

Climate change projected to reduce prescribed burning opportunities in the south-eastern United States

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Abstract. Prescribed burning is a critical tool for managing wildfire risks and meeting ecological objectives, but its safe and effective application requires that specific meteorological criteria (a ‘burn window’) are met. Here, we evaluate the potential impacts of projected climatic change on prescribed burning in the south-eastern United States by applying a set of burn window criteria that capture temperature, relative humidity and wind speed to projections from an ensemble of Global Climate Models under two greenhouse gas emission scenarios. Regionally, the percentage of suitable days for burning changes little during winter but decreases substantially in summer owing to rising temperatures by the end of the 21st century compared with historical conditions. Management implications of such changes for six representative land management units include seasonal shifts in burning opportunities from summer to cool-season months, but with considerable regional variation. We contend that the practical constraints of rising temperatures on prescribed fire activities represent a significant future challenge and show that even meeting basic burn criteria (as defined today) will become increasingly difficult over time, which speaks to the need for adaptive management strategies to prepare for such changes.

Additional keywords: coastal plain, piedmont, managed fire regimes, statistical downscaling, wildfire.

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Introduction

Prescribed burning is widely used to reduce wildfire risk and manage ecosystems to achieve a range of ecological, economic and societal objectives (e.g. [National Academies of Sciences, Engineering, and Medicine 2017](#); [Riley *et al.* 2018](#)). Its use is now so widespread in the United States that the total area burned annually by prescribed fires exceeds that burned by wildfires ([Melvin 2015](#)). Simply put, fire is now primarily a purposeful and managed process in many regions of the US. Given projected changes in key environmental factors that constrain prescribed burning, it is clear that predicting the future of fire will require a better understanding of whether environmental criteria defined by managers who conduct prescribed fires can still be met, thereby allowing fire to be maintained on the landscape and in associated fire-dependent ecosystems.

Prior to ignition of a prescribed fire, a written and approved plan must clearly define suitable weather and fuel conditions, desired fire behaviour and targeted fire effects required to meet predetermined objectives. The suitable range of weather conditions (and other factors) is referred to as the prescription burn window. These conditions must facilitate manageable fire behaviour while protecting the health and safety of nearby communities ([Schweizer and Cisneros 2017](#)) and the personnel conducting fire activities ([Budd 2001](#)).

Meteorological variables used to define the prescription parameters can vary considerably depending on the management objectives and safety constraints. Typically, though, commonly observed variables such as temperature, relative humidity and wind speed are included because of their relevance to many aspects of fire management ([Wade and Lunsford 1989](#)). For instance, relative humidity and temperature are used in fuel moisture calculations that predict fire behaviour through diurnal cycles ([Fosberg and Deeming 1971](#); [Viney 1991](#); [National Wildfire Coordinating Group 2017a](#)). Independent of relative humidity, excessive maximum daily temperatures can lead to heat stress and mortality risk for personnel ([Budd 2001](#)), increase canopy damage ([Wade and Johansen 1986](#)) and limit prescribed burning opportunities owing to elevated regional wildfire risk ([Schultz *et al.* 2018](#)). Wind speed is a critical variable because of its contribution to smoke management ([Chiodi *et al.* 2018](#)) and desired fire behaviour ([Wade and Lunsford 1989](#)). Other variables or indices such as atmospheric mixing height, Keetch–Byram Drought Index, or dispersion indices that are more specific to prescribed fire management may also be used ([Waldrop and Goodrick 2012](#)).

The identification of suitable prescribed burning conditions requires that specific ranges must be defined for relevant environmental factors to meet legal requirements ([Hiers *et al.*](#)

2020). The availability of suitable days for prescribed burning is thus sensitive to atmospheric conditions at the time of ignition (Chiodi *et al.* 2019), with constraints on prescribed fire activities further magnified by stringent air quality regulations (Quinn-Davidson and Varner 2012; Liu *et al.* 2014). Current prescriptions also often reflect decades of experiential knowledge as to what is safe for managers to meet desired ecological objectives (Wade and Lunsford 1989; Waldrop and Goodrick 2012).

The sensitivity of the decision-making process to weather conditions suggests that long-term shifts in the distribution of meteorological variables would strongly impact future opportunities for prescribed burning, the risks faced by managers conducting burns, or both (e.g. Mitchell *et al.* 2014). Yet, there continues to be only a rudimentary understanding of how future climate change could influence the planning and implementation of prescribed fires (Clarke *et al.* 2019). This stands in contrast to wildfires, for which there is a growing body of literature on the risks to communities and ecosystems stemming from anthropogenic climate change (Westerling *et al.* 2011; Balch *et al.* 2017; McKenzie and Littell 2017; Schoennagel *et al.* 2017). Results of such studies nonetheless attest to the challenges that climate change may pose to prescribed burning programs, particularly in regions projected to see increased wildfire risk and where increased investment in mitigative activities will be needed. Here, we address this question by assessing how opportunities for prescribed burning, as represented by fire-prescription parameters for key weather parameters, would be influenced by projected changes in climate.

Our focus is on the south-eastern US, a region where managers conduct prescribed fires on more than 3 million ha annually, an amount that is more than half of the nation's combined total. This extensive burning program reflects conditions specific to the South-east, where fire has been an integral part of the landscape for millennia (Fowler and Konopik 2007; Lafon 2010). Consequently, species with survival or regeneration strategies that allow them to tolerate or quickly recover from fire (e.g. thick bark, buried buds or meristems, light or winged seeds) were prominent in many ecosystems, including pyrophylllic longleaf pine (*Pinus palustris*) ecosystems that are a focus of regional conservation efforts (e.g. Costanza *et al.* 2015; Stephens *et al.* 2019).

The region is also characterised by rapid population growth and extensive suburban development (Terando *et al.* 2014), which impose significant constraints on prescribed burning while simultaneously highlighting the necessity of an active prescribed fire management regime to reduce wildfire risk in these communities (Hiers *et al.* 2003; Ryan *et al.* 2013). The frequent prescribed burning that has been so successful at reducing risk and providing conservation benefits could become more costly, complex, or risky if the desired climatic conditions that govern the availability of safe and suitable days to conduct prescribed fires become less frequent or more erratic. To date, though, modelling-based studies that examine the potential effects of climate change on fire in the South-east have concentrated on wildfire (Prestemon *et al.* 2016; Terando *et al.* 2017) and its relation to drought (Liu *et al.* 2013), rather than addressing the corresponding implications for prescribed fire activities.

To assess the changing opportunities for prescribed burning in the South-east, we use output from a suite of statistically

downscaled Global Climate Models (GCMs) to project changes in three meteorological variables that are commonly used in the definition of burn windows: near-surface air temperature, near-surface relative humidity and 10-m wind speed (for brevity we refer to these variables as temperature, relative humidity and wind speed respectively). Along with air mass stability, these variables are particularly important to managers conducting prescribed fires because they affect: (1) the moisture dynamics of forest fuels, (2) the rate of fire spread, and (3) the vertical transmission of heat (Wade and Lunsford 1989). These factors in turn influence fire behaviour, intensity and severity, thus controlling potential fire regimes (Guyette *et al.* 2014). Temperature is also a critical factor affecting safety conditions for personnel conducting prescribed fires because exposure to extreme heat (or cold) can result in severe health consequences, some of which can be fatal (National Wildfire Coordinating Group 2017b). We stress that our analyses do not seek to project the specific days on which prescribed fires will take place or whether conditions will be within prescription for a given locale as those determinations are dictated by site-specific management objectives. Instead, we focus on the changing nature of the reliability of favourable weather conditions for prescribed fire because, in the absence of such conditions, prescribed burning activities will decrease.

Using these ecologically and operationally relevant burning criteria, we employ a high-resolution historical climate dataset to calculate baseline monthly estimates of the frequency of suitable days for conducting prescribed fires. We then assess how the number of suitable days falling within the burn window would change given spatially explicit projections of future climate conditions from 18 statistically downscaled GCMs under two greenhouse gas climate-forcing scenarios, highlighting results for six land management units that reflect a variety of climatic and ecological conditions throughout the region. We conclude with a discussion of the management implications and potential adaptation strategies that decision-makers will likely need to consider as a warming climate affects their ability to maintain fire on this landscape.

Methods

Study area

Our focal study region is the area encompassed by the Southeast Conservation Adaptation Strategy (SECAS: Southeast Conservation Adaptation Strategy 2018). SECAS was created by a collaborative network of federal and state conservation partners to create a vision for sustaining fish, wildlife and natural resources in changing future landscapes in 15 south-eastern states, the Virgin Islands and Puerto Rico. We included only areas of the SECAS footprint located within the contiguous US in our analyses. To provide insights into subregional changes in the availability of suitable burning days, we also examined future changes in greater detail for six land management units within the region: Big Cypress National Preserve (NPres), Uwharrie National Forest (NF), Land Between the Lakes National Recreation Area (NRA), Chattahoochee National Forest, Ouachita National Forest and Kisatchie National Forest (Fig. 1). These units are located within six different US EPA Level III ecoregions and were selected for their: (1) spatial

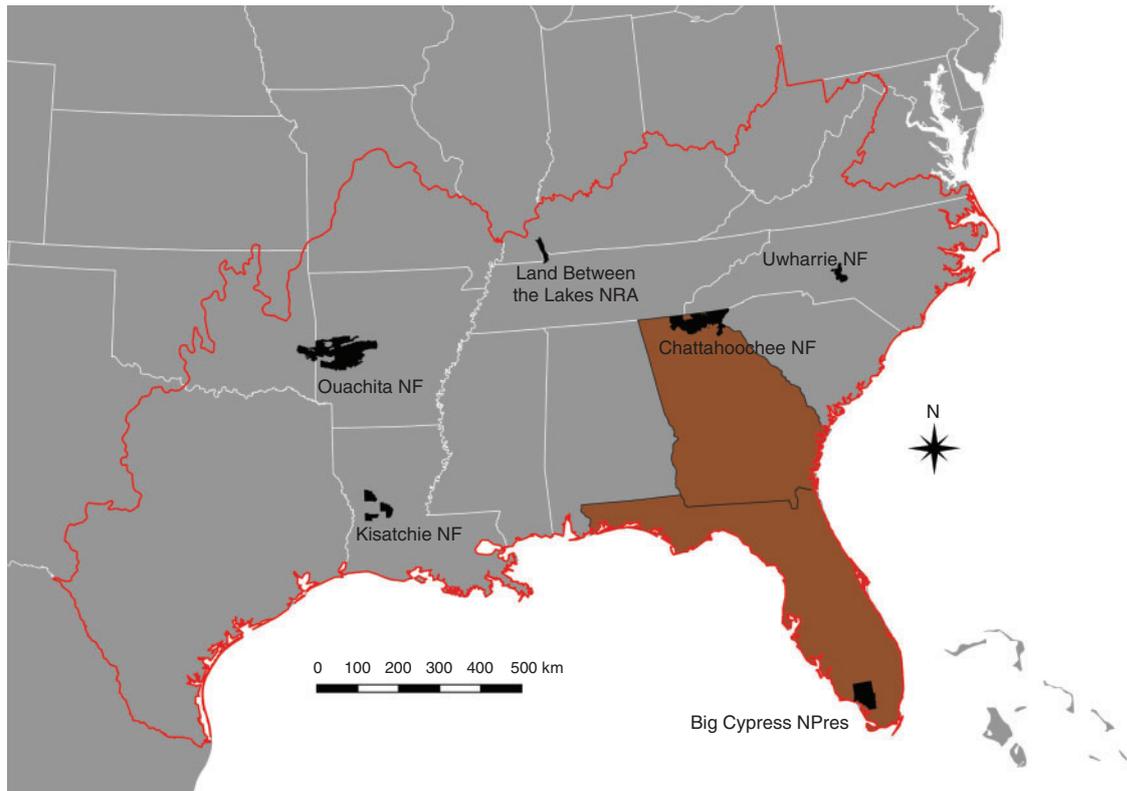


Fig. 1. Location of the study area (red outline) and federal land management units examined in this project. Florida and Georgia, the state sources for the prescribed fire permit records, are shown in brown. Abbreviations: NF, National Forest; NRA, National Recreation Area; NPRES, National Preserve.

coverage, in that they collectively comprise a range of different climate conditions and habitats within the region, and (2) management relevance, in that prescribed fire is an actively used management tool within each.

Prescribed burn windows

Initial thresholds for burn windows were defined using information from published manuals on prescribed burning in the South-east (e.g. Wade and Lunsford 1989; Waldrop and Goodrick 2012; Chiodi *et al.* 2018), guidelines provided for individual prescribed burn unit plans (e.g. Georgia Forestry Commission 2019) and input from regional fire managers. For relative humidity, we defined the burn window as days with relative humidity $\geq 30\%$. Below this value, fire intensities increase and fine dead fuels dry quickly. In many south-eastern states, a relative humidity $< 30\%$ warrants a National Weather Service Red Flag Warning for potentially hazardous fire weather. As relative humidity increases, less fuel will combust, resulting in a lower fireline intensity and patchier burn, which may not be ideal for meeting some management objectives. However, rather than imposing an upper burn threshold, we simply use a lower boundary to exclude conditions under which burning is avoided to reduce the risk of losing containment.

Wind speed influences how fast a fire spreads and plays a role in shaping crown damage and smoke dispersion. Recommendations for wind speeds are complicated because speeds vary greatly within a canopy depending on factors such as

understorey density and height and canopy tree density. In-stand winds of $0.4\text{--}1.3\text{ m s}^{-1}$ measured at eye level are preferred for most fuel and topographic situations, while desired minimum and maximum wind speeds at 6 m are ~ 2.5 and 8.9 m s^{-1} respectively, depending on canopy conditions (Wade and Lunsford 1989). Because fires are often set at even lower values to facilitate containment or to promote spread during winter understorey fires, we used slightly lower burn window thresholds of 2.25 to 8.0 m s^{-1} .

Determining burn window thresholds for temperature was more difficult, in part because recommended air temperatures for prescribed fires depend on the season and objective of the fire. To establish a minimum temperature, we used regional guidelines for winter burning, which hold that temperatures should be above 0°C . Published guidelines for the upper temperature threshold, based on summer burning recommendations, are less precise. Waldrop and Goodrick (2012) state that if the objective is to control undesirable species (or if preserving the overstorey is not a concern), ambient growing season air temperatures should exceed 26°C . They do not, however, provide an upper threshold, and prescribed burning is regularly conducted at much hotter temperatures. States such as Georgia recommend that fires be conducted at ambient temperatures $< 30^\circ\text{C}$, but guidelines used by regional fire managers at Eglin Air Force Base and Apalachicola National Forest (both in northern Florida) cite a maximum threshold temperature of 35°C (J.K. Hiers, pers. comm.). We thus used the mid-point of

these recommended maximum temperatures (32.5°C) as a starting value to represent prescription parameters used regionally. We then analysed regional burn permit data (described in the following section) to refine this temperature window as needed to reflect the temperatures experienced during the time of day when most managers would conduct burns.

Calculating daily availability of suitable burning conditions

We used two datasets to calculate, map and analyse spatio-temporal patterns of burn window availability under current conditions and explore potential changes due to projected anthropogenic climate change over the remainder of the century. For contemporary weather, we used the gridMET dataset (<http://www.climatologylab.org/gridmet.html>; accessed 6 May 2020), which blends spatial attributes of gridded climate data with temporal attributes from regional reanalysis of historical weather using climatically aided interpolation (Abatzoglou 2013). The resulting product is a high-resolution (~4 km) gridded dataset of surface meteorological conditions from 1979 to the present that has been validated and used in several studies (e.g. Abatzoglou and Kolden 2013), including those examining interactions among wildfire and climate change (e.g. Stavros *et al.* 2014; Abatzoglou and Williams 2016; Parks *et al.* 2016).

Future changes in burn window availability were explored using statistically downscaled GCM projections from the MACAv2-METDATA dataset (<https://climate.northwestknowledge.net/MACA/>; accessed 6 May 2020). This dataset downscales GCMs from the Coupled Model Intercomparison Project 5 (CMIP5: Taylor *et al.* 2012) utilising a modification of the Multivariate Adaptive Constructed Analogs (MACA) method with the gridMET observational dataset used as training data (see Abatzoglou and Brown 2012). MACA data, which are bias-corrected to and have the same spatial resolution as gridMET data, are part of the US Climate Resilience Toolkit and have been used in several studies examining potential impacts of future climate change (e.g. Sheehan *et al.* 2015). Model output was available for the CMIP5 historical simulation period (1950–2005) and scenarios representing different 21st century greenhouse gas emissions pathways (2006–99).

Although initial burn window thresholds were selected based on values from the literature and regional managers, we recognised the potential for a mismatch between: (1) the operational use of burn windows in relation to changing conditions throughout the day, and (2) our use of a select set of climate variables to calculate current availability of, and project future frequencies of, suitable burning conditions. The available temperature variables in long-term gridded climate datasets such as gridMET and the downscaled climate model projections in MACAv2-METDATA are typically limited to daily maxima and minima, and across such a wide region, a 32.5°C upper temperature threshold may be less applicable in some locations. Moreover, managers could make use of their own heuristics when deciding whether to conduct a burn, such as using the expected temperature at the time of ignition (typically between 1000 and 1300 hours).

To address these potential discrepancies and ensure that the set of meteorological variables used to project burn window conditions was representative of the actual conditions used by managers, we analysed daily meteorological conditions coincident with burn permits from Florida and Georgia over an 11-year

period from 2006 to 2016 (see Supplementary Material Text S1 for details on this dataset). These permitting records were readily available, consistently archived and representative of the range of habitat types in the study area. Prior to analysis, the site-specific Florida permit data were aggregated to the county level to match the reporting resolution of the Georgia permit data. We removed pile burn permits to focus solely on broadcast fires, which yielded a dataset containing 241 033 burn permit records. If our *a priori* criteria based on the daily extremes of temperature and relative humidity were not highly correlated with the actual prescribed burn criteria used by managers or if the variables inadequately captured surface meteorology at the time of the fires, we would expect a significant number of permits to fall on days with conditions outside the climate variable windows that are based on daily extrema.

We first extracted five meteorological variables from the gridMET dataset for the date of each fire in the permit data: minimum and maximum relative humidity, minimum and maximum temperature, and mean wind speed. Because the permits were aggregated to the county level, values of each variable were averaged for all cells within a county using the Zonal Statistics tool in *ArcGIS ver. 10.4* as an approximation for the weather conditions on burning days. We then calculated basic descriptive statistics and generated histograms of the frequency of meteorological conditions on days when prescribed fires were permitted.

An assessment of the permit data against daily temperature and relative humidity extremes indicated that a significant portion of permitted days fell outside burn windows that were defined based on the gridMET estimated minimum and maximum daily temperatures and relative humidity. The permit data also revealed that most ignition times occurred between 1000 and 1300 hours; in contrast, the daily minimum temperature (and maximum relative humidity) and daily maximum temperature (and minimum relative humidity) in South-eastern forests typically occur at ~0500–0600 and 1500–1600 hours respectively. We therefore developed estimates of hourly temperature and relative humidity for times of day that better reflected conditions anticipated by managers conducting the prescribed fire. We were especially interested in estimating local noon (1200 hours) temperature and relative humidity as this time coincides (approximately) with the midpoint of most prescribed fires.

Methods for estimating hourly temperature and relative humidity from daily extremes widely in their complexity and required inputs (e.g. Kimball and Bellamy 1986; Reicosky *et al.* 1989; Ephrath *et al.* 1996). Some methods were too computationally intensive for the spatial extent of our analyses or required data that were not available for the datasets that we employed, including the MACA data. We thus chose to estimate the local noon temperature using a method that assumes that temperature variation is driven by solar irradiance and provides a smooth transition from minimum to maximum air daily temperature (Campbell 1985):

$$T_{\text{noon}} = T_{\text{min}} + 0.5 \times (\sin(6.283 \times (\text{Hour} - 10)/24) + 1) \times (T_{\text{max}} + T_{\text{min}}) \quad (1)$$

Table 1. Summary of meteorological conditions derived from the gridMET dataset on days with approved burn permits in Georgia and Florida (2006–16)

Suitable burn criteria are: temperature (T; 0 to 32.5°C), relative humidity (RH; > 30%), and wind speed (2.25 to 8.0 m s⁻¹). Daily values that were compared with the burn window criteria included three measures of temperature (minimum, 1200 hours, maximum), three measures of relative humidity (minimum, 1200 hours, maximum), and one measure of wind speed (daily mean). NA, not applicable

	% below lower threshold	% within burn window	% above upper threshold	Percentile values: 2.5th–97.5th
T _{min}	13.1	86.9	0	(−4.5)–23.5°C
T _{noon}	0.3	97.2	2.5	5.6–32.6°C
T _{max}	<0.1	83.5	16.4	8.6–36.1°C
RH _{min}	25.2	74.8	NA	18.2–60.9%
RH _{noon}	2.5	97.5	NA	30.0–70.0%
RH _{max}	<0.1	99.9	NA	59.4–100%
Wind	15.6	84.1	0.3	1.5–6.3 m s ⁻¹

where T_{noon} is the estimated temperature at noon, T_{min} and T_{max} are the daily minimum and maximum temperatures, and Hour is the time to be approximated (set to 12, for noon). We also estimated values for the noontime relative humidity:

$$RH_{\text{noon}} = RH_{\text{max}} + ((T_{\text{noon}} - T_{\text{min}})/(T_{\text{max}} - T_{\text{min}})) \times (RH_{\text{min}} - RH_{\text{max}}) \quad (2)$$

where RH_{noon} is the estimated relative humidity at noon, RH_{min} and RH_{max} are the daily minimum and maximum relative humidities, and T_{min}, T_{max} and T_{noon} are the daily minimum, maximum and noon temperatures as per Eqn 1 (Waichler and Wigmosta 2003). This equation has been shown to perform well in comparison with other approaches when values for daily maximum and minimum relative humidity were available (Bregaglio *et al.* 2010).

Burn windows based on estimated noontime temperature and relative humidity better captured the meteorological conditions that occurred during regional prescribed fire activities (Table 1; Fig. 2). More than 97% of the days on which permits were requested for prescribed fires in Florida and Georgia took place within the selected burn window thresholds as approximated by daily noon temperature (T_{noon}) and relative humidity (RH_{noon}). In contrast, the use of the daily extrema (daily minimum and maximum temperature, minimum relative humidity) to define the burn window only captured between 74.8% and 86.9% of the permitted days (Table 1). We did not estimate noontime wind speed, but the majority (84.1%) of permitted days fell within the burn window for daily average wind speeds, with 15.6% of days having mean wind speeds that fell below the lower wind speed threshold and only 0.3% of days having wind speeds above the recommended upper threshold.

The upper temperature threshold (32.5°C at 1200 hours), in particular, appears to represent a meaningful management threshold for conducting prescribed fires. Fewer than 2% of permits were requested under conditions warmer than this threshold, and those fires accounted for far less than 1% of all permitted burn area (Fig. 3). Further, the size of the largest permitted fires dropped precipitously beyond this threshold, which could indicate a step increase in the perceived riskiness of continuing to conduct mission-critical burns at high

temperatures. Operationally, it is worth noting that an upper threshold of 32.5°C at noon corresponded to burn days with maximum temperatures of ~36–37°C. Such days would already be a source of major heat stress, with most ignitions occurring before noon to avoid unnecessary risk to personnel. This lends further support for the use of this threshold given its correspondence to the fire permit records.

Considering these results, subsequent analyses were based on values of three meteorological variables that were calculated for each 4-km pixel in both the gridMET and MACAv2-METDATA datasets: 1200 hours temperature, 1200 hours relative humidity and daily mean wind speed.

Projecting future changes in the availability of suitable burning conditions

Changes in the number of days meeting burn window conditions under future climate scenarios were analysed using the down-scaled MACA-derived GCM projections. Because projections based on output from any single GCM would severely truncate the estimated range of potential future climatic conditions, we obtained and analysed data from 18 GCMs that had daily outputs for all of the weather variables of interest (temperature, relative humidity, wind speed): BCC_CSM1.1, BCC_CSM1.1(m), BNU-ESM, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, INMCM, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM and MRI-CGCM3 (see Supplementary Material Table S2.1 for the full names of GCMs used in this study). For each GCM, we used the downscaled climate model output for two greenhouse gas emissions scenarios or Representative Concentration Pathways (RCPs): RCP 8.5, which represents a higher emissions pathway and often serves as a scenario that does not include any specific emissions reduction target, and RCP 4.5, a lower emissions scenario that assumes reductions that stabilise emissions, atmospheric greenhouse gas concentrations and radiative forcing of the climate system. Comparing the results against multiple scenarios is important because the uncertainty associated with future emissions due to human activities begins to dominate the total climate model projection uncertainty in the decades after the middle of the 21st century (Hawkins and Sutton 2009).

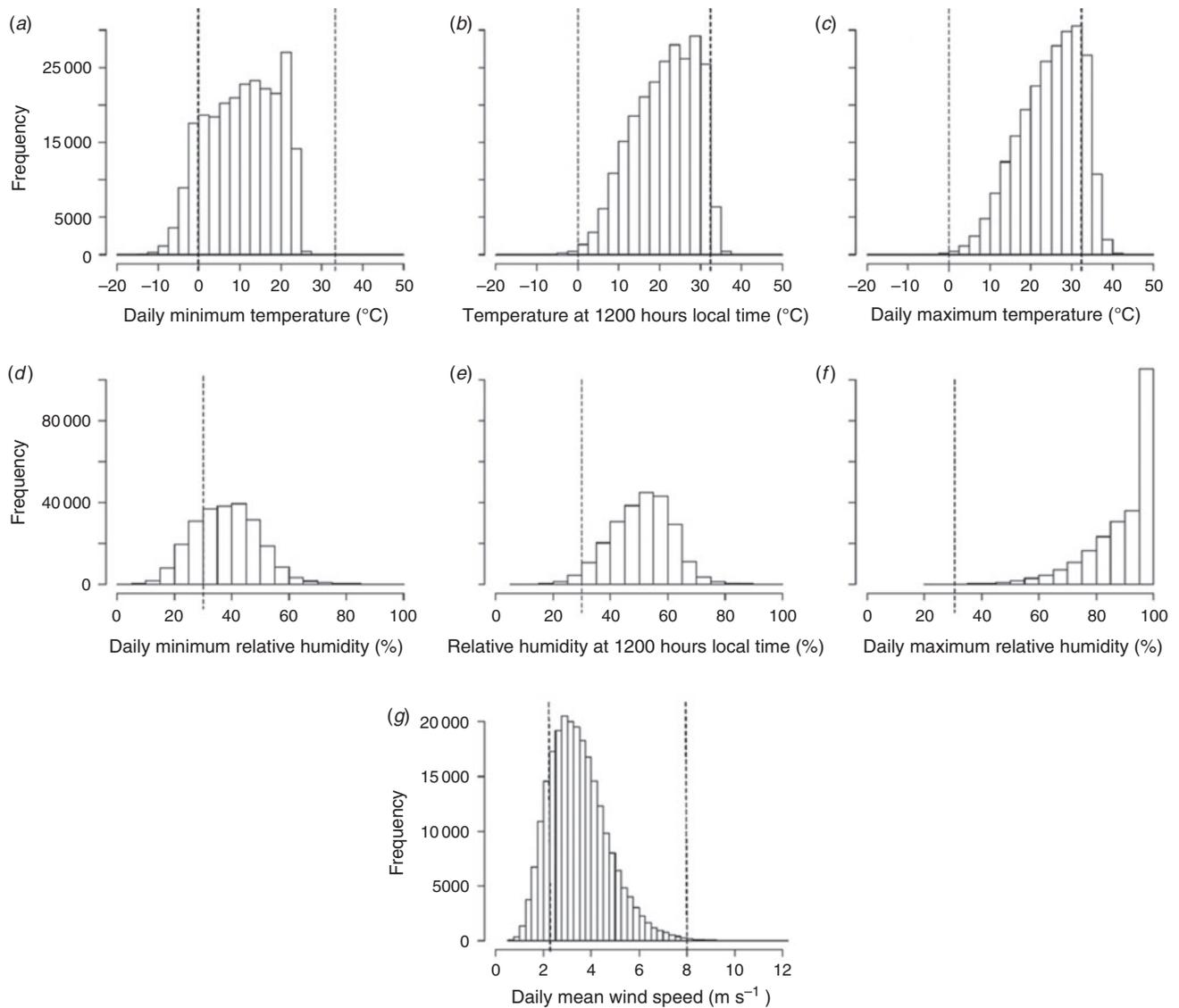


Fig. 2. Surface meteorological conditions derived from the gridMET dataset on days with approved burn permits in Georgia and Florida, 2006–16. Vertical dashed lines indicate suitable burn criteria intervals for temperature (0 to 32.5°C), relative humidity (> 30%), and wind speed (2.25 to 8.0 m s⁻¹).

We produced estimates of 1200 hours temperature and relative humidity for the MACA-derived GCM projections using the procedure described above for analysing the GridMet data, and classified each day from 1950 to 2099 as suitable or unsuitable for prescribed burning based on whether or not it met the burn window criteria for all three climate variables. The resulting number of suitable burning days per month were calculated for each grid cell in the study area. Because changes in the percentage of days meeting acceptable burn conditions might be expected to exhibit seasonal variation, we also aggregated the monthly values based on the downscaled GCMs into three seasons corresponding to common prescribed fire management periods: (1) the ‘winter’ burning season (January and February), (2) the ‘summer’ burning season (June and July), and (3) a ‘transitional’ spring burning season (March, April and May).

Results

Regional changes in seasonal burn window availability

Burn window availability in the historical period (1976–2005) as calculated from the multimodel mean for all 18 downscaled GCMs showed suitable conditions throughout the region during the winter burn season and widespread opportunities during the summer months (Fig. 4, top row). However, the frequency of suitable burning days was projected to decrease substantially during the warm-season months across much of the region under future climates, with the percentage of suitable days dropping from 64.9 to 40.6% under the RCP 4.5 scenario and 21.9% under the RCP 8.5 scenario (Fig. 4, right column). Areas in the south-western part of the study region would experience especially severe declines in which fewer than 10–15% of summer days would remain viable for conducting prescribed fires. Changes in

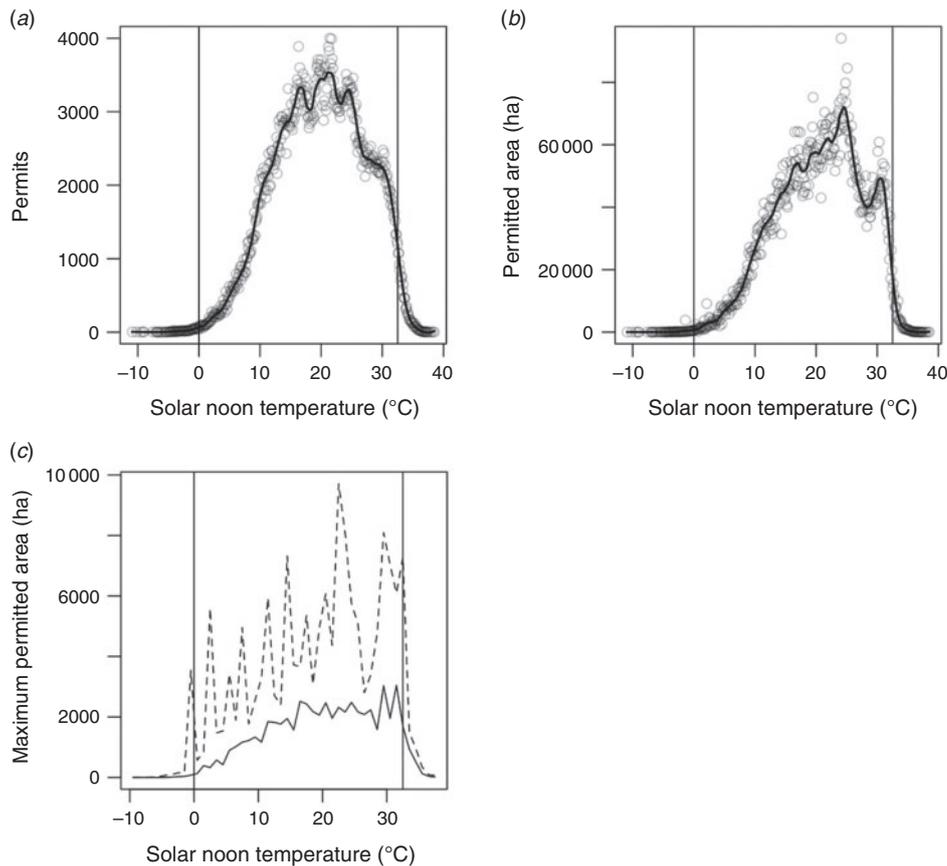


Fig. 3. Relationships between T_{noon} temperature and (a) burn permits issued, (b) total permitted burn area, and (c) maximum permitted burn extent, based on approved burn permits in Georgia and Florida, 2006–16. Data are summarised in (a) and (b) for each temperature occurrence, with a loess curve fit to those data. In (c), all maximum burn extents requested per permit are binned for each degree from -9.5 to 37.5°C (based on units of 0.1°C). The median (solid) and maximum (dashed) values for each bin are then plotted. Temperature threshold values (0 and 32.5°C) are plotted as vertical lines.

climate associated with the RCP 4.5 and RCP 8.5 scenarios generally resulted in few changes in the number of suitable days during winter, with some areas where burning conditions are currently limited by cold winter temperatures (northern locations and higher elevations) even experiencing slight increases (Fig. 4, left column). Overall, the percentage of suitable burn days in the winter season based on the multimodel mean is projected to increase 1.5% under the RCP 4.5 scenario by the end of the 21st century compared with historical conditions (from 76.6 to 78.2% of days) and 3.0% (76.6 to 79.6%) under the RCP 8.5 scenario.

Results for the region-wide seasonal changes in burn window availability were consistent across the downscaled GCMs (Supplementary Material Table S2.2). For the winter burn season, small increases in the percentage of suitable days are projected for 15 of the 18 GCMs under RCP 4.5 (mean: $+2.0\%$; range: -1.5 to $+5.8\%$) and 17 of the 18 GCMs under RCP 8.5 (mean: $+3.8\%$; range: -1.7 to $+7.9\%$). For the summer season, the percentage of suitable days dropped under all GCM projections (often substantially), but there was greater variation in the projected impacts than for winter for both RCP 4.5 (mean: -37.5% ; range: -13.8 to -53.1%) and RCP 8.5 (mean: -66.3% ;

range: -37.0 to -84.6%) scenarios. The GCM range of region-wide projected changes during the transitional spring month showed small decreases in burn-day availability under RCP 4.5 (mean: -4.0% ; range: -5.9 to -0.6%) but was more pronounced under RCP 8.5 (mean: -10.5% ; range: -17.0 to -5.6%).

We explored the challenge confronting managers with respect to how many fewer days would be expected to experience temperatures within the original safe-operating temperature range compared with the historical period by using a bootstrapping procedure to estimate the distribution of projected noontime temperatures on days that historically were favourable for burning (Fig. 5). For each GCM, we repeatedly sampled ($n = 250$) 1-year blocks of Julian dates over the period 2080–99 that corresponded to the same historical Julian dates for which burn permits were issued. The top two panels display histograms for the GCM showing the least (right panel; INMCM under the RCP4.5 scenario) and most (left panel; HadGEM2-ES under the RCP8.5 scenario) amount of warming while the bottom histogram is the same as that shown in Fig. 2b. The HadGEM2-ES model results indicate that the number of original permitted days expected to be above the 32.5°C threshold would rise from 2.5% for the 2006–16 period to 28%, a more than 10-fold increase in

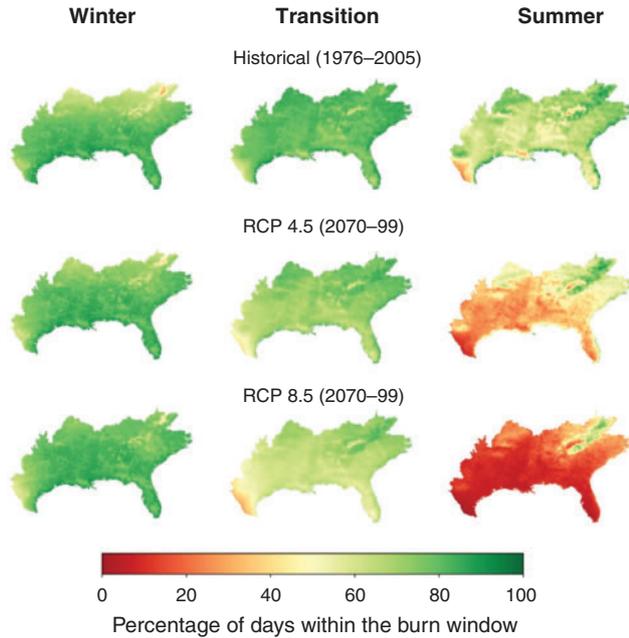


Fig. 4. Historical and projected percentage of days during winter (January and February), transitional (March, April, May), and summer (June and July) burn seasons that fall within accepted burn window conditions. Historical baseline period (1976–2005) and future conditions (2070–99) are averages calculated from 18 downscaled Global Climate Models under two future greenhouse gas emissions scenarios, RCP (Representative Concentration Pathway) 4.5 and 8.5.

out-of-prescription days. In the lower panel, we illustrate these results by overlaying each GCM's 32.5°C threshold that corresponds to the same frequency of days under historical conditions on the original histogram. For example, the results for the HadGEM2-ES model under RCP8.5 are depicted as brown vertical lines at 26.9 and –4.6°C, meaning that the frequency of days in the future falling between 0 and 32.5°C is equivalent to the frequency of days during 2006–16 that experienced noontime temperatures between –4.6 and 26.9°C. Under both emissions scenarios, managers would face new constraints and reduced opportunities to burn on days that currently fall within the safe operating conditions for conducting prescribed fires.

Changes in individual management units

For the six focal management units, declines in suitable burn days through 2099 under RCP 8.5 are driven by projected increases in noontime temperature, particularly in the warm-season months (Fig. 6). Conversely, relative humidity and wind speed under RCP 8.5 were not projected to differ noticeably from the historical record. For the two southernmost units (Big Cypress NPres and Kisatchie NF), the number of suitable burn days was projected to decline from ~15 to fewer than 2–6 per month from May through August as temperatures increased. As a result, the summer burning season was virtually eliminated, with the multimodel mean showing only 5–10% of days meeting the burn window criteria. This loss of summer burn days was again in contrast to the winter burning season, where most days remained within the temperature threshold and the overall

winter burn season was not projected to change noticeably. The management units at higher elevations (Chattahoochee NF, Ouachita NF) or higher latitudes (Uwharrie NF, Land Between the Lakes NRA) showed less drastic projected changes during the warmer months but were nonetheless still projected to experience declines in the percentage of days meeting the burn window criteria.

The annual time series of observed and projected percentages of suitable burn days for each management unit under the RCP8.5 scenario are shown in Fig. 7. The observed burn window suitability based on the gridMET dataset for 1987–2017 (the red line in Fig. 7) showed much greater interannual variability than the ensemble mean (black dotted line), but nearly all of the values fell within the range of the GCM ensemble (shaded grey areas). The range of projected burn window responses was generally largest during the summer burn months compared with the winter and transition seasons. A notable exception to this is seen towards the end of the century, where the range of projected changes in suitable summer burn days at the warmer sites (Big Cypress NPres and Kisatchie NF) actually declines simply because some models project that summer months will no longer have any suitable days to conduct prescribed fires. For the winter season (and the transition season at some sites), the range is comparatively small, with most values falling 5–15% above or below the multimodel ensemble mean.

Unlike the lower-elevation Coastal Plain sites, the percentage of suitable burning days during the winter burning season at Uwharrie NF and Chattahoochee NF was projected to increase slightly (<5%) as warming temperatures brought more suitable days for prescribed fire. Similarly, warming winter conditions led to a greater frequency of suitable burning days at the inland Ouachita NF and Land Between the Lakes NRA sites, but the number of suitable days was lower than for the more eastern units owing to more frequent penetration of cold air masses. When coupled with the more restrictive summer conditions, the result was a narrower set of months for burning centred in spring (February–April) and late fall (autumn) (November).

Throughout our analyses, the results using data for the RCP 4.5 scenario are qualitatively similar to those for RCP 8.5, except there is less projected warming over the 21st century, which increases the availability of burn days in the warm-season months (see Supplementary Material Table S2.2, Figs S2.1, S2.2).

Discussion

Fire management in a time of rapidly changing climate

Our analysis of a large dataset of prescribed fire permits confirmed that a simple and static set of meteorological criteria can effectively characterise the vast number of burning activities conducted by managers in the south-eastern US. When coupled with projections from a suite of 18 statistically downscaled climate models under two greenhouse gas forcing scenarios, the results depict a future in which there would be substantial reductions in late spring and summer opportunities for prescribed fire in the region. These lost opportunities are driven by elevated maximum temperatures causing high-heat days that currently are viewed as unsuitable or too risky for conducting burns. Prescribed fire is one of the most important strategies available to forest managers to reduce wildfire risk and achieve

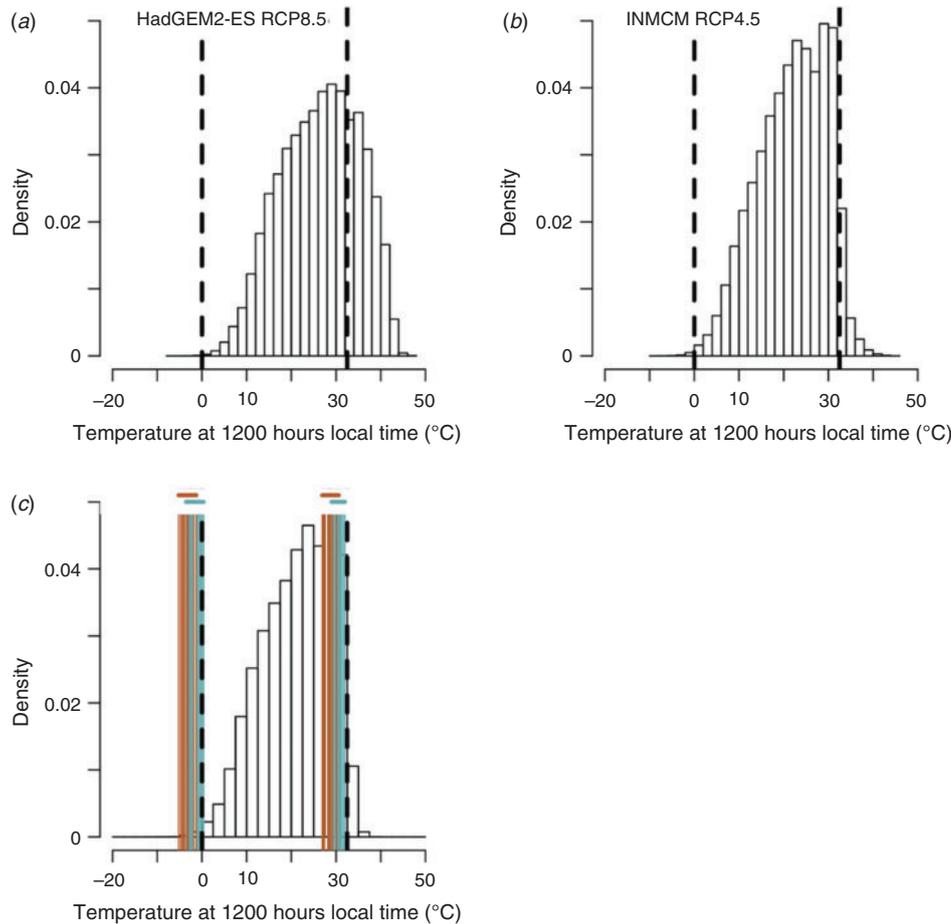


Fig. 5. Projected shifts in the frequency of noontime temperatures experienced on permitted burn days in Georgia and Florida, 2006–16. The histograms in (a) and (b) and the vertical lines in (c) are based on 250 bootstrapped time series samples for each Global Climate Model (GCM) over the period 2080–99. Individual histogram results for the two GCMs showing the most and the least warming are shown in (a) and (b) respectively, with the current prescription parameter range of 0–32.5°C shown as vertical dashed lines. The vertical blue-green and brown lines in (c) are placed at the historical noontime temperatures that coincide with the future frequency position of the 0–32.5°C range. For example, the vertical brown line at 26.9°C shows that only 72% of noontime temperatures are projected to be below 32.5°C for the HadGEM2-ES GCM under the RCP (Representative Concentration Pathway) 8.5 emissions scenario by the end of the 21st century. Historically, 72% of noontime temperatures were below 26.9°C. The multimodel ensemble ranges for both scenarios are shown as horizontal brown (RCP 8.5) and green (RCP 4.5) lines.

ecological objectives in the US and globally, but current practices will be challenged by projected warming trends with both practical and ecological consequences.

In addition to the dramatic declines in summer burn opportunities, the projected changes in climate would lead to increasing variance and decreasing reliability in late spring and early fall burn windows under the current criteria. This change would constitute an important potential impact to management because of the widespread use of prescribed fire in a region where current climatic conditions generally support near year-round burning. There is a strong consensus across climate models and emission scenarios that significant region-wide declines in burning opportunities would occur beginning around the middle of the century, driven primarily by rising temperatures during the summer and spring months. A notable caveat to these results

is that many (but not all) of the GCMs show early-onset declines in suitable burn days that are not borne out by the historical observations, particularly in the summer months. If the regional climates simulated by some ensemble members are biased towards conditions that are too warm and dry (or warming and drying too rapidly compared with reality), then the expected timeframe to experience significant reductions in suitable burn days would be delayed.

A reduction in opportunities for prescribed burning would have significant impacts on risks associated with wildfire in a region that can experience high temperatures and a rapid build-up of fuels (Stambaugh *et al.* 2009). Prescribed burning programs are an effective tool for lessening wildfire risk, with prescribed fires reducing both the number and impact of wildfires for up to 2 years post burn (Addington *et al.* 2015).

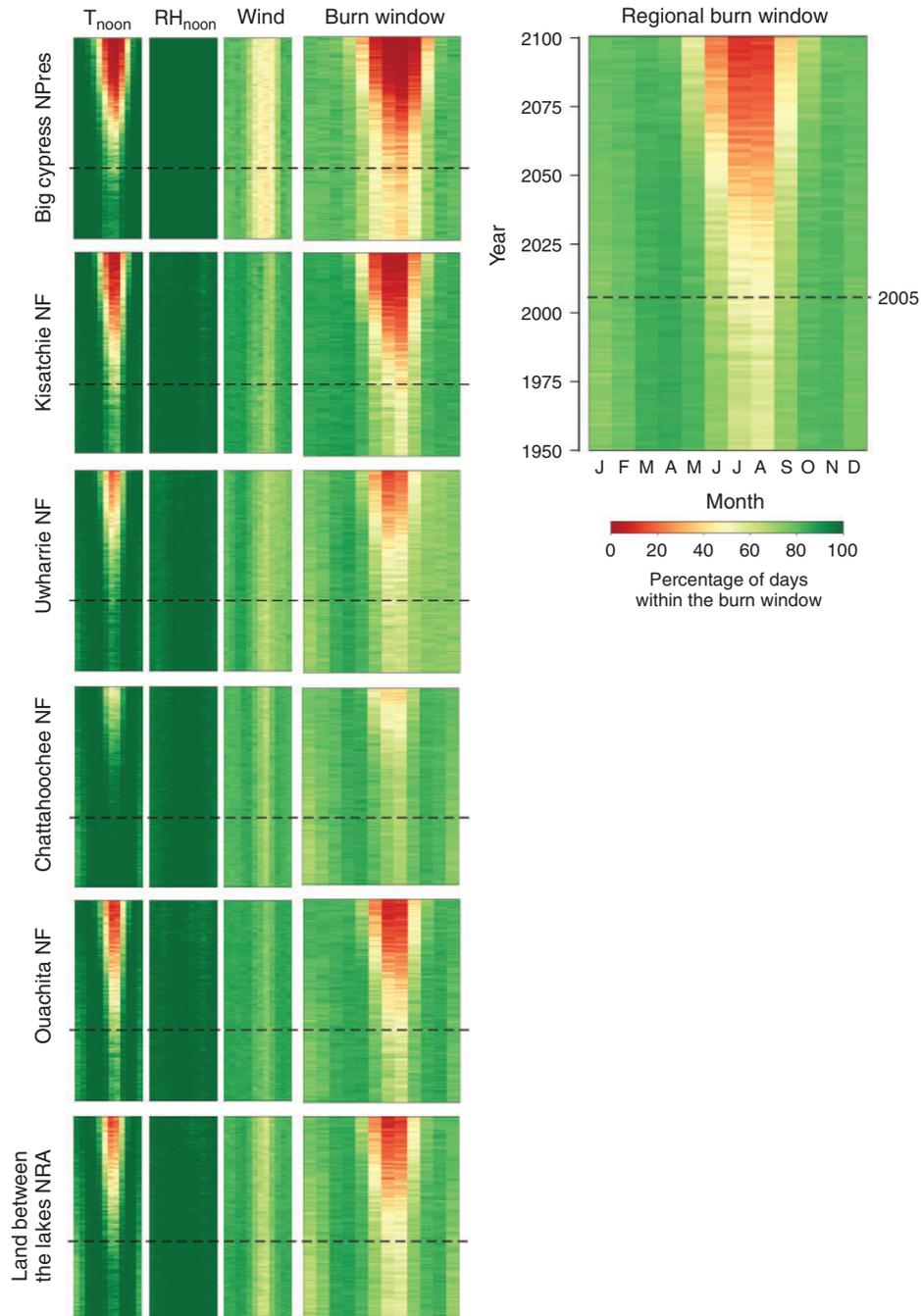


Fig. 6. Percentage of days per month meeting suitable burning conditions based on three weather variables individually and collectively at six management units across the study area. Values represent averages based on 18 Global Climate Models under RCP (Representative Concentration Pathway) 8.5. The regional burn window represents average values for all pixels contained within the study region.

However, the application of prescribed fire is sensitive to seasonal and interannual droughts, which can reduce their spatial extent (Nowell *et al.* 2018) and shorten the efficacy of risk reduction (Addington *et al.* 2015). Future changes in relative humidity were not projected to have a substantial effect on burn window availability and timing (Fig. 6, Fig. S2.1), but projections of future precipitation are more uncertain

(Easterling *et al.* 2017). Although not directly considered here, there is a non-trivial risk that climate change could result in more frequent or intense droughts, mainly through increased drying as evapotranspiration rates increase (Wehner *et al.* 2017). In particular, most of the western and southern portions of the study region are projected to experience drier conditions in spring and summer. Virtually any increase in wildfire activities

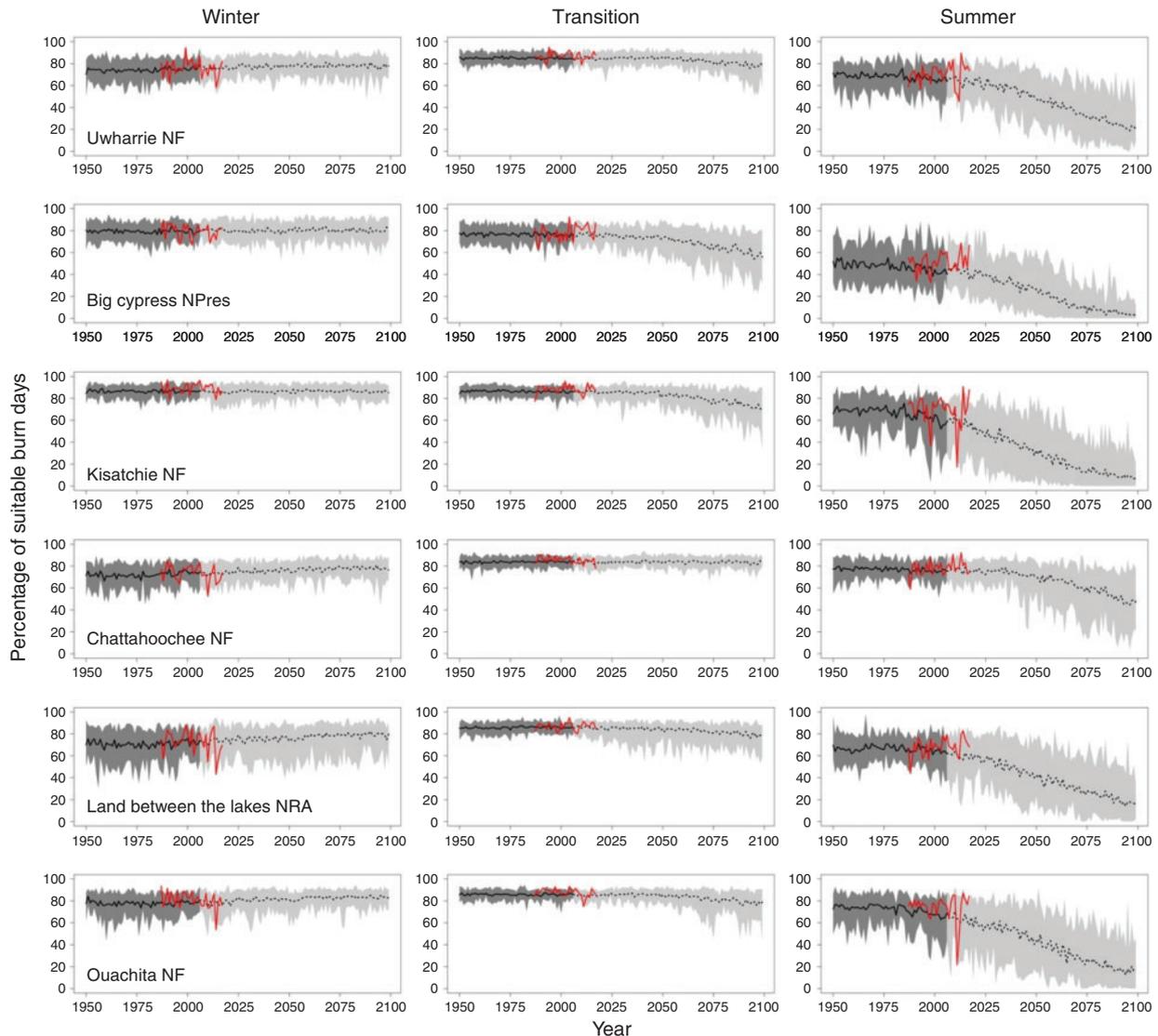


Fig. 7. Time series of percentage days considered suitable for prescribed burning at six management units for three burning seasons: winter (January, February), transitional (March, April, May), and summer (June, July) burn seasons. The red line indicates observed conditions over the period 1987–2017 based on surface meteorological data from the gridMET dataset. Dark and light grey shading represent the range of results from 18 Global Climate Models (GCMs) under a high greenhouse gas emissions scenario (RCP (Representative Concentration Pathway) 8.5). The solid (historical) and dashed (future) black lines are the multimodel mean value from all 18 GCMs. Differences in shading distinguish bounds for the CMIP5 historical simulation period (1950–2005: darker) from the future simulation period (2006–99: lighter).

(throughout the US) would further divert management resources during the summer months and shoulder seasons, which are already projected to lose burn windows in this study. In addition to the increased risk that accompanies lost opportunities for fuel reduction through prescribed burning activities, such a scenario would increase wildfire risk by promoting meteorological conditions favourable for the ignition and spread of the largest wildfires (Liu *et al.* 2014; Prestemon *et al.* 2016; Terando *et al.* 2017), resulting in more forests being exposed to higher-severity wildfire events associated with extreme fire weather (Prichard *et al.* 2017; Krofcheck *et al.* 2019).

Beyond increased wildfire risks due to drier conditions and declining fuel moisture, rising warm-season temperatures will

likely add to the complexity of maintaining air quality standards during prescribed fires. Smoke management remains a primary impediment to the implementation of prescribed fire in the region (Hu *et al.* 2008), and ozone production in summer months already restricts prescribed fire activities adjacent to metropolitan areas (Liu *et al.* 2009). The high sun angle and elevated temperatures experienced during much of the spring through fall seasons in the South-east facilitate ozone formation from volatile organic compounds found in smoke, particularly in the region's pine forests (Akagi *et al.* 2013). CMIP5 projections of warm-season relative humidity changes by the end of the century show only modest decreases for the region (average decreases of 1.8 and 3.7% for RCP4.5 and RCP8.5 respectively),

suggesting that the projected warming would still occur within a very humid environment. The attendant stagnant air masses may further restrict prescribed burning through concerns over emissions and non-attainment of Clean Air Act regulations (Odman *et al.* 2009).

A reduction in the availability and reliability of warm-season burning opportunities would have significant consequences for many native ecosystems in the South-east given the critical role that fire plays in the conservation, management and restoration of biodiversity and ecological resilience in these systems (e.g. Kirkman and Jack 2017). Decisions about how and when to apply prescribed fire in the US have often addressed replicating the pattern of fires ignited by lightning or preindustrial humans under the assumption that it will best promote native species in fire-prone regions (in the sense of the historical fire regime concept; Freeman *et al.* 2017). Prescribed fire activities in the South-east for much of the 20th century have been concentrated in the winter months, largely owing to ease of fire control, but land managers have also used warm-season months to expand burning opportunities and meet ecological objectives that are not possible through the use of winter and early spring burns. The projected loss of burn days in late spring and summer would further curtail efforts to use summer season burns (which were common under many historic fire regimes; Platt *et al.* 2015) to promote certain components of biodiversity and forest resilience (Platt *et al.* 1988; Bishop and Haas 2005). Moreover, projected increases in the variance of days falling within the burn window during spring, which accounts for a large percentage of burned area in the region (Nowell *et al.* 2018), would represent a significant challenge to fire managers' ability to reliably achieve ecological objectives.

Subregional variation in climate change effects

Our analyses indicated consistent region-wide changes in the frequency of suitable burn days over the remainder of the 21st century, but there was substantial subregional spatial variation in the projected responses for both summer and winter burn seasons. During the summer, decreases exceeding 50% of the days currently falling within the burn window were widespread under RCP 8.5 and common under RCP 4.5. Summer declines were greatest in the southern and south-western portions of the region, where the length of the burning season was often already limited (Fig. 4). The south-western portion of the study area was also projected to experience modest decreases in suitable burning conditions during winter that, when coupled with the virtual elimination of a summer burning season, would represent a significant challenge to the use of prescribed fires as a management tool.

Individual landscapes, represented here by the six management units that were examined in greater detail, showed nuanced effects on prescribed burn windows over time and between scenarios. The Coastal Plain sites (Big Cypress NPres and Kisatchie NF) were projected to lose nearly all summer burn days by 2099 under the RCP 8.5 scenario (Figs 6 and 7). Summer reductions were slightly less drastic in more inland areas of the North Carolina Piedmont (Uwharrie NF), US Interior Highlands (Ouachita NF) and US Interior Plateau (Land Between the Lakes NRA); these are, however, locations where it is already less common to use summer prescribed fires to manage hardwood

forests, potentially mitigating some losses of opportunity. Chattahoochee NF, which is located at the southernmost extent of the Blue Ridge Mountains, is buffered by its elevation and showed the smallest decline in number of summer days within burn prescription.

Potential adaptation strategies

Attempts to maintain seasonal burn activities by widening prescription windows to include hotter temperatures ($T_{\text{noon}} > 32.5^{\circ}\text{C}$) are likely to result in both altered ecological fire effects and adverse impacts to personnel. With rising temperatures in the ranges projected, vapour pressure deficits would be expected to rapidly increase, affecting plant productivity, phenology and survival (e.g. Hatfield and Prueger 2015). This rise in vapour pressure deficit with increasing temperature would occur despite model predictions of little change in relative humidity under either scenario. It is unclear how the increases in relative plant stress, particularly in summer months, will alter post-fire effects in a region where vegetation is adaptive to frequent fire, particularly given that increased mortality with drought stress is well documented in the region and other frequently burned ecosystems (McDowell and Allen 2015; O'Brien *et al.* 2018).

More practically, relaxing the temperature criteria is likely to dramatically increase the risk of heat stress for fire crews in the region as the increased warm season temperatures are projected to still co-occur with high levels of relative humidity (Carter *et al.* 2018). Domitrovich and Sharkey (2010), for example, suggest that the risk of heat-related illness for wildland firefighters increases at temperatures exceeding $\sim 32.5^{\circ}\text{C}$ when relative humidity is above 30%. Thus, even if fire managers were willing to accept the potential ecological consequences of relaxing the maximum temperature threshold, concerns over risks to personnel might prevent (or at least limit) such a decision.

Seasonal and diurnal adjustments to the timing of prescribed fires may allow managers to continue to meet their objectives while avoiding some of the risk associated with expanded temperature windows. In five out of the six management units, $\sim 75\%$ of days during the transitional burn season (spring months) are projected to remain within the prescription criteria regardless of the emissions scenario. In the fall months (September, October, November), losses of suitable burn days are projected to be larger, particularly under the RCP 8.5 scenario. Nevertheless, at least 50% of days are projected to remain within prescription at five sites for the RCP 8.5 scenario (Fig. 6), while all sites remain above 50% suitable days for the RCP 4.5 scenario (Fig. S2.1). Shifting burn windows to the fall may allow managers to compensate for the loss of summer burn days for risk management objectives. In contrast, the winter and spring transitional burn seasons are both already heavily used to accomplish the majority of burning in some areas of the region. It therefore seems unlikely that significant additional utilisation of those burn seasons would occur unless weekend burning becomes more common.

Many managers use diurnal patterns of fuel moisture to accomplish burn objectives, but night-time burning has been heavily regulated over the past several decades owing to air quality concerns. Earlier daytime starts to conduct fires within

prescription may also be present in our analysis of current burn windows. The fact that noontime temperatures and relative humidity (rather than daily extremes) appear to more accurately characterise periods of prescribed burning suggests that managers already take advantage of small windows of opportunity with favourable conditions. More aggressive exploitation of morning ignition times, non-traditional burning days (e.g. weekends and holidays), or technological assistance (e.g. unmanned aerial vehicles) may be needed to allow managers to maintain prescription windows and accomplish societal objectives in a warmer future.

Summary and conclusions

To assess the impact of climate change on prescribed fires, we leveraged a decade of fire permit records from two south-eastern states to identify prescribed burn windows for commonly recommended environmental variables. Using a high-resolution, statistically downscaled climate model dataset, we projected, mapped and analysed potential changes in prescribed fire opportunities across the south-eastern US, a region that conducts more than 3 million ha of prescribed fire annually. Our results point towards a future for prescribed fire opportunities in which managers and decision-makers will likely have to confront difficult trade-offs and greater constraints on their burn programs. There was a consensus across GCMs and scenarios that continuing current practices would result in sharp declines in burn opportunities over time, with the greatest projected reductions in prescribed fire opportunities concentrated in the summer months regardless of the emission scenario. The consequences of missed burn opportunities may even be larger than those expected based on our model projections because a sharp reduction in suitable warm-season (i.e. spring through fall) days implies that the length of time before the next burn opportunity arises could also increase. Adapting to these changes would likely require managers to consider a range of actions and strategies to maintain current levels of prescribed fire. Adaptation strategies such as changing the timing of burns (either seasonally, weekly, or daily) or relaxing burn window criteria (Chiodi *et al.* 2019) could result in maintaining opportunities, but not without their own set of trade-offs and risks with respect to public health, personnel safety, biodiversity impacts, ecological restoration and air quality objectives. Given the spatial and seasonal variation in projected changes to prescribed fire opportunities, successful adaptation strategies will likely be characterised by reliance on local innovations. Without such changes, the projected climatic changes would likely result in significant reductions in prescribed fire activities in this region that is critically dependent on managed fire regimes for ecosystem resilience.

Conflicts of interest

The authors declare no conflicts of interest.

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