Evaluating an attempt to restore summer fire in the Northern Great Plains

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# Abstract

There is growing interest in diversifying human-managed fire regimes. In many North American grasslands, late growing season burns re-introduce fire to periods most prone to lightning-driven fire prior to wildfire suppression policies. We report here on restoring summer fire in central North Dakota, USA, from a research project in which summer burns were only completed in two out of four years for which summer burns were planned. We use remotely-sensed imagery and local weather data to assess whether fuel or weather conditions limited burning in the summer, and to compare fire environmental conditions and subsequent burn severity across prescribed burns conducted in the spring and summer. Finally, we review historical data to determine if conditions have changed in either the spring or summer burn seasons over 42 years. Although burn severity generally declined with fuelbed greenness in the spring, summer burns could effect as high of severity as spring burns despite having greener fuelbeds. What little phenological change seems to have occurred at the study location over 42 years—slightly greener fuelbeds and slightly lower relative humidity in spring—likely offset each other to some degree. Overall, we found little evidence that being able to complete summer burns was anomalous, and conclude that it is reasonable for managers to incorporate late growing season fire into prescribed fire programs with the caveat that some summers will simply be too wet and/or too green to burn.

**Keywords:** Burn severity; Phenology; Seasonality of fire; Pyrodiversity

**Statements and Declarations** The authors declare no competing interests.

# Introduction

Fire is essential to the maintenance of grasslands and other open ecosystems, and has been described as a key component of restoring pre-colonial ecological conditions (Fuhlendorf et al. 2017; Bond 2021). The nature of fire in a given ecosystem is described as a regime. While determining the vegetation layer(s) that carry fire and the typical frequency and intensity of burning are relatively straightforward, seasonality and ignition source are much more difficult to reconstruct (McGranahan and Wonkka 2021). As such, the appropriate season(s) in which to burn is among the most debated aspects of fire restoration projects.

Burning in different seasons can produce different effects. While combustion in the wildland fire environment is theoretically possible whenever a competent ignition source is introduced to a sufficient amount of dry vegetation, climate often determines whether these conditions occur simultaneously. Lightning is the primary source of natural ignitions responsible for most fire starts prior to the emergence of hominids several hundred thousand years ago (Pyne 1994). As humans evolved and their technological capacity increased, so too did the influence of their ignitions. In regions with extant cultural fire use, the seasonality of fire is often dictated by localized and traditional land-use goals (McGranahan et al. 2022). In most Western countries, however, cultural burning has been replaced by systematic, command-and-control fire management in which most unplanned ignitions are suppressed and intentional burning occurs under strict prescriptions (e.g., Steen-Adams et al. 2017).

Restoring summer fire is of particular interest among managers in the North American Great Plains, where the influence of Indigenous ignitions was extensive and interacted with climate (Boyd 2002; Roos et al. 2018). Prescribed fire in the Great Plains has conventionally occurred while vegetation is dormant, although Engle and Bidwell (2001) argued prairie was resilient to fire in any season and challenged managers to consider summer burns. Although subsequent research has shown benefits of summer fire for diversity and productivity (Ansley and Castellano 2007; Decker and Harmon-Threatt 2019), a survey of grassland managers found that summer remains the least frequent season for prescribed fire (Harmon-Threatt and Chin 2016). Meanwhile, wide variability in responses to seasonal fire have been reported within and across plant functional groups, often driven by disproportionately large responses by few species (Steuter 1987; Biondini et al. 1989; Sparks et al. 1998; Mndela et al. 2023). Considerable variability in responses to summer fire has been attributed to the fact that higher humidity and fuel moisture during the growing season often reduce fire intensity and effect lower severity (Steuter 1987; Tangney et al. 2022).

The Northern Great Plains might have had one of the most pronounced differentials in fire seasonality between lightning-caused and anthropogenic ignitions. Fire was frequent in the region for at least 400 years prior to European colonization (Umbanhowar 1996). Contemporary accounts of fires set by Native Americans and early Europeans beginning in 1673 identified a bimodal pattern of human-set fires in the spring and fall (Higgins 1986). But for the last 80 years, at least, lightning-caused fires occurred predominately in late July and August (Higgins 1984; McGranahan and Wonkka 2024).

In this paper we report on mixed results in conducting summer prescribed fire in the Northern Great Plains. As researchers attempted to restore spatially-patchy prescribed fire to grazed mixed-grass prairie, two patterns of fire were introduced: one in which an entire one-quarter patch was burned each spring, and another in which half of the patch—one-eighth of the pasture—was burned in the spring, followed by the second half-patch scheduled for a late summer burn, in an attempt to provide a late-season flush of high-quality forage (e.g., Allred et al. 2011; Nichols et al. 2021) and determine whether a greater number of patches would increase spatial heterogeneity (e.g., McGranahan et al. 2018). While all spring burns were completed as planned, summer fires were only completed in two out of four years. Here we present seasonal and long-term remotely-sensed burn severity and fuel data alongside weather information in considering whether being able to conduct summer burns was exceptional or more likely to be the norm based on historical patterns.

# Methods

## Study location

The prescribed fire restoration project was established at the North Dakota State University Central Grasslands Research Extension Center, near Streeter, in south-central North Dakota, USA (99°25′W, 42°42′N). Vegetation at the Center is typical northern mixed-grass prairie with substantial abundance of the non-native C3 grasses *Poa pratensis* and *Bromus inermis*. In 2017, a research project began in which 12, 65-ha pastures were assigned to one of each of three management strategies (N = 4), none of which involved internal fences: continuous grazing, in which livestock had unhindered access to pastures with no additional disturbance; spring-only patch burning, in which a 16-ha patch was burned each spring and livestock allowed unhindered access; and spring-summer patch burning, in which half of a 16-ha patch was burned in the spring, and the second half scheduled to be burned in the summer. All pastures were stocked with approximately 22 Angus *Bos taurus* cow-calf pairs from May-October; see Duquette et al. (2022) for a complete description of the study location and experimental design.

Forty prescribed fires were conducted over four years, 2017–2020. All 32 planned spring burns were completed, between 25 April and 25 May. Only eight of 16 planned summer burns were completed: 4 in 2017, and 4 in 2020, between 13-25 August. Burn units were surrounded with plowed mineral firebreaks and ignitions varied between backing and head fires, and interior strip ignitions, with handheld drip torches.

## Data

Two types of data are presented here: remotely-sensed imagery from earth observation satellites, and weather data logged by the Center’s mesonet weather station. We used remotely-sensed data from two separate sources. For the study period alone, 2017–2020, we used the European Space Agency’s Sentinel-2 mission, multispectral imagery at 10 10 m resolution in the visible and near-infrared region and 20 20 m in the red-edge and shortwave infrared regions. Data are collected and produced at 5-10 day intervals. For historical context, 1990–2022, we used Landsat resources from the US Geological Survey (Landsat 5, 7, and 8 Level 2, Collection 2, Tier 1 Surface Reflectance), which provide multispectral imagery at 30 30 m resolution at 7-14 day intervals; Sentinel-2 only began in 2016, while the first Landsat 5 mission launched in the mid 1980s.

Remotely-sensed data consisted of two indices: the Normalized Burn Ratio (NBR; Key and Benson (2006)), which is used to estimate burn severity, and Normalized Difference Vegetation Index (NDVI; Rouse Jr et al. (1974)), used to estimate greenness of vegetation. Sentinel-2 imagery was retrieved from the online Copernicus Browser using a custom EvalScript to return values for each index as a separate band in a geo-referenced raster file; each scene was inspected to ensure cloud-free imagery over pasture locations beginning with the first snow-free scene through to the final snow-free scene each year. To calculate burn severity, we subtracted the first post-fire image from the most-recent pre-fire image for each burn unit, generating a burn severity index known as differenced Normalized Burn Ratio (dNBR; Key and Benson (2006)). Estimates of fuel greenness were made with the NDVI from the same most-recent pre-burn image.

Landsat imagery was processed with Google Earth Engine (Gorelick et al. 2017) using a custom script to merge missions over time, mask clouds, and calculate NDVI for the burn seasons defined above, 1990–2022. See Supplemental Information for scripts used for both Copernicus and Google Earth Engine.

Remotely-sensed values were extracted from raster images at sample points using the *terra* package for the **R** statistical environment (Hijmans et al. 2022; R Core Team 2024). Data from the patch-burned pastures were retrieved from gridded points assigned with 30 m spacing never less than 10 m from the edges of burn units, with ponds and ephemeral water bodies within burn units excluded. Data from unburned control pastures were retrieved from points used in forage quality assessments by Wanchuk et al. (2024).

Weather data—which included air temperature, relative humidity, dew point, windspeed, and vapor pressure deficit—were retrieved from the North Dakota Agricultural Weather Network’s Streeter station (NDAWN 2023). To characterize day-of fire weather for burn days, we calculated mean values for operational burn periods (1000–1700 hrs) from hourly data for days recorded as having at least one completed fire. To characterize seasonal fire weather, we used daily precipitation totals to eliminate days with more than 25 mm precipitation—days no fire would be conducted under any other circumstance—and calculated mean values for the operational period for each spring (25 April–25 May) and summer (7–27 August) burn season. Seasonal values were determined for both the study period (spring and summer burn seasons, 2017–2020) and the historical range (1 April–31 October, 1990–2023). Historical trends in both Landsat NDVI and fire weather are available in Supplemental Information.

To examine potential changes in conditions over time, all data related to the fire environment—NDVI, cumulative rainfall, and average hourly fire weather data for the operational period—were summarized for each burn season in the first and final decades of the dataset, 1990–1999 and 2012–2022, respectively.

## Statistical analysis

Difference in NDVI between spring and summer for the four study years was tested via analysis of deviance ( test), in which with a linear mixed-effect model was compared against an intercept-only, null model, each fit with the lmer function in the *lme4* package for **R** (Bates et al. 2015). Linear relationships between dNBR and NDVI were first tested for a difference between spring and summer trends using analysis of deviance ( test), then within each season ( test), using generalized mixed-effect regression models fit with a Gamma distribution using glmer from *lme4*. Pasture (block) and year were fit as random effects.

To compare mean values for each year of the study period to historical ranges, we calculated scores as a measure of deviation from the mean (Schober et al. 2021) by subtracting the historical mean from the seasonal value, and dividing by the historical standard deviation. *Anomalies* were defined as values more than one standard deviation above or below the historical mean; *statistical significance* at = 0.05 occurs when .

Potential temporal changes in fuel greenness and fire weather variables from early in the historical dataset (1990–1999) and recent values (2012-2022) were tested as differences in means using ordinary least squares regression ( test) at = 0.05.

# Results

Grassland fuelbeds were less green during each of the spring fire seasons (Sentinel-2 NDVI 0.3-0.4) than in the summer (NDVI > 0.5; = 134, 0.001), with the two seasons in which summer burns could not be completed being the most green (NDVI > 0.6; Fig. 1A). Burn severity ranged widely within and across seasons and years (Fig. 1B); despite having categorically higher greenness (Fig. 1A), summer burning effected the same range of variability in burn severity as in the spring. The relationship between dNBR and NDVI varied between seasons ( = 8.4, 0.01). Among summer burns, there was no linear relationship between dNBR and NDVI ( = -0.97, 0.05). Among spring burns, there was a general decline in burn severity with increasing fuelbed greenness ( = -4.7, 0.001).

Fuelbed greenness, as measured by Landsat NDVI, during the four spring burn seasons was within or slightly above typical values for the 42-year historical period (Fig. 2A; Table 1). Summer seasons with completed burns were very near the historical mean NDVI (Table 1), while summer seasons without completed burns had the highest NDVI anomalies (2018, = 0.76; 2019, = 1.52). In terms of cumulative rainfall, all four spring seasons were at or below historical values (Fig. 2B; Table 1). Years in which summer burns were not completed had the highest anomalies in cumulative precipitation (2018, = 1.6; 2019, = 0.8). Conversely, cumulative precipitation in years in which summer burns were completed was at least 1 standard deviation below the historical mean (2017, = -1.04; 2020, = -1.3).

Day-of-burn fire weather varied widely within and across the four study years, and generally spanned the entire range of historical values (Fig. 3). However, wind speeds on the day of prescribed burns never exceeded the historical median in either season, and only one burn day exceeded the historical median relative humidity (Fig. 3). Seasonal averages in fire weather for each of the four study years also ranged widely relative to historical means. In summer, especially, there were no patterns in the magnitude and signs of fire weather anomalies that distinguished years in which summer burns were completed, and those in which they were not (Table 2).

Few substantial changes in the fire environment appear to have occurred since the 1990s in either spring or summer burn seasons (Fig. 4, Table 3). The only statistically-significant change was an increase in spring fuelbed greenness ( = 3.8, < 0.001). In two instances—spring windspeed and summer rainfall—the more apparent temporal trend was for greater variability around the typical range, rather than substantial shifts in typical values.

# Discussion

We used remotely-sensed imagery and weather data to assess whether, in the four years summer burns were planned in a research project in the Northern Great Plains, the fuel and weather conditions of the two years in which burns were completed, or conditions of the two years in which burns were not completed, were more likely to represent normal conditions based on historical patterns. Comparing seasonal values to historical ranges suggested that not being able to complete summer burns were the anomalies. As such, completing prescribed fire in the late growing season in the Northern Great Plains is a reasonable management objective. However, prairie fuelbeds might simply be too green to carry fire in some years, likely those with above-normal rainfall over the course of the growing season.

At a seasonal level, these data provide little indication that fire weather posed a barrier to conducting summer fire, and instead pointed to fuelbed greenness. This pattern complements regional wildfire trends, which show an increase in wildfire frequency with lower summer precipitation and higher temperatures and drought indices (Clabo 2018). Overall, burn season fire weather in our data was highly variable across study years, and burn day weather spanned the gamut (the exception was wind speed, which was below average in all study years). Take, for example, relative humidity: for the four years summer burns were planned, two years were above average ( scores 0.9 and 0.5), and two years were below average ( scores -0.6 and -0.9), but each set included a year in which summer burns were completed and a year in which burns were not completed. In a study of these and similar grasslands that included a subset of the spring fires reported here, higher wind speed and greater vapor pressure deficit contributed to higher rates of spread, a measure of fire intensity (McGranahan et al. 2023). But overall, the statistical analysis provided little explanation for the substantial variability in fire behavior.

However, experience does suggest fire weather conditions can limit specific prescribed fire operations. For example, a burn was planned around a favorable weather forecast on 13 August 2018, and a full crew was on-site that morning. But relative humidity did not fall as predicted in the spot weather forecast, remaining above 50% until 1500 hrs (the burn was called off by 1400 hrs after repeated test fires failed to spread). Certainly, actual weather defies forecasts in all seasons. But in the context of summer prescribed fire, when fuels are more green and windspeed potentially lower (Fig. 4), stubborn relative humidity is more of a barrier in the absence of mitigating factors.

Consistent with a wide body of research on land surface phenology, the single statistically-significant change in the fire environment over the 42 year period at our study location was increased spring fuelbed greenness (Table 3). Earlier spring green-up over recent decades has been documented worldwide in northern temperate ecosystems generally (Xu et al. 2018; Ren et al. 2024), and in temperate US rangelands, specifically (Zimmer et al. 2022). While earlier spring green-up in grasslands has been broadly attributed to increased spring precipitation and higher temperatures (Post et al. 2022), managers in the Northern Great Plains must also deal with non-native cool-season grasses that are particularly responsive to earlier onset of the growing season (Gasch et al. 2020). Conversely, observed trends toward lower spring dewpoint and relative humidity (Fig. 4), although not statistically-significantly different at this single weather station, suggests drier air could potentially mitigate spring fuelbed greenness.

While these historical comparisons suggest the spring burn season is perhaps most susceptible to global changes, complex interactions between drivers of global change introduce substantial uncertainty. In addition to continental-scale increases in air temperature and variability in precipitation (Kukal and Irmak 2016; Pendergrass et al. 2017), fire managers in the Northern Great Plains must also deal with local changes. For example, native grasslands in the region—including the rangeland considered here—have been invaded with exotic, cool-season grasses that green up early, change fuel structure, and reduce rate of spread (Yurkonis et al. 2019). Even if trends towards lower relative humidity might mitigate greener fuelbeds in the spring, cumulative seasonal rainfall, fuelbed greenness, and relative humidity likely all increase together in the summer, when plants are photosynthetically active, creating potential barriers to summer burns. Conversely, the non-native cool-season grasses of the Northern Great Plains, especially *Poa pratensis*, are widely known to be susceptible to summer drought (Etter 1951; Meyer and Funk 1989; Liu et al. 2008); dormancy due to water stress reduces fine fuel moisture and potentially facilitates fire spread. Given these bimodalities, we suggest that the greater the presence of non-native cool-season grasses in fuelbeds of the Northern Great Plains, the more extreme managers might expect the potential magnitude of fuel and fire responses to year-to-year variability in precipitation.

Furthermore, regional atmospheric modification might also modulate the effectiveness of prescribed fire even if local conditions are amenable for burning. Put simply, fire intensity generally increases with atmospheric instability, which facilitates rapid convection of smoke away from the reaction zone and draws in fresh oxygen for combustion (Potter 2012). Instability, meanwhile, is modulated by soil moisture and land use: arid areas tend to have lower soil moisture and greater convective potential, but greater atmospheric moisture can increase stability (Chapman and Carleton 2021; Hiestand et al. 2024). Evidence from the US Corn Belt suggests transpiration from highly-productive crop fields contributes to atmospheric moisture content (Hill et al. 2019), and the western spread of the Corn Belt into the Great Plains is well-established (Wright and Wimberly 2013). But the potential interactions and impacts of regional climate and land-use changes on fire management have not been sufficiently explored.

Research into opportunities to conduct prescribed fire might apply the “land surface phenology” approach to the fire environment (Hanes et al. 2014; Zimmer et al. 2022), rather than conventional attempts to assess changes in the availability of “weather windows”—the set of conditions under which prescribed fire might possibly be conducted (e.g., Weir 2011). While some research has used the concept of the weather window to identify seasonal shifts in potentially favorable burn conditions—e.g., Yurkonis et al. (2019) showed a decrease in early spring burn days and an increase in late summer burn days for central North Dakota—the focus on prescriptions generally masks interactions between mitigating and exacerbating factors, fails to account for fuelbed dynamics, and is agnostic to antecedent weather and fuel conditioning. We suggest instead an approach that uses the type of data presented here to classify the seasonality of fuels and fire weather to investigate temporal changes in the phenology of the fire environment as a whole.

Table 1: Seasonal deviations from historical averages in Normalized Differenced Vegetation Index (NDVI) and year-to-date precipitation for spring and summer burn seasons, as presented in Fig. 2. Anomalies determined by scores (parentheses) and categorized as above, below, or within 1 standard deviation of the historical mean. 2018 and 2019 were the years in which no summer burns were conducted; all spring burns were conducted in all years.

| Variable | Year | Spring | Summer |
| --- | --- | --- | --- |
| NDVI | 2017 | Above (1.02) | Within (-0.04) |
|  | 2018 | Within (-0.2) | Within (0.76) |
|  | 2019 | Within (-0.69) | Above (1.52) |
|  | 2020 | Above (1.1) | Within (0.02) |
| Precipitation | 2017 | Within (-0.86) | Below (-1.04) |
|  | 2018 | Below (-1.04) | Above (1.6) |
|  | 2019 | Within (-0.36) | Within (0.8) |
|  | 2020 | Within (0.05) | Below (-1.3) |

Table 2: Seasonal deviations from historical averages in four fire weather variables for spring and summer burn seasons, as presented in Fig. 3. Anomalies determined by scores (parentheses) and categorized as above, below, or within 1 standard deviation of the historical mean. 2018 and 2019 were the years in which no summer burns were conducted; all spring burns were conducted in all years

| Variable | Year | Spring | Summer |
| --- | --- | --- | --- |
| Dew Point | 2017 | Within (-0.97) | Below (-1.19) |
|  | 2018 | Within (0.34) | Within (-0.16) |
|  | 2019 | Within (-0.74) | Within (-0.09) |
|  | 2020 | Within (0.86) | Above (1.23) |
| Relative Humidity | 2017 | Within (-0.7) | Within (-0.61) |
|  | 2018 | Within (-0.9) | Within (-0.93) |
|  | 2019 | Within (-0.19) | Within (0.91) |
|  | 2020 | Within (0.99) | Within (0.48) |
| Vapor Pressure Deficit | 2017 | Within (0.45) | Within (-0.17) |
|  | 2018 | Above (1.45) | Within (0.98) |
|  | 2019 | Within (-0.67) | Below (-1.22) |
|  | 2020 | Within (-0.98) | Within (-0.13) |
| Wind speed | 2017 | Within (-0.6) | Below (-1.38) |
|  | 2018 | Within (-0.85) | Below (-1.72) |
|  | 2019 | Below (-1.36) | Below (-1.02) |
|  | 2020 | Below (-1.09) | Within (-0.51) |

Table 3: Results of statistical models comparing, within each season, early period (1990-1999) to late period (2012-2022) values for fuelbed greenness and five fire weather variables in the historical dataset (Fig. 4).

| variable | Spring | Summer |
| --- | --- | --- |
| Fuelbed Greenness (NDVI) | t = 3.8, P < 0.001 | t = 1.9, P > 0.05 |
| Cumulative rainfall | t = -0.053, P > 0.05 | t = 0.42, P > 0.05 |
| Dew Point | t = -1.3, P > 0.05 | t = -0.51, P > 0.05 |
| Relative Humidity | t = -1.5, P > 0.05 | t = -0.57, P > 0.05 |
| Vapor Pressure Deficit | t = 0.75, P > 0.05 | t = 0.32, P > 0.05 |
| Wind speed | t = -0.96, P > 0.05 | t = -2, P > 0.05 |

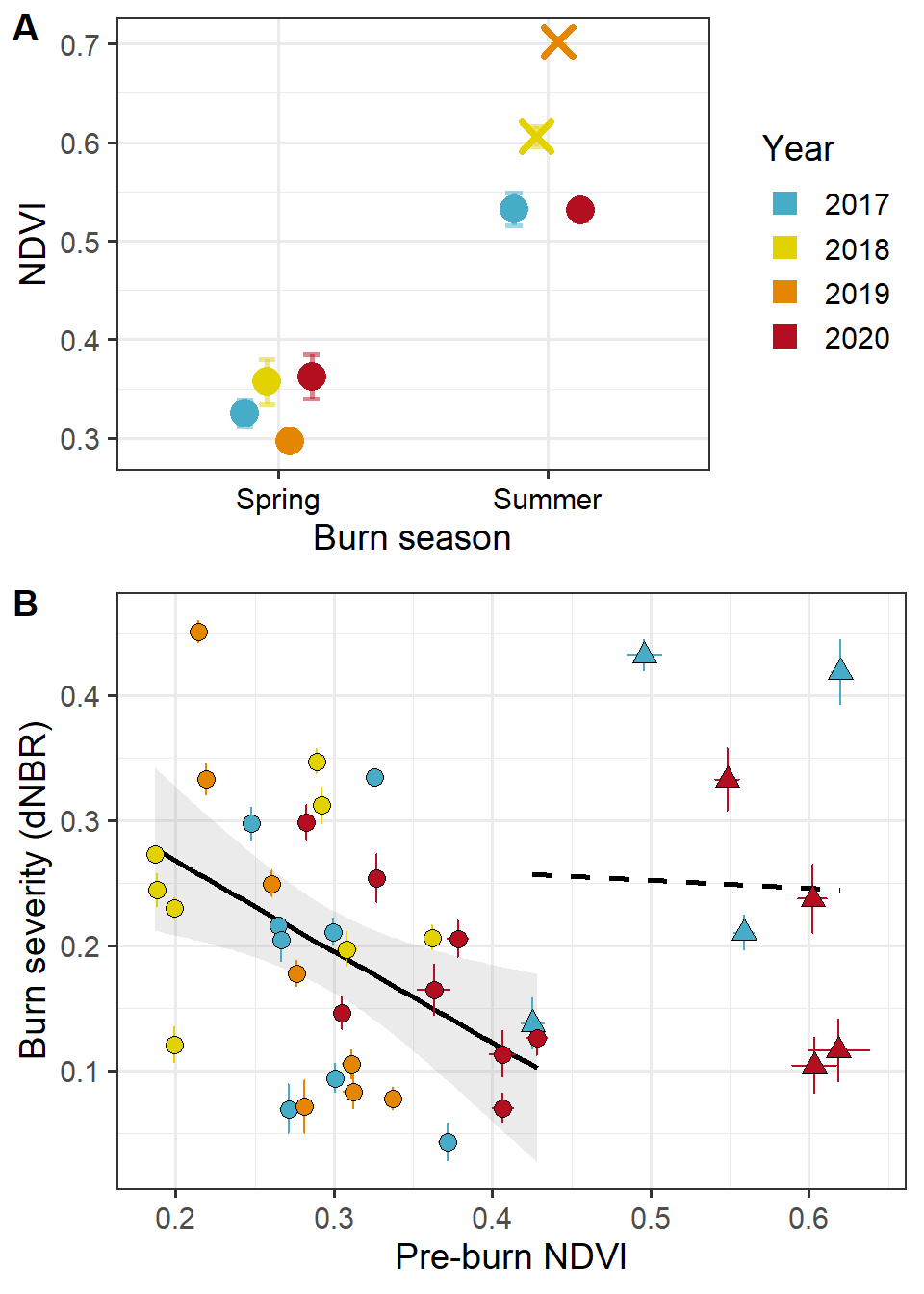


Fig. 1: Sentinel imagery summarized for the study years. A: Normalized Difference Vegetation Index (NDVI), gathered from four adjacent unburned pastures to avoid confounding effects of prescribed burns, was greater in summer burn seasons than spring burn seasons ( = 134, 0.001). X denotes seasons in which burns were not completed. B: Burn severity (differenced Normalized Burn Ratio, dNBR) plotted against fuelbed greenness (NDVI) retrieved from the pre-burn Sentinel-2 image used for pre-fire NBR. Points represent mean for individual prescribed fires with associated standard error: circles indicate spring burns while triangles denote summer burns. The statistical relationship between dNBR and NDVI differs between seasons in generalized mixed-effect models ( = 8.4, < 0.01). dNBR declined as NDVI increased in spring burns ( = -4.7, < 0.001; solid trendline, plotted as ordinary least-squares regression with 95% confidence interval, = 0.22); summer burns have no significant relationship (broken trendline).

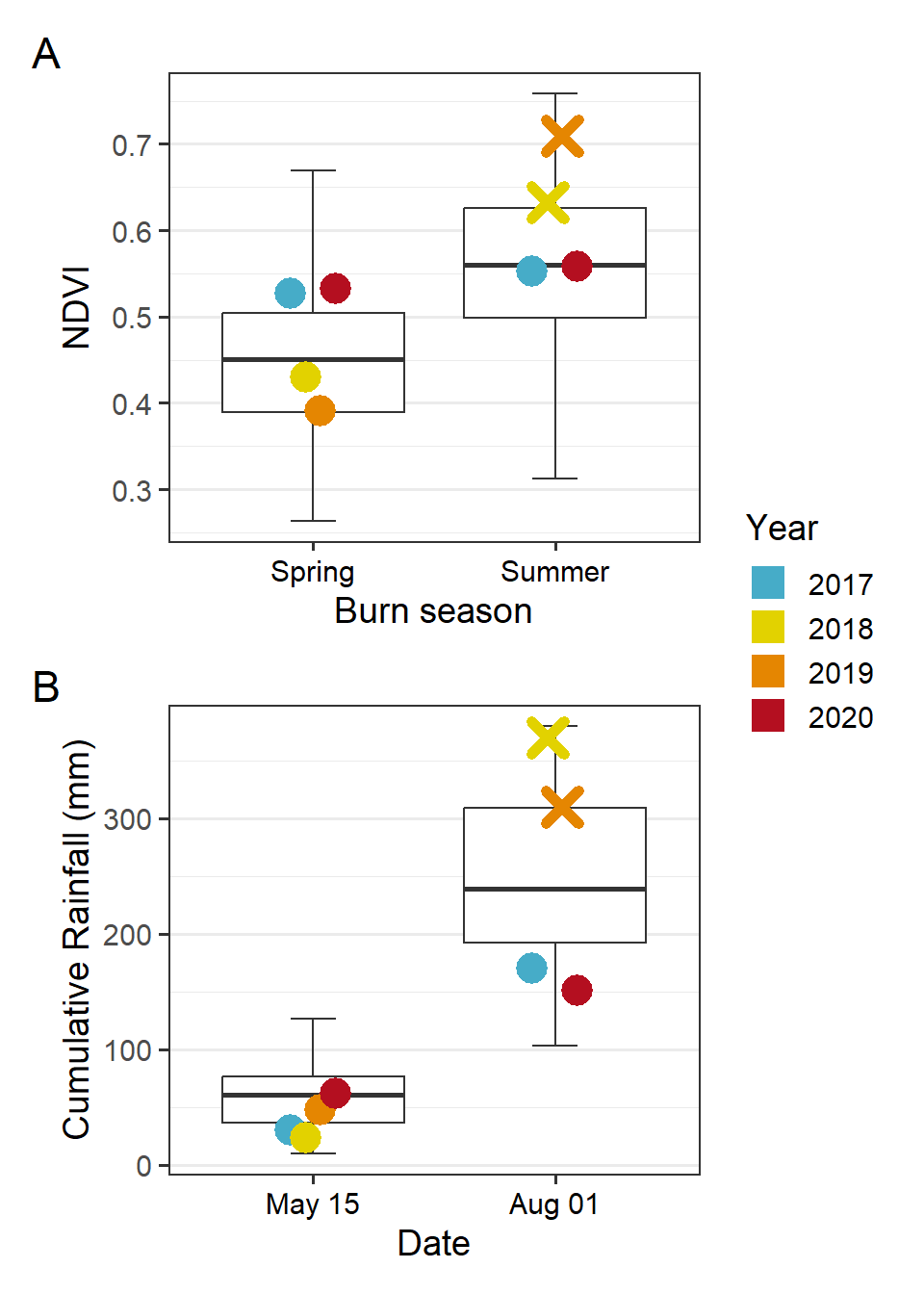


Fig. 2: Study season data (points) plotted within the context of 42-year historical trends (boxplots). X indicates seasons prescribed fires were not completed. A: Normalized Difference Vegetation Index (NDVI) data retrieved from Landsat imagery. B: Annual growing season rainfall accummulated by two specific dates associated with the spring and summer burn seasons, respectively.

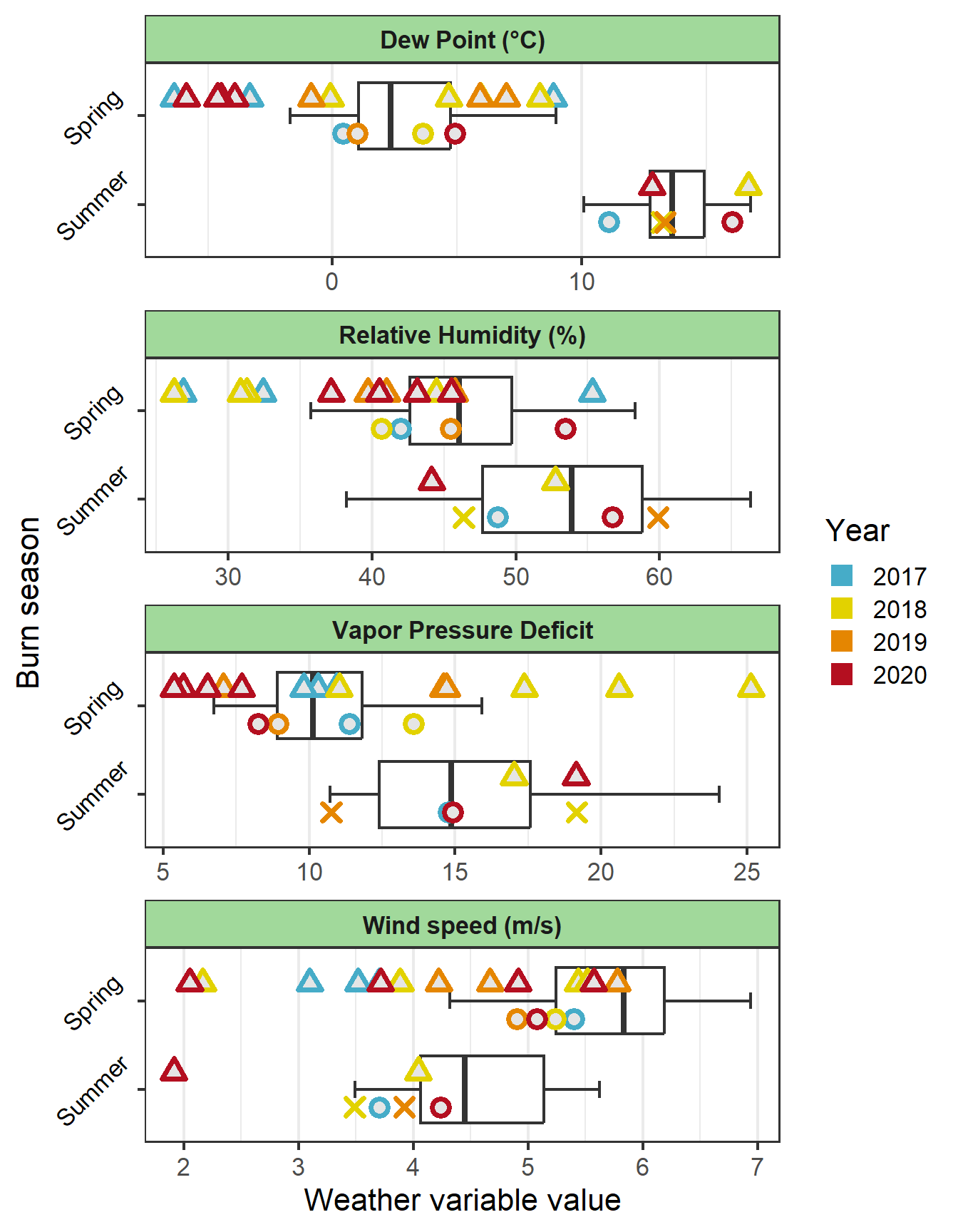


Fig. 3: Four fire weather variables plotted by burn day values (open triangles), study season means (open circles and X for seasons without completed burns), and 42-year historical trends (boxplots).

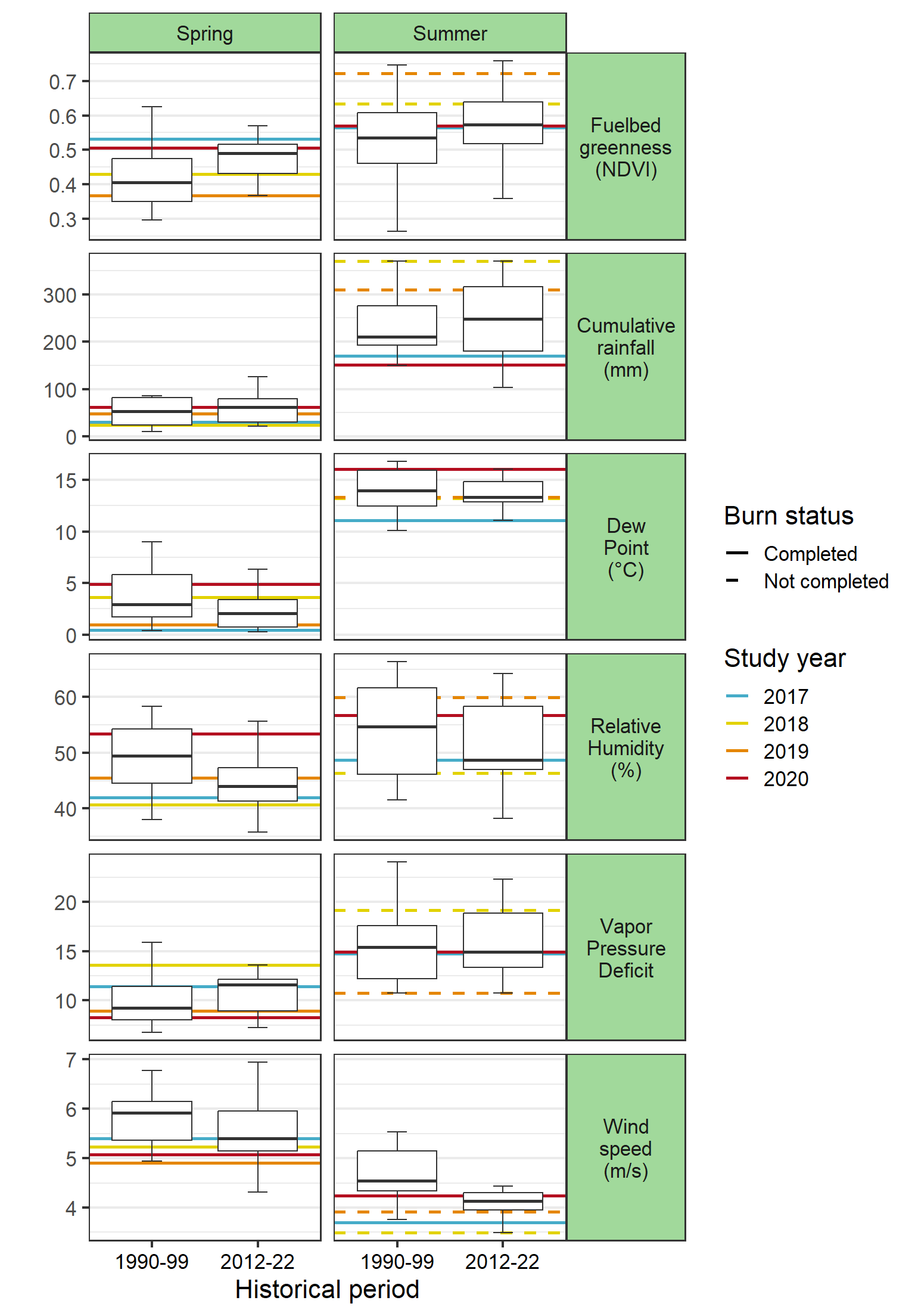


Fig. 4: Temporal comparison of phenological changes in the fire environment over 42 years. Boxplots represent data from the first decade of the dataset used here (1990-1999) to the final decade (2012-2022), by burn season. Horizontal lines represent average conditions for the four study years (2017-2020). Table 3 reports statistical tests of early vs. late periods for each season by each variable; Supplemental Information Table 1 reports z scores for each study year against historical values.

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