

RESEARCH ARTICLE

Will land use land cover change drive atmospheric conditions to become more conducive to wildfires in the United States?

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Abstract

The increase in wildfire risk in the United States in recent decades has been linked to rapid growth of the wildland-urban interface and to changing climate. While there have been numerous studies on wildfires and climate change, few have separately assessed the impact of climate response to land-use-land-cover change (LULCC) on wildfires. In this study, we analyse two 10-year regional climate simulations driven by the current (2011) and future (2100) land-use-land-cover patterns to assess modifications by the projected LULCC to the frequency and severity of fire-prone atmospheric conditions described by two fire weather indices, the Canadian Forest Fire Weather Index and the Hot-Dry-Windy Index. The simulation corresponding to future land-use-land-cover pattern yields higher surface temperature and vapour pressure deficit and lower precipitation compared to the simulation with the current pattern in areas where urbanized landscapes replace forests and grasslands, such as along the Piedmont and outside the Chicagoland region, while in areas where croplands replace forests, such as the southeast Coastal Plains, the results are reversed. These changes to local and regional atmospheric conditions lead to longer fire seasons and more extreme fire-weather conditions in much of the eastern United States, specifically in the Southeast and Ohio River Valley where significant urban expansion is projected by the end of the century. Whereas in Southern California where some highly flammable shrublands will be replaced by urban or crop lands, fire-prone atmospheric conditions are likely to be less frequent and less extreme in the future. However, much of California moves towards a year-round fire season under the projected LULCC. The results suggest that by altering atmospheric conditions, LULCC may play an important role in determining fire regime, but the effects are highly heterogeneous and regionalized.

KEYWORDS

climate change, fire behaviour, fire weather, land use change, wildfires

1 | INTRODUCTION

Wildfires have occurred on the Earth's surface since the emergence of terrestrial plants approximately 420 million years ago (Bowman *et al.*, 2009), and in recent decades have been responsible for nearly 865 million acres (350 million hectares) of land burned per year globally (Giglio *et al.*, 2013). Wildfires can cause loss of life and infrastructure (Gill *et al.*, 2013), impair health, and reduce visibility (Spracklen *et al.*, 2007). Wildfires can also change species composition (McKenzie *et al.*, 2003), biodiversity (Moreira and Russo, 2007) and broad-scale biogeochemical cycles (Amiro *et al.*, 2001; Nave *et al.*, 2011).

Although humans have always coexisted with the effects of wildfires, recent wildfire trends are eliciting concern among researchers and the public (McKenzie *et al.*, 2003; Krawchuk *et al.*, 2009; Prior and Eriksen, 2013; Doerr and Santin, 2016; Schoennagel *et al.*, 2017; Radeloff *et al.*, 2018). In the United States, the annual average areas burned have more than doubled from about 3.3 million acres (1.3 million hectares) per year in the 1990s to over 7 million acres (2.8 million hectares) per year in the 2000s, while the number of wildfires has decreased from an annual average of about 78,600 fires in the 1990s to about 72,400 fires since 2000 (Hoover and Hanson, 2018; Jakes *et al.*, 2007). The opposite trend between areas burned and the number of wildfires is attributable to increases in both the number and size of large wildfires (e.g., fires over 100,000 acres) and the lengths of the fire season across much of the United States (Dennison *et al.*, 2014; Balch *et al.*, 2017; Jain *et al.*, 2017; Hoover and Hanson, 2018). However, the national and regional trends exhibit significant complexity, which complicates efforts to assess the impact of projected changes in the factors that affect wildfire frequency and size on possible future wildfire activity (Flannigan *et al.*, 2006; Malevsky-Malevich *et al.*, 2007; Barbero *et al.*, 2015; Balch *et al.*, 2017; Schoennagel *et al.*, 2017; Nagy *et al.*, 2018).

Various factors, both natural and human, can influence wildfires. The natural factors are interrelated and affect wildfires across a range of scales. Operating at continental and decadal spatiotemporal scales, climate is the dominant factor in determining wildfire regimes (Bowman *et al.*, 2009; Pechony and Shindell, 2010; Drobyshev *et al.*, 2012). Climate also influences regional- and local-scale factors, such as weather and vegetation conditions, which in turn affect wildfire regimes and the evolution of individual wildfires (Moritz *et al.*, 2005; Littell *et al.*, 2016; Kitzberger *et al.*, 2017). Climate bounds the range of weather and vegetation conditions for a given location, providing an overall framework for

identifying wildfire regimes and potential (Jolly *et al.*, 2015). At regional and local scales, meteorological variables such as temperature, relative humidity, wind speed, and precipitation influence the amount and condition of vegetated material, collectively referred to as “fuel” in the context of wildfire science (Schroeder and Buck, 1970). Meteorological variables determine moisture accumulation in live and dead fuel that, along with additional fuel attributes such as type, condition, and amount (referred to as “fuel loading”), are critical for determining if conditions favourable to wildfire ignition exist in a region or at a specific location (Dennison *et al.*, 2006; Westerling *et al.*, 2011; Schmidt *et al.*, 2016). The potential for fuel to burn is also influenced by regional soil moisture conditions, which can either promote the growth of plants or inhibit that growth and contribute to wilting (Vinodkumar *et al.*, 2017). Several studies have attempted to quantify how regional soil moisture and local meteorological variables affect wildfire potential across the landscape (Keetch and Byram, 1968; Dolling *et al.*, 2005; Garcia-Prats *et al.*, 2015).

The effects of weather conditions and fuel factors are tied somewhat to topography and regional geomorphology. In fact, wildfire behaviour has classically been described as an interrelated triangle between weather conditions, fuel, and topography (Countryman, 1972; Schmidt *et al.*, 2016). Topography influences wildfires in a manner that is temporally static but spatially varying, affecting everything from soil to vegetation to atmospheric conditions (Bennie *et al.*, 2008; Ebel, 2013; Calviño-Cancela *et al.*, 2017; Whitman *et al.*, 2018). Moreover, terrain can channel or disperse wind, affecting fire behaviour, as is evidenced by the Santa Ana wind and its influence on wildfires in southern California (Billmire *et al.*, 2014). Different orographic and geomorphic features have also been shown to influence fire spread after ignition (Povak *et al.*, 2018).

Nevertheless, the most dynamic factors that affect wildfire regimes are fuel and weather, both of which are related to climate. Climate is projected to change considerably in the 21st century, resulting in nonlinear and region-dependent changes to wildfire regimes, although current scholarship suggests a global trend towards increased wildfire risk (Flannigan *et al.*, 2009; Liu *et al.*, 2010; Yue *et al.*, 2014; Abatzoglou and Williams, 2016; Di Virgilio *et al.*, 2019). A significant body of literature has established the relationship between climate change and wildfires at global, continental, regional, and local scales. In the western United States, for example, earlier spring and reduced soil moisture are driving an increase in wildfire activity, but the magnitude of the effects varies spatially due to interrelations between the aforementioned variables and other

factors (Westerling *et al.*, 2006; Abatzoglou and Kolden, 2013; Littell *et al.*, 2016).

One of the major drivers of climate change is land use land cover change (hereafter, LULCC) and the contribution of LULCC to climate change varies with the conversion between different types of land use land cover (hereafter, LULC) and the spatial and temporal scale at which the conversion occurs. At local and regional scales, LULCC is manifested in biophysical effects that alter energy and water exchange between the earth's surface and its atmosphere, which in turn modifies local and regional atmospheric conditions. Studies have indicated that conversion from grasslands to croplands, as found across the south and central Great Plains of the United States, tend to lower sensible heat flux and enhance moisture flux, leading to cooling and increased atmospheric moisture levels especially over irrigated croplands (Bonan, 1997; Stohlgren *et al.*, 1998; Adegoke *et al.*, 2003; Mueller *et al.*, 2016). A substantial reduction in moisture flux has been linked to conversion of forests to grasslands or pastures for grazing operations, but a variable influence on regional moisture flux is found when forests are converted to croplands (Pielke *et al.*, 2007). LULCC at continental scale, most notably tropical deforestation, can alter large-scale atmospheric circulations by changing global aerosol loading and radiative forcing and thus global energy budget (Devaraju *et al.*, 2015, 2018; Duveiller *et al.*, 2018). These local, regional and global climate changes due to LULCC, in combination with the direct alteration of LULCC to fuel types, contribute greatly to changes in wildfire regimes (Foley *et al.*, 2005; Pielke, 2005; Butsic *et al.*, 2015). Given the complex relationships between LULCC, climate, and wildfire activity, predicting the responses of wildfires to LULCC and climate change is therefore a highly involved task. To date, most studies investigating how climate change might affect future wildfire regimes (Liu *et al.*, 2010; Di Virgilio *et al.*, 2019) rely primarily on projections from climate models for given greenhouse-gas-emissions scenarios that are generated by considering multiple emissions factors, including LULCC. Few studies have separately assessed climate change impact on wildfire regimes attributable directly to LULCC.

In this article, we assess how regional climate changes induced solely by LULCC could alter wildfire regime. The assessment is based on high-resolution regional-climate-model (RCM) simulations using current and projected future LULC patterns across the contiguous United States (CONUS). For the purpose of this analysis, greenhouse-gas levels and meteorological initial and boundary conditions remain unchanged in the RCM simulations in order to isolate the effects of LULCC on simulated atmospheric conditions that could affect wildfire activity. This type of approach that allows only one specific factor (in this case LULC) to change during the

course of model simulations is common in climate research. For example, Bonan (1997) examined the effects of LULCC on the climate of the United States through general-circulation-model (GCM) simulations with three (natural vegetation, modern vegetation, and a maximum agricultural) LULC scenarios. Also using a GCM, Devaraju *et al.* (2015) investigated the effects of large-scale deforestation on climate across the globe especially the monsoon regions by comparing a control simulation using a preindustrial landscape with simulations in which trees are replaced with grasses across the entire globe or in one of the three climate zones (boreal, temperate, and tropical), respectively. Conversely, Laguë and Swann (2016) systematically evaluated the response of clouds, global energy transport, and precipitation to afforestation of the northern mid-latitudes by incrementally convert what is present-day grassland or agriculture land to broadleaf deciduous trees in the GCM simulations. A major limitation in these and many other GCM or RCM studies of LULCC effect is the use of idealized LULCC scenarios that do not reflect reality. The RCM simulations we analyse here utilized a realistic LULCC scenario. Although a number of other climate modelling studies also utilized realistic LULCC scenarios (Huang *et al.*, 2020), the LULCC impact assessment did not go beyond prime climate variables.

LULCC-induced changes to climate variables interact to affect wildfire regimes. For example, a warming climate implies a stronger evapotranspiration that increases wildfire risk, but warming may also enhance convection and thus increase convective precipitation that tends to dampen wildfire activity. In this study, the integrated effects of LULCC-induced local and regional climate changes on wildfire activities are measured using two fire weather indices: the Canadian-Forest-Fire-Weather Index (CFFWI, Van Wagner, 1987) and the Hot-Dry-Windy Index (HDWI, Srock *et al.*, 2018). The CFFWI is a well-established fire index used worldwide in a variety of fire regimes, while HDWI is a new index that is gaining popularity in the United States and in other parts of the world (McDonald *et al.*, 2018). By comparing how these indices and their derived indicators would change under projected LULCC, we can elucidate how LULCC affects the atmospheric conditions essential for wildfires.

2 | METHODS

2.1 | Data

The primary data used in this study come from two 10-year RCM simulations using the Weather Research and Forecasting (WRF) model (Skamarock *et al.*, 2007).

These simulations were designed to isolate the contribution of LULCC to regional climate change across CONUS. The model domain was centred over the central CONUS, extending outwards to neighbouring countries and oceans (approximately 50–140°W, 15°–60°N). The domain was comprised of 359×259 horizontal grid points of 15-km spacing and 28 vertical layers stretching

upward from the surface to 100 hPa in the atmosphere. To isolate the effects of LULCC, two 10-year simulations were carried out, driven by identical initial and boundary conditions provided by the North American Regional Reanalysis (Mesinger *et al.*, 2006) for the period 2006–2015. The only difference between the two simulations was in the LULC types prescribed at the lower

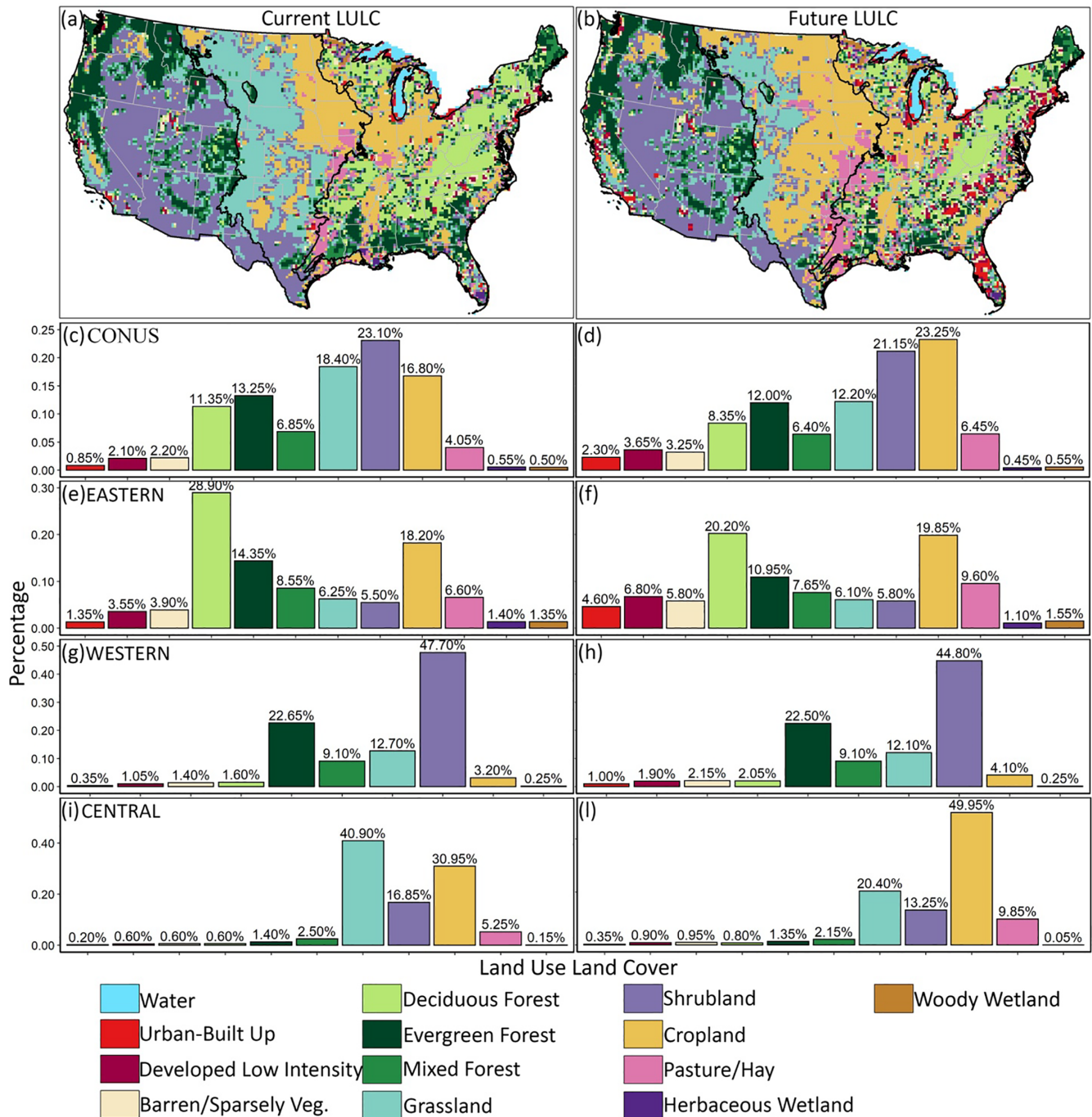


FIGURE 1 The current (2011) and future (2100) LULC categories derived from the National Land Cover Database: (a,b) spatial patterns for the CONUS and percentages for (c,d) the CONUS, (e,f) eastern region, (g, h) western region, and (i, j) central region. Light grey lines in (a, b) refer to state boundaries, while the black lines outline the eastern, central and western regions as described by the level I ecoregions developed by the United States Environmental Protection Agency [Colour figure can be viewed at wileyonlinelibrary.com]

model boundary: one simulation used 2011 LULC pattern (current) and the other used 2100 LULC pattern (future) based on the United States Geological Survey annual national-scale estimates for 2006–2100 using the FORECASTING SCEnarios of Land-use Change (FORE-SCE) modelling framework (<https://landcover-modeling.cr.usgs.gov/projects.php>) for the A1B greenhouse-gas-emissions scenario (Nakićenović *et al.*, 2000) (Figure 1). More details about the model configuration and physical parameterizations were given in Nikolic *et al.* (2019). A comparison of the RCM simulation of 2011 LULC with gridded climate analysis (Supporting Information) indicates that the simulation captured reasonably well the observed magnitude and spatial distribution of climate elements across CONUS.

2.2 | Fire weather indices

The impact of atmospheric conditions on wildfires in this study is represented by two quantitative numerical indices that require only meteorological inputs: the Fire Weather Index in the Canadian Forest Fire Danger Rating System (CFFI) and the Hot-Dry-Windy Index (HDWI). The CFFI (Van Wagner and Pickett, 1985; Van Wagner, 1987), although developed for assessing potential wildfire dangers for boreal forests, is used as a wildfire danger index by fire and land managers in the United States and around the world (Pearce and Alexander, 1994; Lee *et al.*, 2002; Groot *et al.*, 2006; Dimitrakopoulos *et al.*, 2011). The CFFI has six components: three fuel moisture codes for consideration of fuel moisture effects on wildfire occurrence, and three fire behaviour indices that account for the effects of surface weather conditions, particularly winds, on fire behaviour once a wildfire starts. All six components depend on daily values of 2-m temperature and relative humidity, 10-m wind speed, and 24-hr accumulated precipitation, with larger numbers indicating fuel moisture and surface weather conditions more conducive to dangerous wildfires.

The CFFI, which has fuel components that accumulate over time, is not designed to be computed during winter conditions (i.e., it should only be computed during the “fire season”). As described in Field *et al.* (2015), the beginning and ending dates of a fire season are usually determined by snow cover or surface temperature. For regions that experience substantial snow cover, which is defined as having a mean snow depth of at least 10 cm and snow on the ground for 75% of the days during the 2 months prior to the onset of the fire season, the calculation begins when a location has been snow-free for three

consecutive days and ends on the first day of snow arrival. For other regions, the calculation begins when the mean daily temperature is 6°C or above for three consecutive days and ends when it has dropped to below 6°C for three consecutive days. For broad-scale consistency and because RCM-simulated snow cover and depth are known to be much less reliable than simulated surface temperature (Minder *et al.*, 2016), we adopt the temperature criterion for defining fire season for the entire CONUS. We use a mean daily temperature of 6°C, although other temperature thresholds, for example, 12°C or 5°C, have been used to parameterize fire-season length in some studies (Flannigan and Wotton, 1993; McElhinny *et al.*, 2020).

The HDWI is a fire weather index developed to indicate when the atmosphere has the potential to contribute to dangerous wildfire behaviour (Srock *et al.*, 2018). The index has been shown to be effective for identifying dangerous fire-weather conditions using historical data (Kulseth, 2018; Worsnop and Scheuerer, 2020). HDWI is solely a weather index that neither explicitly nor implicitly accounts for fuel conditions. The index is calculated by taking the product of wind speed (U) and vapour pressure deficit (VPD):

$$\text{HDWI} = \text{VPD} \times U \quad (1)$$

where U is the maximum wind speed in the lowest 500 m of the atmosphere and VPD is the maximum surface-adjusted VPD calculated by adiabatically lowering air from each model level in the lowest 500 m to the surface. Since both U and VPD are positively defined, continuously varying variables, HDWI is also a continuous positive number for which higher values indicate weather conditions more favourable to dangerous wildfire behaviour.

Depending on the temporal resolution of the data used, high values of both CFFI and HDWI are most often driven by afternoon conditions (typically 1200–1800 local standard time). To ensure the applicability of these indices to the entire CONUS, we adopt the approach utilized by Jolly *et al.* (2015) and replace afternoon values with the daily maximum temperature, daily minimum humidity, and daily maximum wind speed determined from the 3-hourly model output to the 10-year RCM simulations. Classifications of CFFI values vary with fuel and climate. For example, CFFI values 13–24 (>24) signify high (extreme) fire dangers for Canadian boreal forests with CFFI >19 separating a spread day from a non-spread day (Podur and Wotton, 2011), 24–38 (>38) for maritime pines (Palheiro *et al.*, 2006) and 49–60 (>60) for Mediterranean environments (Dimitrakopoulos

et al., 2011). As a relatively new index, HDWI has no established thresholds, and whether a HDWI for a given day or location indicates the potential for dangerous wildfires has been determined by comparing HDWI values to historical values calculated from a reanalysis dataset (McDonald *et al.*, 2018). To apply CFWI and HDWI to the entire CONUS that spans multiple climate regimes, we adopt the method of Jolly *et al.* (2015) and define a “fire-weather day” as a day on which the normalized daily index value exceeds 50% of all historical values in the 10-year simulations. In other words, for a given day and a given model grid cell,

$$I_{\text{norm}} = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} * 100 \geq 50\% \quad (2)$$

where I_{max} and I_{min} are the maximum and minimum index values in the daily time series over the entire 10-year period. Because the criterion for dangerous wildfire conditions should remain the same for the current and future climate, the 50% threshold values are established using the 10-year current LULC simulation.

2.3 | Regions

The daily values of the CFWI and HDWI from the current and future LULC simulations are used in CONUS-wide and regional analyses (Bailey, 2014; Omernik and Griffith, 2014). To delineate regions, United States Environmental Protection Agency (EPA) Level I ecoregions are used, which contain the following subdivisions: Northeastern Forests, Eastern Temperate Forests, and Tropical Wet Forests (Eastern region); Great Plains (Central region); Northwestern Forested Mountains, North American Deserts, Marine West Coast Forest, Mediterranean California, Temperate Sierras, and Southern Semi-arid Highlands (Western region). The three regions are outlined in Figure 1. Additional information about these ecoregions can be found online at EPA: <https://www.epa.gov/eco-research/ecoregions-north-america>.

3 | RESULTS

3.1 | Land-use-land-cover change

Before discussing the simulated response of the two indices to LULCC, we examine how LULC in the CONUS is projected to change between current (2011) and future (2100) under the FORE-SCE framework. The projected

LULC scenario for 2100 anticipates an increase in human-modified LULC (e.g., Urban-Built Up, Developed Low Intensity, Cropland and Pasture/Hay) and a decrease in natural LULC (e.g., Deciduous, Evergreen, and Mixed Forest, Grassland, Shrubland, and Herbaceous and Woody Wetland) (Figures 1 and 2). The majority of LULCC is projected to occur across the Eastern (Figure 1e,f) and Central (Figure 1i,j) regions. Specifically, nearly a quarter of model grid cells in the Central region are expected to convert from natural to human-modified land use, as grassland and shrubland (decreasing by 20.5% and 3.6%, respectively) are replaced mostly by croplands and pasture/hay (increasing by 19% and 4.6%, respectively) (Figure 1i,j). LULCC in the Eastern region is marked by urbanization, with the number of urban grid cells increasing from 1.3% to 4.6%, and with developed low-intensity land nearly doubling from 3.5% to 6.8% (Figure 1e,f). Though less substantial, the projected LULCC in the Western CONUS is similarly characterized by expansion of urban and croplands into shrub or grasslands in areas such as the Central Valley of California and the Columbia Basin of eastern Washington (Figure 1g,h).

3.2 | Fire-season length

For this analysis, we adopt two definitions for fire-season length. The first, which is based solely on temperature and is used for the CFWI calculation, considers a fire season to begin (end) when the mean daily temperature is at or above (below) 6°C for three consecutive days, and the second, which is based on fire weather index, defines fire season as the number of days in a year for which normalized daily fire weather index value exceeds 50% of the historical values (Equation (2)) (Jolly *et al.*, 2015; Abatzoglou *et al.*, 2019).

An analysis of the temperature-based fire-season length under current LULC shows that the starting/ending dates of the fire season (Figure 3) are primarily dependent on latitude, elevation, and proximity to oceans. Fire seasons start (end) progressively later (earlier) towards the north and higher elevations. The fire season is almost year-round along the Gulf and Southern California coasts. In contrast, over the higher terrain of the northern Rockies, Cascades, and the Sierra Nevada, fire season is limited mostly to the astronomical summer months. Across most of the CONUS, fire season starts sometime in spring and ends in fall, with the exact dates varying by location.

The effects of projected LULCC on the temperature-based fire-season length are more pronounced in the

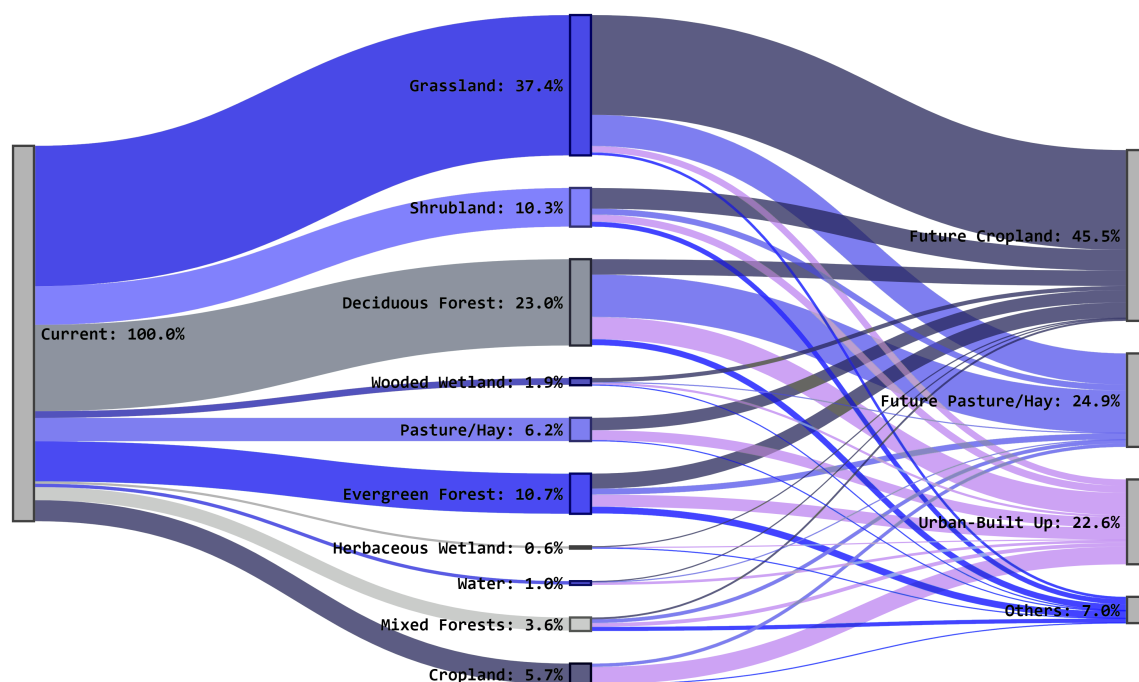


FIGURE 2 Sankey diagram illustrating the current to future LULC conversions in percentages calculated relative to the number of grid cells over which LULC changes are projected [Colour figure can be viewed at wileyonlinelibrary.com]

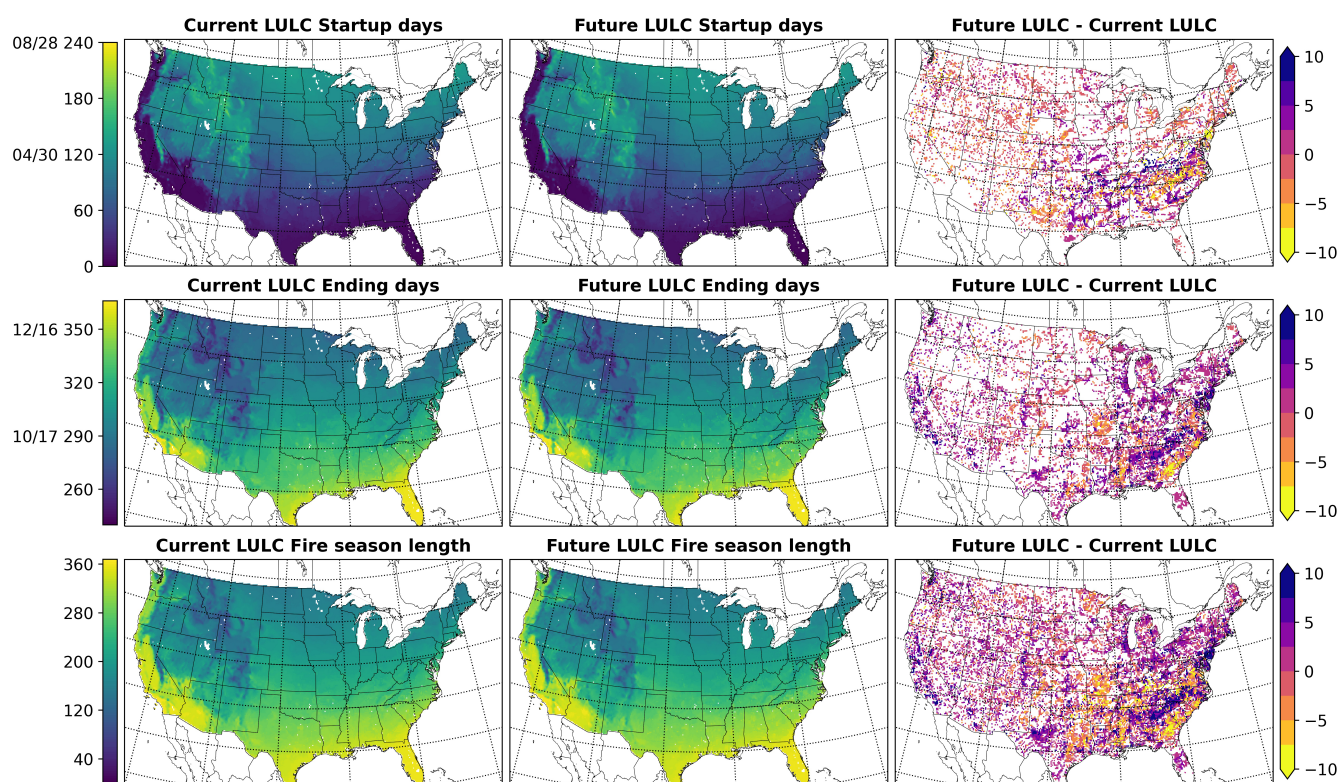


FIGURE 3 Temperature-based fire-season starting (top) and ending (middle) dates (Julian day and calendar date) and fire-season length (days) (bottom) averaged over the 10-year simulations with the current (left) and future (centre) LULC patterns and the differences between the future and current values (right, white denotes absolute differences less than 1) [Colour figure can be viewed at wileyonlinelibrary.com]

eastern than in the western CONUS (Figure 3). Changes in the west occur mainly in California where fire seasons are projected to become even longer due to LULCC. In the Southeast, fire-season length under projected LULCC increases in a corridor stretching from north-northeastern Georgia, through the Carolinas, and into Virginia, at locations where forest-to-urban conversion is projected. However, to the southeast of this corridor across southern Georgia and coastal areas of the Carolinas, where forest-cropland conversion is expected, fire seasons are likely to be shorter. Shorter fire seasons are also indicated in the south and central Plains and in the lower Midwest, where grassland-cropland conversion is projected, and over areas of eastern Texas and southern Missouri where pasture/hay will replace forests. These LULCC-induced changes in fire-season length based on simulated temperature differences are consistent with previous findings that transformation of forests to urban areas in the Appalachians and the southeastern United States significantly increases surface temperatures (Xian *et al.*, 2020), while conversion of forests to croplands in eastern and central United States lowers surface temperatures due mainly to the changes in albedo and Bowen ratio (Bonan, 1997, 1999).

Simulated fire-season length can vary due to changes in the starting and/or the ending dates. The relative contribution of the earlier/later starting/ending dates to the increase/decrease in fire-season length can be quantified using a ratio of the changes in the ending dates to the changes in the fire-season length (Figure 4). The ratio is positive when a longer (shorter) fire season corroborates with later (earlier) ending date and negative when a longer (shorter) fire season corresponds to earlier (later) ending date. Except for a few isolated areas, the ratios are nearly always positive, suggesting that the lengthening or

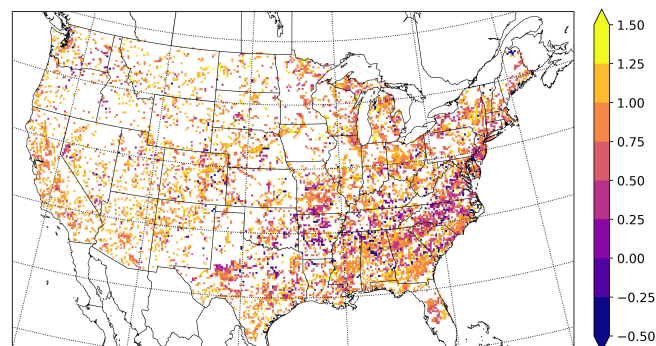


FIGURE 4 The ratio of the changes in the fire season ending dates to the changes in the fire season length. White areas are where the difference in either the fire season ending dates or season length between the current and future LULC is less than 1 day [Colour figure can be viewed at wileyonlinelibrary.com]

shortening of fire-season length correspond mostly to the delay or advance of the ending dates. More areas appear to have ratios greater than 0.5, indicating a larger contribution from the changes in the ending dates than those in the starting dates to the changes in fire-season length.

We next examine LULCC-induced changes to fire-season length defined using CFWI and HDWI according to Equation (2). Despite the inclusion of humidity and wind speed in the two indices, in addition to temperature, the overall spatial pattern (Figure 5) remains similar to that of temperature-based fire-season-length change (Figure 3). Whereas the magnitude of the changes across western CONUS appears to be independent of the specific index, the increase in fire-season length in central and particularly eastern CONUS is longer by several days for CFWI-based than for HDWI-based fire-season length. Differences are also observed between the index-based and temperature-based fire-season-length change. For example, the index-based fire season is expected to lengthen due to LULCC across the lower and mid Atlantic states, while temperature-based fire-season is likely to increase along a corridor of major urban expansions stretching from north-northeastern Georgia, through the Carolinas, and into Virginia, but decrease slightly in areas southeast of this

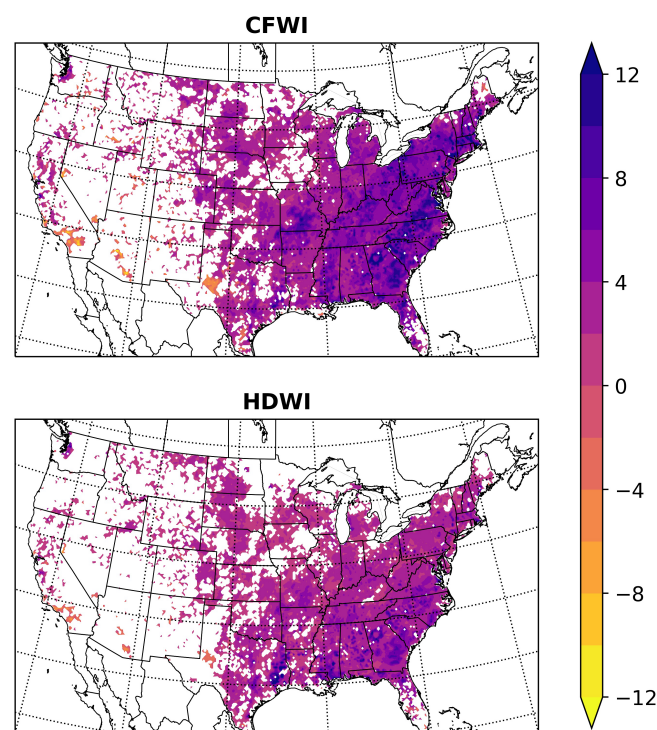


FIGURE 5 The differences between the future and current LULC simulations of fire-season lengths derived based on the number of days when the normalized CFWI (top) and HDWI (bottom) values exceed 50% of their respective historical values. Note white denotes absolute differences less than 1 [Colour figure can be viewed at wileyonlinelibrary.com]

corridor across southern Georgia and coastal areas of the Carolinas where forest-cropland conversion is projected. Differences also occur in Arizona, Utah and southern

California where an increase is expected for temperature-based fire season but no change or slight decrease is expected for index-based fire-season length.

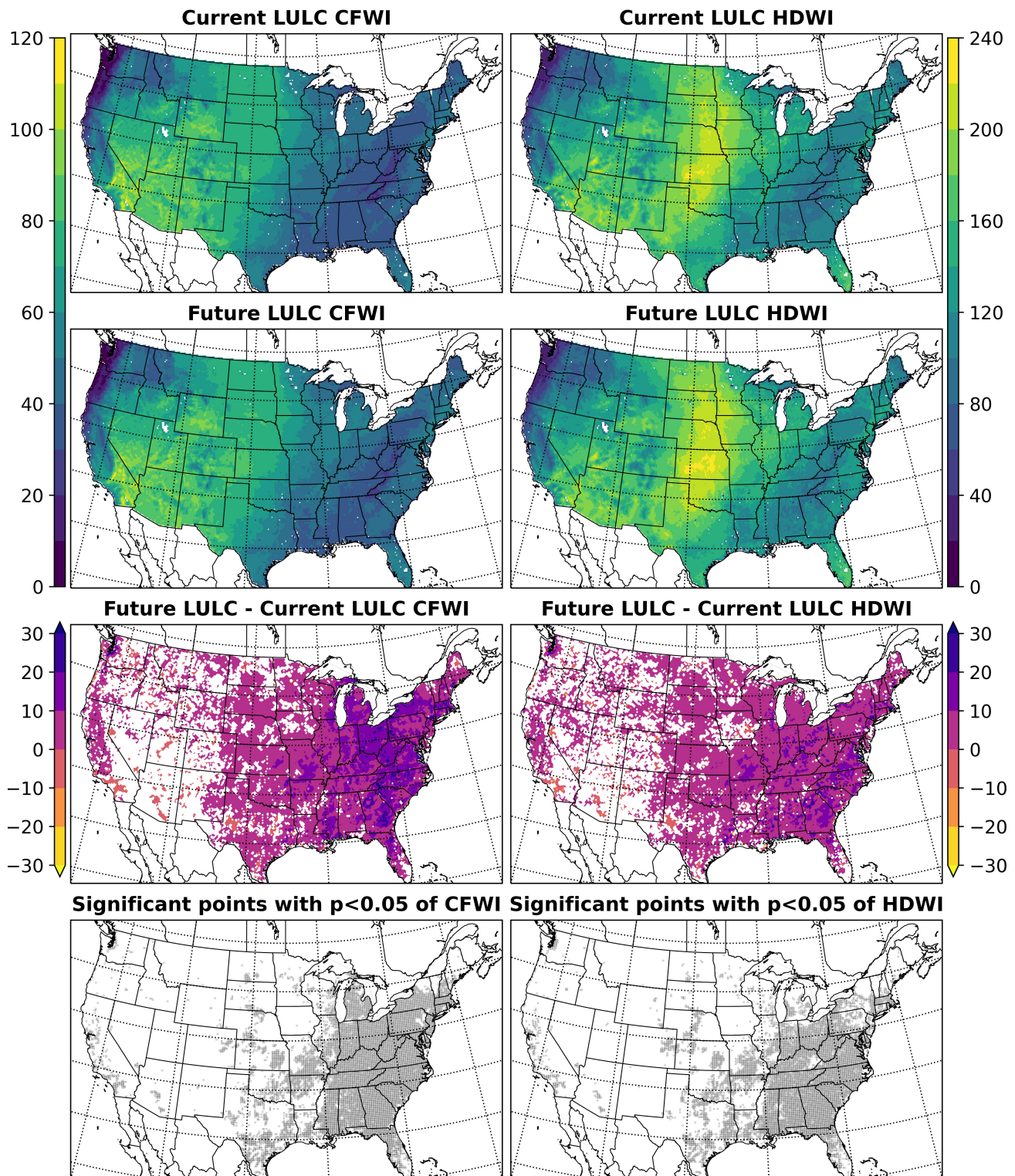


FIGURE 6 The median values of daily CFWI (left) and HDWI (right) indices averaged over the 10-year simulations with the current (1st row) and future (2nd row) LULC patterns and the percent differences between future and current LULC simulations (3rd row, note white denotes absolute differences less than 1) and statistical significance ($p \leq .05$) (4th row) [Colour figure can be viewed at wileyonlinelibrary.com]

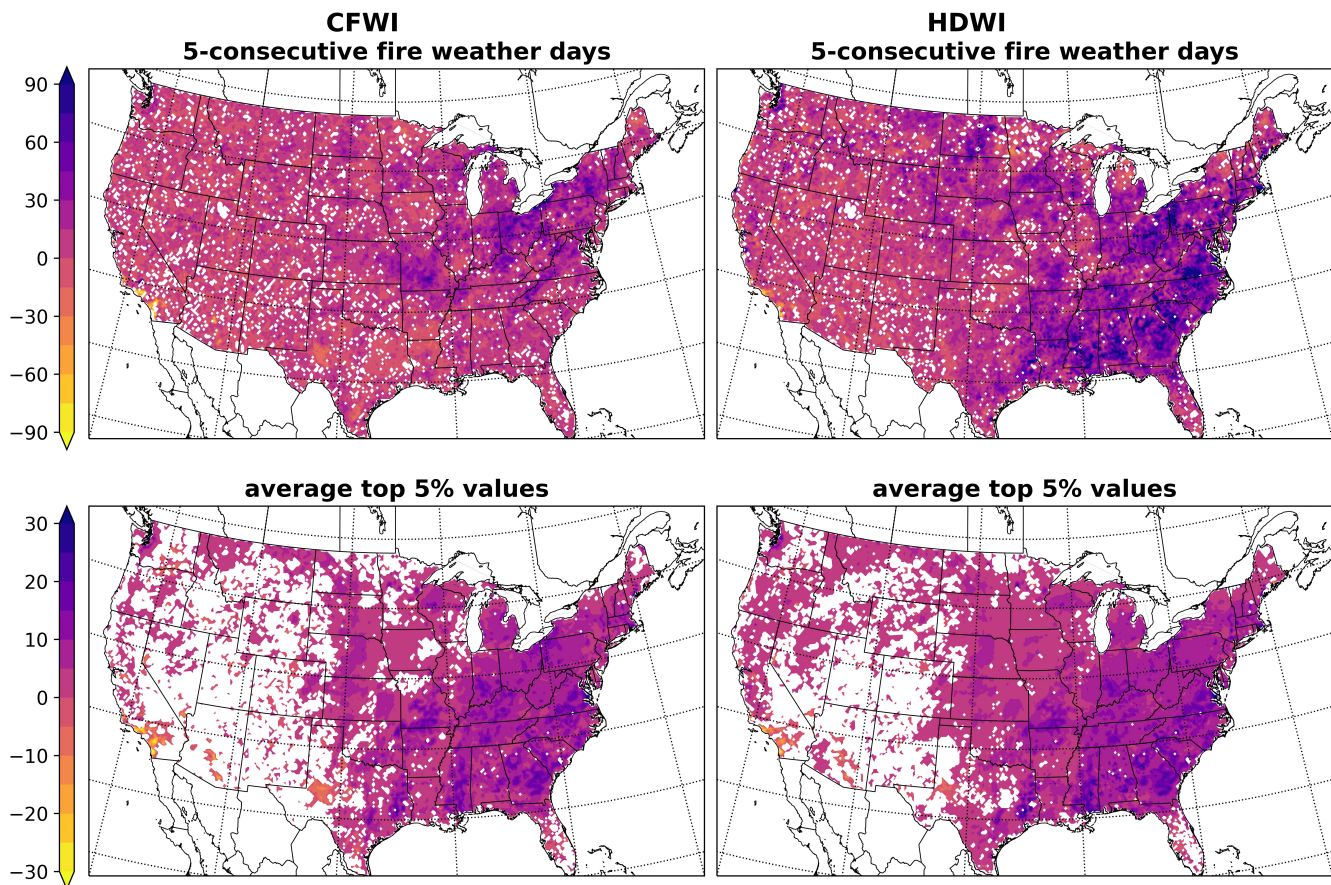


FIGURE 7 Percent differences between the future and current LULC simulations of the total number of 5-consecutive-fire-weather-day events (top) and the top 5% index averages (bottom) derived based on the CFWI (left) and HDWI (right) values. Note white denotes absolute differences less than 1 [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Fire weather indices

3.3.1 | Spatial pattern across CONUS

We first examine LULCC-induced changes to average fire-weather conditions by comparing the 10-year fire-season-averaged median CFWI and HDWI values in the current and future LULC simulations (Figure 6). For both indices, the overall spatial pattern is similar in the two simulations, with higher values in the Southwest, Intermountain West, and the Great Plains, and lower values in the Southeast, Northeast, and especially along the Pacific Coast. The similarities between the two simulations suggest that projected changes in LULCC alone do not substantially alter the overall spatial pattern of fire-weather conditions across CONUS. The two indices, however, exhibit maximum values at different locations - CFWI values peak in the Intermountain West, while HDWI values peak in the Great Plains. These differences can be explained by their different formulations. CFWI includes precipitation and the high CFWI values in the Intermountain West and Southwest reflect the lack of

rainfall in these regions. HDWI does not include precipitation and, instead of using surface temperature, humidity and wind as in CFWI, it utilizes maximum values within the lowest 500 m of the atmosphere, which explains the HDWI peak over the Great Plains where a low-level jet (a wind speed maximum usually found in the lowest 500 m of the atmosphere) prevails in the warm seasons (Doubler *et al.*, 2015).

Despite differences in the spatial distributions of the 10-year fire-season-averaged median values of the two indices, the changes between the current and future LULC simulations show a remarkably similar spatial pattern with statistically significant increases of 10–30% over the eastern CONUS, particularly in the Southeast, the eastern portion of the Midwest, and the southern part of the Northeast, and decreases of generally less than 10% in some areas of the western CONUS, particularly in the Southwest, southern California, east of the Cascades in the Pacific Northwest, and in parts of Texas. Comparing the two indices, both the values and the areas covered by the increases in CFWI are slightly larger than those of HDWI, particularly in the upper Midwest, but the drop

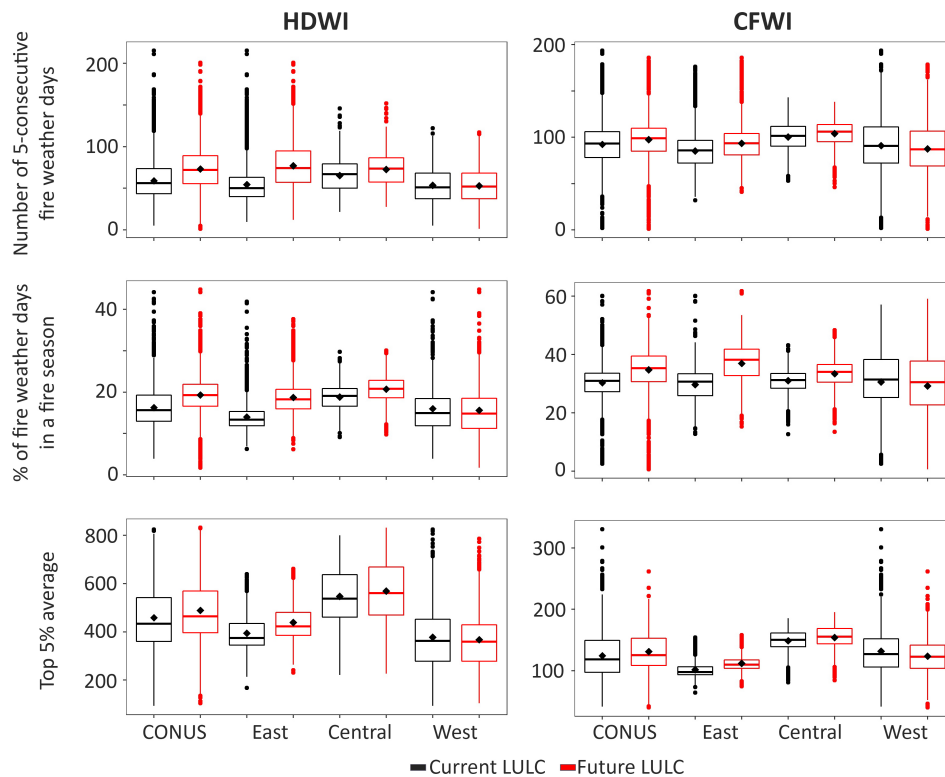


FIGURE 8 Summary statistics of the future and current LULC simulations of the total number of 5-consecutive-fire-weather-day events (top), percent fire-weather days in a fire season (middle) and top 5% index average (bottom) derived based on the HDWI (left) and CFWI (right) values over all grid cells in the east, central, west regions and the CONUS. Each box represents the 1st (Q1) and 3rd (Q3) quartiles of the interquartile distribution (IQR). The horizontal line and the rhombus indicate the distribution median (Q2) and the mean, respectively. The whiskers represent the limits (minimum and maximum) of the IQR (5% and 95%, respectively), while the solid circles indicate the outliers. The black and red color refer to the current and future LULC patterns, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

in the index values and the locations where the decreases occur in western CONUS show little dependency on the particular index.

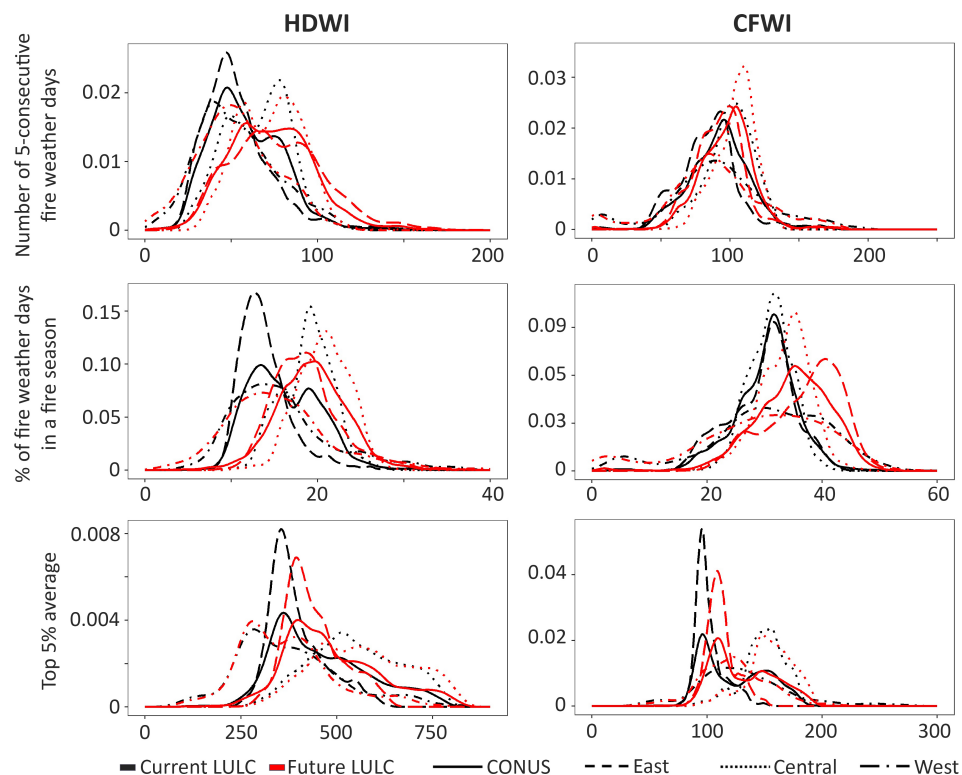
We next examine the projected response of extreme fire-weather conditions to LULCC. Extreme fire-weather condition is generally more of a concern to fire and resource managers than average fire-weather condition. Extreme fire-weather condition is evaluated by the occurrence of consecutive fire-weather days and by the top index values. Changes in the frequency of consecutive high index values would suggest a change in the conditions associated with the largest and most dangerous wildfires, which often occur during events wherein atmospheric conditions associated with dangerous wildfire behaviours persist for multiple days. Here, we examine the frequency of 5-consecutive-fire-weather-day events and the average top 5% index values (Figure 7). Different thresholds (7-day events and top 10% values) yielded similar results (not shown). The spatial distribution of the LULCC-induced changes to extreme fire-weather condition is similar to changes in average fire-weather condition, where much of the Southeast, Midwest and lower Northeast CONUS experience an increase in the occurrence of 5-consecutive-fire-weather-day events and in the magnitude of the top 5% index values and some areas of the western CONUS experience a decrease from the current to the future LULC simulations. The largest increase in the frequency of

5-consecutive-fire-weather-day events reaches 90% in some areas of the Southeast and Ohio River Valley, as compared to the largest decrease of about 50% in some areas of the southern California. The changes in the top index values are smaller and also uneven, with increases of 20–30% in many areas and decreases of generally less than 15%. Comparing the spatial pattern of the LULCC-induced changes diagnosed with HDWI with those diagnosed with CFWI, the former suggests a widespread increase in the occurrence of 5-consecutive-fire-weather-day events in the Southeast, eastern and lower Midwest, the lower Northeast, and in areas of the northern Plains, while the latter suggests increases that are mostly limited to the Ohio River Valley. The two indices differ little when it comes to diagnosing the LULCC-induced changes to the top 5% index values.

3.3.2 | Regional distribution

The above discussion has revealed substantial regional differences in the LULCC-induced changes to the mean and extreme fire-weather conditions. These regional differences are further elucidated by computing summary statistics (Figure 8) and density distributions (Figure 9) of the three fire weather indicators (average percent fire-weather days in a fire season, total number of 5-consecutive-fire-weather-day events and average top 5%

FIGURE 9 Density distributions of the future (red lines) and current (black lines) LULC simulations of the total number of 5-consecutive-fire-weather-day events (top), percent fire-weather days in a fire season (middle) and top 5% index average (bottom) derived based on the HDWI (left) and CFWI (right) values over all grid cells in the east, central, west regions and the CONUS [Colour figure can be viewed at wileyonlinelibrary.com]



index values) across all model grid cells in CONUS and within the Eastern, Central, and Western regions outlined in Figure 1.

For the Eastern and Central regions, the future mean/median values are higher across all three indicators derived from both indices and the changes are larger in the Eastern than the Central region. In the Western region, the mean/median values show little change or a slight decrease from the current to the future LULC simulations. The interquartile ranges show little change or slight future widening for all three indicators in the Eastern and Central regions, but the results are mixed for the Western region with both indices suggesting a slight narrowing in the ranges of the two extreme fire weather indicators in response to the projected LULCC.

The changes in the density distribution from current to future LULC simulations also vary considerably among the three regions (Figure 9). For all three indicators derived from the two indices, the distribution corresponding to the future LULC is flatter and broader, with a shift towards higher values compared to the current LULC in the Eastern region and to a lesser degree the Central region. The differences between the current and future distributions are smaller for the Western region because the projected LULCC is limited to smaller areas in this region compared to the other two regions where LULCC is much more prevalent. These results suggest that LULCC is likely to produce a future increase in both the average and extreme fire-weather conditions

in Eastern CONUS, though the spatial variation within the region also increases.

4 | DISCUSSION

The results presented here indicate that atmospheric conditions for dangerous wildfires should be expected to vary regionally and unevenly in the CONUS as LULCC occurs over the 21st Century. Specifically, LULCC-induced changes to atmospheric conditions would contribute to more frequent and intense wildfires in the Southeast, the Ohio River Valley, and across portions of the Great Plains, and to less frequent and intense wildfires in southern California and other areas of the Intermountain West. Importantly, these results do not imply a reduction in wildfire danger for southern California, which has seen destructive wildfires in recent years; the findings only indicate that changes in atmospheric conditions attributable to LULCC would contribute less to dangerous wildfires in this region. This result is in agreement with recent studies suggesting that LULCC plays a less prominent role in shaping future wildfire regimes than global climate change related to increasing greenhouse gas emissions (Pechony and Shindell, 2010). However, our results indicate that LULCC may still affect wildfire conditions at regional scale. Thus, it is beneficial to discuss these changes on a regional basis.

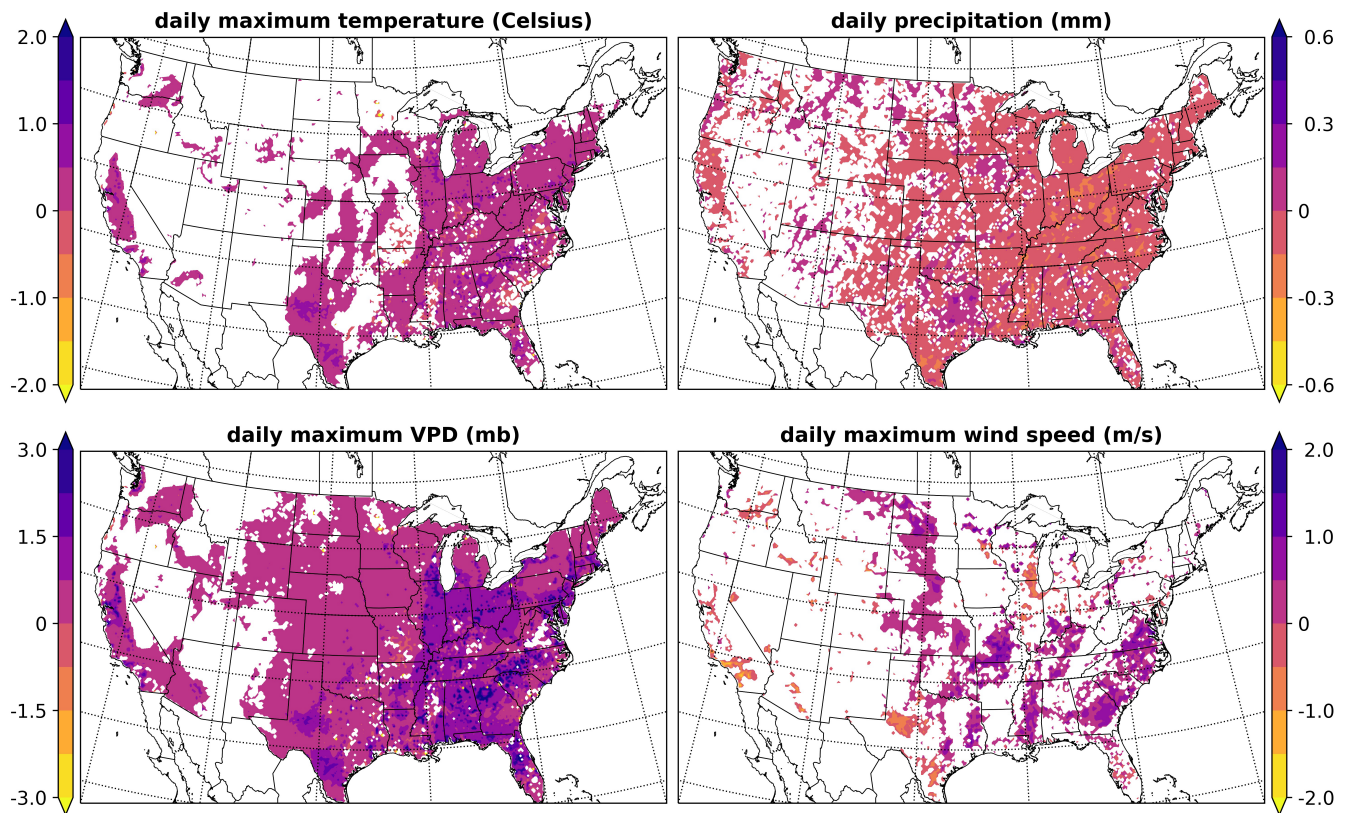


FIGURE 10 The differences between the future and current LULC simulations of the annual mean daily maximum 2-m air temperature, daily maximum 10-m wind speed, daily accumulated precipitation and daily maximum surface-adjusted vapour pressure deficit in the lowest 500 m of the atmosphere. Note white denotes absolute differences less than 0.01 for precipitation and less than 0.1 for other variables [Colour figure can be viewed at wileyonlinelibrary.com]

LULCC-related alterations to fire-season length and dangerous wildfire conditions are manifested regionally in two ways. First, some changes are confined within regions, such as the Piedmont and the coastal plains in the southeastern CONUS. In these regions, LULCC provokes distinct atmospheric responses. Other changes are occurring more subtly at the boundary between geologic, pedogenic, or biogeographic subregions, such as at the western boundary of the Alleghany Plateau in the Ohio River Valley. Since geology, soils, and biogeography all affect LULC patterns (Bauer *et al.*, 2004), the regionality of these results is reasonable.

4.1 | Southeast

The region that exhibits some of the most statistically significant changes in simulated fire-season length and fire-prone atmospheric conditions is the southeastern CONUS, which encompasses the swath of land from eastern Texas to the Potomac River and includes some of the fastest growing metropolitan areas in the CONUS. Here, fire-season length and dangerous fire-weather conditions

respond significantly to trends in urbanization and the conversion of forests to croplands. The epicentres for these changes are the currently forested lands of the coastal plains from Georgia to Virginia and the growing urban centres of the Piedmont, such as Atlanta and Charlotte, plus other areas such as Memphis and Washington, DC.

In both subregions, the simulated atmospheric response to projected LULCC suggests more frequent and severe fire-weather conditions in the future. Deforestation is likely driving this response in both subregions as the conversion of forests to urban lands has been linked to an increase in regional wildfire risk (Pitman *et al.*, 2012; Findell *et al.*, 2017). The localized response to deforestation in the Southeast diverges with regards to fire-season length, however. While temperature-based fire-season length increases along the urbanizing Piedmont, it decreases on the coastal plains due to the localized effects of cropland expansion. Specifically, maximum annual temperatures drop in these areas of the coastal plains (Figure 10), thus reducing fire-season length. Such results align with other studies that found the areas experiencing a conversion of natural habitats to

croplands cooled when the crops were in situ (Bonan, 1997; Bonan, 1999; Ge, 2010), while irrigated croplands demonstrated similar cooling effects on surface temperatures regionally (Adegoke *et al.*, 2003; Boucher *et al.*, 2004). However, fire-season length, when calculated as the number of days when normalized fire weather index values exceed 50% of the historical values, would increase in the coastal plains. This growth would occur alongside a rise in the frequency and intensity of extreme fire-weather conditions, possibly because of a drop in precipitation and an increase in VPD as well as an increase in wind speed under projected LULCC (Figure 10). These LULCC-related changes in temperature, VPD and precipitation in the Southeast are in general agreement with other studies of LULCC and regional climate (Pielke *et al.*, 2007; Chen and Dirmeyer, 2017).

4.2 | Ohio river valley

The other region projected to experience significant LULCC-induced changes in fire-season length and fire-weather conditions is the Ohio River Valley. According to the projected changes in both indices, almost the entire valley is expected to experience conditions more prone to wildfires in response to LULCC. In particular, the CFWI-based changes in fire-weather conditions are widespread across the region, with nearly the entire states of Ohio and West Virginia witnessing a significant increase in both mean and extreme index values. The HDWI-based values show a smaller, but still statistically significant increase in the frequency of fire-prone weather conditions under the future LULC scenario. Both indices suggest more frequent and severe fire-weather conditions from western New York through central Ohio to Kentucky along the western side of the Alleghany Plateau, which also represents a biogeographic boundary between eastern deciduous forests and the more agricultural lands to the west.

Both indices are responding to a series of complex land use shifts. Roughly, LULCC in the region can be characterized as one shift between pasturelands to urbanized landscapes and another shift from forests to pasturelands. Additionally, some croplands in the central Ohio River Valley are expected to be transformed to urbanized areas by 2100. These shifts affect key regional climate components – temperature, VPD and precipitation (Figure 10), which in turn drive the proliferation of dangerous fire-weather conditions. While maximum temperatures rise modestly by less than 1°C under future LULC conditions, VPD rises and precipitation drops significantly. These meteorological factors jointly drive the increase in the frequency of fire-prone

weather conditions across the region, even in areas such as West Virginia where deciduous forests remain steadfast. Correspondingly, these weather factors also extend the wildfire season later in the year by 2100 in many areas of the region including mid-Ohio, around Indianapolis, and along the south bank of the Ohio River. Interestingly, LULC in the state of West Virginia largely remains unchanged between now and 2100, but both indices, particularly CFWI, suggest an increase in the frequency of fire-prone weather conditions in the future. This result is important because it indicates that the continuity of atmospheric motions can extend the influence of LULCC beyond where it occurs.

4.3 | Central Plains

The Central Plains, a key agricultural region, do not exhibit the scale of change seen in the eastern CONUS. Yet, the highest CONUS values for the HDWI are in this region, which extends from Texas in the Southern Plains to the Dakotas at the Canadian border. This is unsurprising, as the HDWI is associated with high wind speeds and VPD in the atmospheric boundary layer, which are conditions found in this region. Despite the elevated HDWI values, the rise of dangerous wildfire conditions from the 2011 to the 2100 LULC scenarios appears modest, if evenly spread, over the region and statistically significant only in subregions where larger deviations from the current scenario are found. The most significant increase in dangerous wildfire conditions is in the tallgrass prairie subregions of Kansas and Oklahoma, where grassland-to-pastureland conversion is projected. Smaller increases occur in areas where croplands replace grasslands. These increases in fire-prone weather conditions appear to result from slightly drier (larger VPD) and windier atmosphere under future LULC scenarios (Figure 10).

Understanding fire weather responses to LULCC is critical as this region is susceptible to long-term aridity and has been the epicentre of decadal droughts, such as the 1930s Dust Bowl event and megadroughts that last centuries (Cook *et al.*, 2016). Fire and drought have been linked in several studies (Westerling and Bryant, 2007; Seabrook *et al.*, 2011; Alho and Silva, 2012; Turco *et al.*, 2017) and, according to the RCM simulations (Figure 10), several LULCC-induced changes in weather and climate patterns portend difficulties in portions of this region. For example, LULCC seems to drive higher maximum temperatures, higher VPD and lower winds in the Permian Basin subregion but lower temperatures and higher winds in portions of Kansas and Oklahoma.

4.4 | California

California has witnessed several devastating and deadly wildfires in the last two decades. Understanding fire weather here is a matter of critical importance. The state already has some of the longest fire seasons in the CONUS and our findings suggest the season may extend to the entire year under the projected LULCC. This lengthening of the fire season accompanies the conversion of shrublands at the periphery of the southern California urban megaregion to an urbanized landscape. Large urbanized areas are well-known conduits of the urban-heat-island (UHI) effect (Tran *et al.*, 2017), a phenomenon reflected in our results as maximum temperatures and VPD increase in the urban megaregion (Figure 10). Farther north, croplands along the Central Coast and in the San Joaquin and Sacramento Valleys are expected to be converted to urbanized areas, which also drives up maximum temperatures and VPD. This finding is consistent with other studies suggesting that much of California will move towards a year-round fire season in the future (Jain *et al.*, 2017).

Yet, despite a near-ubiquitous fire season, LULCC is likely to reduce the occurrence of fire-prone weather conditions in southern California, as areas previously at the WUI become well within the urban megaregion. The expansion of the southern California urban megaregion comes partly at the expense of chaparral shrubland, an ecosystem highly adapted and susceptible to wildfires (Moreno *et al.*, 2013). The reduction of this ecosystem area leads to an overall decline in dangerous wildfire conditions, although the resulting UHI effect lengthens the fire season. This is not replicated farther north where urban environments replace croplands, not chaparral. In fact, the projected LULCC by 2100 would lead to an increase in the fire-prone atmospheric conditions broadly across much of northern California and more sharply around cities, such as the San Francisco Bay area, and along the foothills of the Sierra Nevada in areas near the locations of the Carr and Camp fires.

4.5 | Other regions

Other regions show less significant, but nonetheless important fire weather responses to LULCC. Portions of the Cascades, the Willamette Valley, and the Puget Sound region mirror the response seen in the Sierra Nevada. Both fire indices suggest that fire-prone weather conditions in these regions become more frequent due to the conversion of forests to urbanized areas and pasturelands. Elsewhere across the western CONUS, the shrubland-to-cropland conversion lowers LULCC-related

wildfire risk, as shrublands often provide an excellent source of fuel. For example, gambel oak (*Quercus gambelii*) shrubland, found throughout western Colorado and the Southwest, are often loaded with fuelwood and contribute to “explosive” fire behaviour, such as that seen in Colorado's 1994 South Canyon Fire on Storm King Mountain that claimed the lives of 14 firefighters (Kaufmann *et al.*, 2016). Wildfire risk is also lowered by conversion of shrublands to urban landscape in areas surrounding Phoenix and Tucson in Arizona, a situation similar to that of southern California.

5 | CONCLUSION

In this study, we attempt to isolate LULCC-induced changes to climate variables, specifically temperature, VPD, wind, and precipitation, and investigate their combined effects, as estimated by two fire weather indices (CFWI and HDWI), on fire-season length and the frequency and severity of atmospheric conditions conducive to wildfires across CONUS. This is accomplished by comparing 10-year (2006–2015) high-resolution RCM simulations under current (2011) and future (2100) LULC scenarios. The projected LULCC is dominated by the conversion from natural landscapes (e.g., forest, shrubland, grassland) to anthropogenic landforms (e.g., urban, cropland, pasture and hay).

Since LULCC is regionalized, its effect on climate variables is regional as well. Thus, the effects of LULCC are highly heterogeneous, with LULCC-induced maximum temperatures rising where urbanized landscapes replace forests and grasslands, such as along the Piedmont and outside the Chicagoland region, and decreasing where croplands replace forests, such as the southeastern coastal plains. When these uneven climatological effects are applied to deriving fire-season length and fire-prone atmospheric conditions, the results unsurprisingly are regionalized. LULCC-related changes in conditions conducive to wildfires, as estimated by CFWI and HDWI, increase significantly in much of the eastern CONUS, specifically in the Southeast and Ohio River Valley, and decrease in urbanizing southern California, where some highly flammable shrublands are replaced by urban environments by 2100. Yet, this decrease in fire-prone conditions masks an important finding of our study – that much of California moves towards a year-round fire season by 2100 merely based on LULCC-induced changes to temperature. These results in fire-season length and fire-prone conditions in our study demonstrate that LULCC plays an important role in determining fire regime, but the effects are heterogeneous and regionalized.

This study has several limitations. First, the results are based on RCM simulations using a single model with one set of physical parameterizations. Although this approach has been widely used in studies of regional climate change, an ensemble approach with multiple models or multiple runs from a single model would not only allow the assessment of the overall trend of the changes, but also the uncertainties associated with the assessment. Second, the study uses only two fire weather indices - the inclusion of additional indices would lend more confidence on the conclusions. It should also be noted that while the CFWI can be used to indicate wild-fire ignition potential, the HDWI has no fuel information and thus cannot be used for this purpose. Therefore, any assessment of overall wildfire occurrence based on the HDWI results alone should be undertaken with caution. Third, the study assumes LULCC is the sole driver for regional climate change, neglecting changes due to increasing greenhouse gas emissions that may either reinforce or counter the LULCC-induced change in different regions. Fourth, the LULCC-induced change is realized only through changes in biophysical parameters such as albedo and roughness that influence surface energy and water cycle. Other natural (i.e., biogeochemical) or non-natural (i.e., agricultural irrigation, crop rotation) factors can also directly modify surface energy exchange with the atmosphere (Mueller *et al.*, 2016). For example, widespread irrigation practice in places such as the Midwest and central Plains where grassland is converted to cropland is found to decrease temperature but increase evapotranspiration and precipitation (Adegoke *et al.*, 2003; Pielke *et al.*, 2007), lowering potential for wildfires. Fifth, the relatively coarse resolution of 15 km used in the RCM simulations may be inadequate in resolving the modifications of LULCC to complex-terrain phenomena such as the Santa Ana winds that are critical for fire spread in southern California. Consequently, the results in highly complex terrain should be interpreted with caution. Finally, it is worth noting that the current study focuses exclusively on the sensitivity of fire-weather conditions to projected LULCC, whereas LULCC can also more directly affect wildfire activities by changing fuel type and fuel conditions. For instance, an increase in the frequency of extreme fire-weather conditions resulting from conversion from natural burnable systems (e.g., forest, grassland, shrubland) to man-made non-burnable system (e.g., urban landscapes) and an increase in ignition potential associated with the growth of WUI may be mediated by fuel reduction. On the other hand, increased temperature associated with forest-urban conversion contributes to not only higher frequency of extreme fire-weather conditions but also fuel aridity, both of which favour extreme fire behaviour. A comprehensive

understanding of LULCC-modifications on climate, fire weather and fuel conditions and their multi-scale interactions requires modelling with coupled climate, weather, fire behaviour and fuel modelling systems.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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