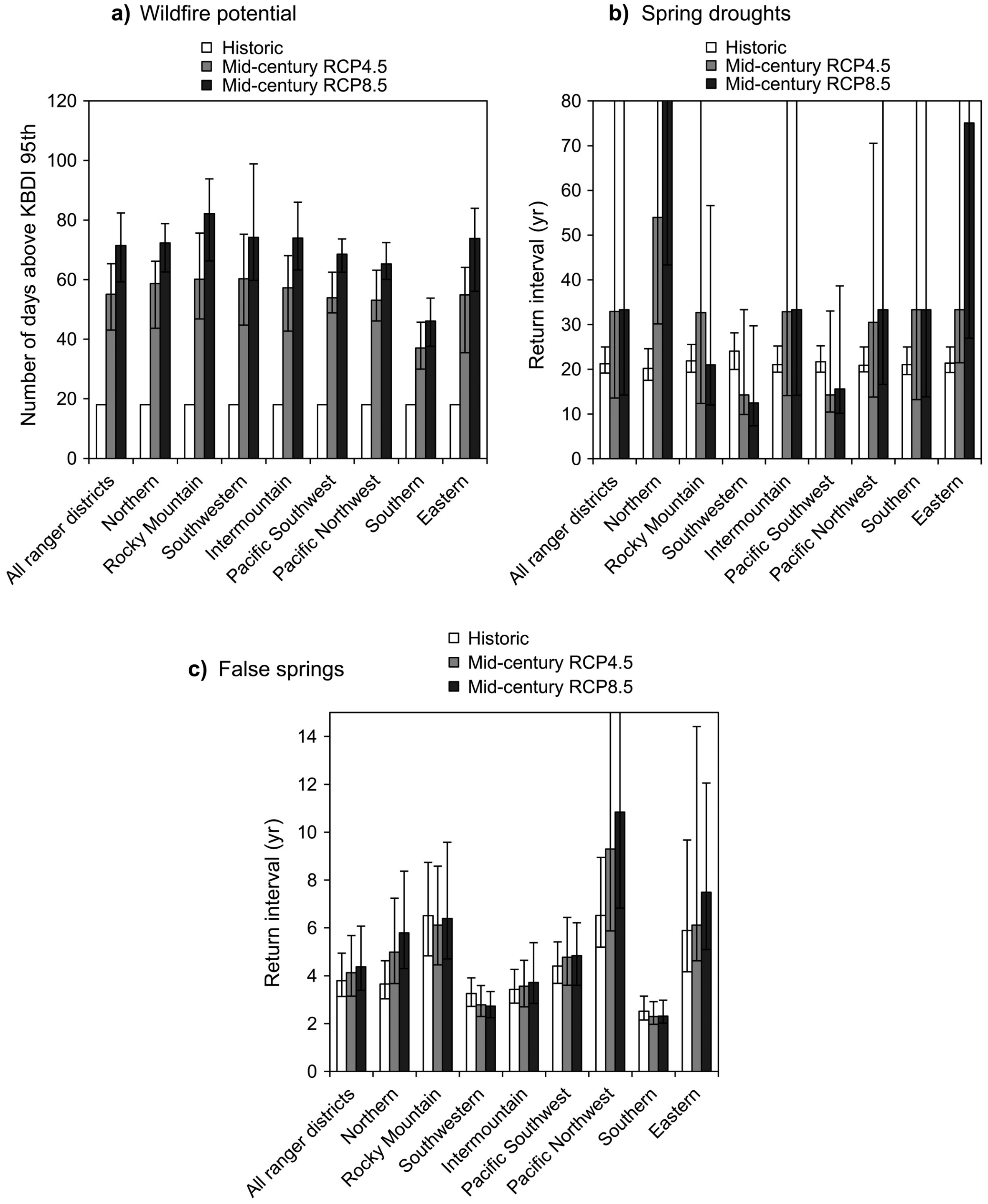

FIG. 3. Projected changes in (a) wildfire potential, (b) spring droughts, and (c) false springs on Forest Service lands summarized at the administrative region level. The columns in the bar charts report the median value for each administrative region and the vertical segments the 25th and 75th values across the 19 climate models. Wildfire potential is measured based on the number of days above the 95th percentile Keetch-Byram Drought Index (KBDI 95th), while droughts and false springs are measured based on return intervals in years. Mid-century RCP 4.5 and 8.5 correspond to medium-low and high-emission scenarios, respectively. The small variation in the return interval for droughts in the historic period is due to modeling. For clarity and effective communication of key results, return intervals >80 yr (for spring droughts) and >15 yr (for false springs) are not shown in this figure; full range of values can be found in Appendix S1: Fig. S1.

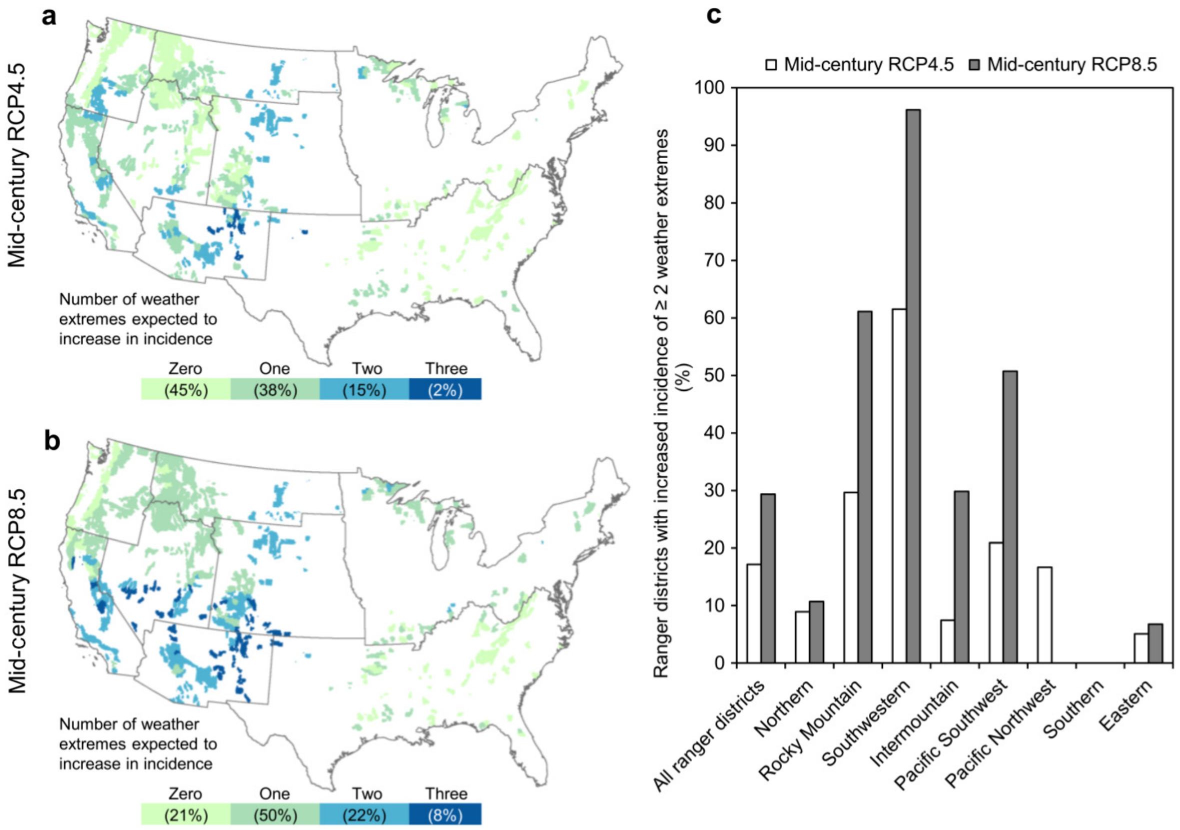

FIG. 4. Assessment of multiple weather extremes (wildfire potential, spring droughts, and false springs) on Forest Service lands. Panels a and b show the number indices projected to increase under the two emission scenarios. Panel c reports the proportion of ranger districts projected to see increases in two or more weather extremes in each administrative region. We considered an increase to occur if the rate of change was >20% above the current rate for spring droughts and false springs, and >60 d above KBDI 95th for increases in wildfire potential.

districts expected to see increases in two or more weather extremes – 62% or 96% of all ranger districts depending on the climate scenario, followed by the Rocky Mountain and Pacific Southwest regions (21% or 61%). On the other hand, increases in two or more weather extremes were rare in the more northern and eastern regions. The proportion of ranger districts predicted to increase in two or more weather extremes ranged from 0% to 11% in the Southern, Eastern, and Northern regions.

Sensitivity analysis

So far, we considered an extreme weather type to increase if the predicted increase in frequency was >20% above the current frequency for spring droughts and false springs, and >60 d above KBDI 95th for increases in wildfire potential. As would be expected, the number of ranger districts projected to see increases in two or more weather extremes decreased with increasing threshold values used to define a substantial change (Appendix S1: Fig. S2). However, these threshold changes did not qualitatively alter the main findings of our study at the regional level. In this sense, the Southwestern, Rocky Mountain, and Pacific Southwest regions were typically projected to have the greatest number of ranger districts with increases in two or more weather extremes, with higher values typically under the RCP 8.5 scenario. Certainly, some ranger districts within each region would fail to exceed new threshold levels, but the ranking of regions according to increasing threat and management complexity remained insensitive to threshold levels.

DISCUSSION

Lands managed by the U.S. Forest Service deliver important benefits to local communities and to the Nation, and provide habitat for many species and biotic communities of conservation concern (Groves et al. 2000, Loucks et al. 2003, Stein et al. 2008, Caldwell et al. 2014). Can Forest Service lands retain the benefits to both humanity and biodiversity under future climates? The answer depends, in part, on whether managers can anticipate potential effects of a changing climate and plan accordingly (see Fig. 4 in Millar and

Stephenson 2015). Our study showed that future climates are expected to increase the likelihood of weather conditions that promote wildfires, spring droughts, and false springs, but with strong variability among regions and ranger districts. The heterogeneity we observed in the degree to which different administrative land units may be subject to increases in weather extremes is an important consideration if the Forest Service is to address these threats strategically. Geographic variation in climate conditions that affect the likely occurrence of potential threats forms the basis for allocating limited land management resources in a manner that targets those areas most vulnerable to a particular threat or group of threats. Our choice of looking at multiple planning scales within Forest Service lands was to highlight the prospect for hierarchically structured allocation rules that partition management funds.

Wildfires are a major concern for the Forest Service and other land management agencies given the strong ecological, social, and economic consequences (DeBano et al. 1998, Spracklen et al. 2009, Stephens et al. 2013, Jolly et al. 2015, National Interagency Fire Center 2017). We found that all Forest Service ranger districts are projected to see an increase in the number of days exceeding the 95th quantile of KBDI by mid-century. Nearly one-third to three-quarters of all ranger districts are expected to exceed 60 d over KBDI 95th, representing an increase of more than 233% over historical levels. However, these increases are far from uniformly distributed across the conterminous United States. Overall, wildfire potential is expected to increase to a much greater degree across ranger districts in the West (where the Forest Service owns nearly 20% of the landscape) compared to ranger districts in the East (where the Forest Service owns only 5% of the landscape), a pattern consistent with findings of previous studies (Liu et al. 2013, Barbero et al. 2015, Abatzoglou and Williams 2016). The higher KBDI 95th values in the RCP8.5 scenario as compared to the RCP4.5 scenario is likely due to a divergence in temperature between the two scenarios (see Fig. 2 in Wuebbles et al. 2014).

Our other two indices, spring drought and false springs, both showed more diverse responses with strong geographic signals. Unlike wildfire potential and its consistent pattern of increase under future climates, spring droughts and false springs increased, decreased, or showed no change, depending on the region. The frequency of spring drought conditions was projected to increase in southwestern regions, and decrease in the northern and eastern regions. Indeed, spring droughts in the Southwestern and Pacific Southwest regions were projected to almost double, which is consistent with projected changes in mean spring precipitation from both the CMIP5 models (RCP8.5) and the older CMIP3 models (A2 scenario; Walsh et al. 2014). In those regions, increases in the frequency of spring droughts could have cascading effects in wildlife communities. These communities would be affected by reduced resource availability throughout the year because of a reduction in overall vegetation production, flowering, and seed production (Easterling 2000, Parmesan et al. 2000). Furthermore, mean temperature and extreme heat events are projected to increase in the Southwest and Pacific Southwest regions (Walsh et al. 2014). The combination of higher temperatures and drier conditions could further reduce reproductive success and habitat (e.g., wetlands) availability for avian species (Bolger et al. 2005, Erwin 2009), and exacerbate physiological stress on trees (Luce et al. 2016).

Modest changes in false springs were projected, with "no change" being the most frequent mid-century classification of ranger districts under RCP4.5 (61%) and RCP8.5 (47%). Moreover, the number of ranger districts with more frequent false spring events is about one-half, on a percentage scale, of the number projected on national wildlife refuges, which are another large system of public lands in the United States (13–16% vs. 25.5–26.5%, respectively; Martinuzzi et al. 2016). This difference can be attributed to a higher concentration of national wildlife refuges in the Great Plains, the main ecoregion expected to see increases in the frequency of false springs (Allstadt et al. 2015), compared to Forest Service lands. However, many national grasslands are located in the Great Plains, suggesting that false springs may disproportionally affect these unique Forest Service lands. Overall, this reinforces the idea that threats from future climates are not transferable across land management agencies, and assessing the lands individually for each agency is needed to effectively identify potential threats.

Areas with increased incidence in multiple types of weather extremes pose major challenges for land management. We found that a substantial number of ranger districts (17–30%) are projected to see increases in two or more indices. Overall, the Southwestern, Rocky Mountain, and Pacific Southwest regions supported the greatest proportion of ranger districts with increases in two or more weather extremes; these regions may need special management attention. The combination of multiple types of weather extremes could substantially alter the magnitude and mix of ecosystem services derived from Forest Service lands (Hurteau et al. 2014, Millar and Stephenson 2015, Duan et al. 2016). Overall, our study revealed the presence of strong spatial patterns of potential threats that should be considered when making land management decisions.

In terms of management recommendations, avoiding actions that could exacerbate the effects of climate-driven disturbances should be the first principal for increasing resilience and adaptation on Forest Service lands (see Vose et al. 2016). For example, although fuel treatments designed to reduce the severity of future fires are a primary tool available to managers (Calkin et al. 2015), the consequences of implementation should not be overlooked. Fuels reduction may alter ecological integrity (Hutto et al. 2016), degrade water quality (Schroder et al. 2016), or increase a system's vulnerability to future drought despite short-term reductions to stand-level water use (McDowell et al. 2006). The mechanisms responsible for vegetation stress are complex and a number of key manipulative experiments are required in order to understand the interdependencies among climate-driven mechanisms (McDowell et al. 2011). Furthermore, effective forest management under climate change will likely necessitate local solutions that are appropriate for the particular forest type, as management practices that work in certain regions might not work in others (see D'Amato et al. 2013, Kerhoulas et al. 2013, Jones et al. 2016).

However, there are also some management actions with less uncertainty as to their unintended consequences. For example, reducing surface fuels by using prescribed fire to reduce the likelihood of uncharacteristically severe fire (Calkin et al. 2014), or the use of ecological fire management principles (Ingalsbee 2015) that introduce more wildfire on the landscape, represent actions designed to restore fire-adapted systems as long as they minimize risks to property and life (Hutto et al. 2016). Employing prescribed burns or restoring wildfires may be viable options for reducing hazardous fuels or slowing vegetation change and associated impacts to carbon cycling and biodiversity (Hurteau et al. 2014, North et al. 2015). For areas with increased spring droughts, altering the structural or functional components of vegetation, minimizing drought-mediated disturbance such as insect outbreaks, and managing for riparian areas and a reliable flow of water are potential options (Oliver et al. 2013, Nimmo et al. 2015, Vose et al. 2016). Moreover, the Forest Service has a goal of conserving species of conservation concern. Identifying which of those species are sensitive to wildfire disturbances, spring droughts, or false springs is an important step in assessing those ecosystem elements that may be threatened by future climate changes. Yet, land managers should also expect shifts in species distributions and new combinations of species arising from future environmental changes, and should also consider their options when deciding how to respond (Lugo 2012).

In addition to avoiding actions that could make things worse, analyses such as those presented here offer managers basic information about where management efforts may be needed. As noted by Millar and Stephenson (2015), anticipating where systems are most vulnerable to increases in disturbances allows managers to seize opportunities to minimize the costs associated with those events, or to ease system transitions to states that are better adapted to the new climate context. The fact that a large number of ranger districts (55% or 79% for RCPs 4.5 and 8.5, respectively) were projected to see increases in at least one of our indices indicates that most Forest Service managers should expect some climate change consequence. To assist in that, we have summarized the projected changes for each ranger district and have included it in the supporting information (Data S1), available online.

As with any modeling effort, our study is subject to some limitations. Despite modeling mean and long-term conditions adequately, General Circulation Models tend to underestimate extreme weather due to model limitations and their low resolution (Wehner et al. 2010, Sillmann et al. 2013). Additionally, weather variability may be muted by the process of debiasing and downscaling the GCM output (Maurer et al. 2010) and the inherent difference between point processes (e.g., weather station data) and gridded weather products (Behnke et al. 2016). In general, modeled and gridded products tend to underestimate frequencies of short-term extremes on both ends of the temperature spectrum, and tend to overestimate light rain days while underestimating heavy precipitation events. Among the indices we included, false springs may be underrepresented if they are based on a single cold day occurring at the right time of year (but see Allstadt et al. 2015). Similarly, KBDI does not respond to precipitation events under 0.5 cm, so an overrepresentation of light rain events in monthly totals may underreport rainfall in the KBDI calculation. However, our examination of relative changes between historical and future time periods within each model should be robust to these issues. In particular, SPI is based on a 3-month precipitation total and is completely relative to the modeled data during the historical period.

In addition, wildland fire potential is best described as a combination of available fuels, suitable weather conditions, and sources of ignitions. The Keetch-Byram Drought Index is a simple, weather-driven index of soil moisture variations that does not include information about fuel dynamics or ignition triggers. Therefore, it can only be treated as a climate-mediated proxy for changes in wildland fire potential (Liu et al. 2010). Rainfall deficits, and subsequent drought, can have differential impacts on fire potential. For example, in semiarid regions, lack of rainfall can prevent fine fuel growth and thus limit wildland fire potential (Littell et al. 2009, Stavros et al. 2014). In areas where spring droughts lead to less fine fuel accumulation, we may expect the effects of KBDI increases to be somewhat moderated, but areas that are more limited by summer weather conditions may witness more fire activity under increased drought. The true ecological context of climate and fire relationships can only be properly evaluated when vegetation/fuel dynamics and seasonal climate are explored concurrently (Littell et al. 2009). Our analysis, however, does give substantial insight into how future climate may affect wildland fire potential under the assumption that fuels and ignitions sources are not limiting.

Last, we have ignored other players (i.e., biotic and abiotic) that can also have important effects on the ecosystem services derived from national forests under future climates. For example, increased outbreaks and the spread of plant pathogens and pests (Bentz et al.

2010, Sturrock et al. 2011), and increased susceptibility to invasion by nonnative species (Gallardo et al. 2017) have been shown, or hypothesized, to be affected by environmental conditions under climate change (Malmström and Raffa 2000, Garrett et al. 2006, Hellmann et al. 2008). Fire risk is also expected to increase due to other factors, including an expected increase in cloud-to-ground lightning under future climates (Romps et al. 2014), and the continuing increase of people and infrastructure near Forest Service lands (Radeloff et al. 2010), which is likely to increase human fire ignitions (Price and Bradstock 2014). Furthermore, vegetation and forest fuel conditions will likely change as a result of future climate change, but the KBDI does not consider potential changes in vegetation. A comprehensive understanding of shifts in the ecosystem services portfolio under climate change will require a more complete accounting of potential drivers of change, including the mechanistic treatment of disturbance interactions.

Forest Service lands provide a broad variety of ecosystem services and benefits to people and biodiversity. Our work provides novel information about future changes in weather extremes for land managers and policy makers, and reveals that future climate changes could alter the incidence of key drivers of ecological changes in substantial ways. Climate change adaptation in large public land holdings, like those of the U.S. Forest Service, should incorporate multiple weather extremes from future climate changes.

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