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Key Points:

- Soil temperatures provided earlier estimates of growing season onset than air temperature
- 5 cm soil temperature using a 5°C threshold agreed best with normalized difference vegetation index estimates of growing season onset
- Soil temperatures can improve start of season estimates over air temperature

Supporting Information:

Supporting Information may be found in the online version of this article.

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Evaluation of Air and Soil Temperatures for Determining the Onset of Growing Season

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Abstract While air temperature has commonly been used to define the onset of the growing season (plant uptake of soil nutrients), there is evidence in the literature suggesting vegetation growth is sensitive to soil temperature. As soil temperature observations become increasingly available from monitoring networks, differences in the start of season (SOS) estimates based on both above and below-ground temperatures should be explored. In this study, air, surface, and soil (at depths of 5, 10, and 20 cm) temperature from the U.S. Climate Reference Network were used to estimate SOS at 104 stations across the U.S.. Temperature thresholds of 0, 5, or 10°C were used to estimate the SOS as the earliest date of the year when temperatures remained above each threshold. SOS dates based on temperature were compared with MODIS-satellite-derived normalized difference vegetation index (NDVI). Results indicated that the day-of-year of SOS based on soil temperature occurred about two months earlier than SOS estimates from air and surface temperatures. Overall, 5 cm soil temperature SOS estimates using a 5°C threshold matched well with SOS_{NDVI}; albeit, only slightly better than air temperature SOS estimates using the 0°C threshold. This was in part because air temperature conditions were more likely to dip back below a given threshold with the passage cold fronts than soil temperatures. This often resulted in later air temperature SOS estimates particularly in years with sub-freezing late season cold fronts. This suggests soil temperature can improve SOS estimates for many locations across the U.S.

Plain Language Summary The start of the growing season is an important moment when vegetation cover begins to interact with and influence atmospheric conditions. Estimates on the timing of growing season start dates has traditionally been done using air temperature observations. However, recent studies have indicated that soil temperature conditions can also be an important indicator of plant growth and development. In this study, air, surface, and soil temperature data were used to estimate the start of the growing season. Overall, soil temperatures were found the earliest start dates followed by air (~6 weeks later) and surface (8 weeks later) temperature estimates. Comparisons with satellite measures of vegetation development revealed that the earlier soil temperature growing season start dates were similar to satellite based estimates for more stations than air temperature start of season dates. However, these results varied regionally with air temperature start of season dates better aligned with satellite estimates in southern portions of the U.S. and soil temperature estimates having lower measures of error in the mid to northern regions of the U.S. These results suggest that soil temperature conditions can provide improved estimates of growing season start dates for many locations across the U.S.

1. Introduction

The time of year when vegetation begins their uptake of moisture and nutrients from the soil and exchanges carbon with oxygen in the atmosphere is an important phenological period for plants known as the start of the growing season, or start of season (SOS). The SOS date is when vegetation cover begins to interact with and influence the surrounding environment. The interannual variation of the SOS has been found to contribute to the variability in several environmental dynamics, including stream flow, drought, forest fire, agriculture (Betancourt et al., 2005), and can impact complex weather patterns through land-atmosphere interactions (changes in surface roughness, albedo, and partitioning of surface energy; Ault et al., 2011; Lin et al., 2014). As a result, phenological development has often been used as an indicator of climate change (Ault et al., 2015; CaraDonna et al., 2014; Lindner et al., 1997; Menzel & Fabian, 1999; Schwartz et al., 2006) and as a measure of climatic impacts on flora and fauna (Walther, 2010), which is sensitive to species, biotic, and ecosystem interactions. Allstadt et al. (2015) noted that earlier greenup due to warming springtime conditions can increase the likelihood and severity of damaging frosts during late season cold waves in a false spring event. However, results of climate and climate impact studies based on SOS are sensitive to how the initial sign of nutrient uptake is characterized (Schwartz & Hanes, 2010; Walther & Linderholm, 2006).

The three methods generally used to estimate the start of the growing season include: (a) in-field observation of plant phenological stages (Schwartz et al., 2012; Van Vliet et al., 2003), (b) satellite-derived indices of plant phenological development (Cai et al., 2017; Schwartz, 2003), and (c) temperature-based indices that use predetermined thresholds to describe when environmental conditions are ideal for vegetation growth (Schwartz et al., 2012). These temperature indices can be based on either an accumulation of degrees above a threshold, such as growing degrees, or as an indication of the initial day temperature conditions remained above a threshold. In this study, the latter approach will be used to estimate the SOS date. Since in-field phenological observation records are sparse and discontinuous (Schwartz et al., 2006), the climate community has traditionally estimated SOS using the more widely available temperature indices. The advantages of using these metrics to estimate SOS is that these measures provide long term and spatially complete data that are also well modeled in regional and climate simulations to estimate future changes in phenological activity related to climate change. In addition, temperature metrics have been used to provide guidance to agricultural communities on planting dates (Abendroth et al., 2017; Bollero et al., 1996). However, these metrics are not directly linked to vegetation development, and the uncertainty and accuracy of these SOS estimates deserves further attention.

Many studies on climate and plant phenology have indicated that air temperature is an important climate variable for determining plant growth and development (Chmielewski and Rotzer 2002; Myneni et al., 1997; Sherry et al., 2007; Suni et al., 2003a, 2003b; White et al., 1999). While growing season has traditionally been defined as the period between the last and first day of frost (0°C; Robeson, 2002), Walther and Linderholm (2006) reported several additional metrics that aggregate (i.e., average) air temperature conditions over multiple days with differing thresholds to define the growing season (start and end). Suni, Berninger, Vesala, et al. (2003) and Lin et al. (2014) both found that 5-day averaged air temperature conditions were relatively good estimators of start of season in their studies; however, their choice of threshold (i.e., 0°C or 5°C) to estimate SOS varied based on location/vegetation cover.

Soil temperature data have also been proposed as indicators of start of season (Baldocchi et al., 2005; DeLucia et al., 1991; Jarvis & Linder, 2000; Schwarz et al., 1997). Studies on plant physiology have shown that belowground temperature plays an important role in determining aboveground phenology, especially in herbaceous plants. Schwarz et al. (1997) showed that both daily minimum air and soil temperatures displayed a linear relationship with net photosynthesis. Minimum soil temperature accounted for about 90% of the change in net photosynthesis. Other studies also showed that low soil temperatures limit plant photosynthesis and stomatal conductance (Carter et al., 1988; DeLucia & Smith, 1987; Lopushinsky & Max, 1990) where critical reduction of plant photosynthesis processes occurred when soil temperatures fell below 10°C (Day et al., 1990, 1991; DeLucia, 1986; Lippu & Puttonen, 1991). Agricultural studies have shown that cooler soil temperatures, despite moist conditions, can inhibit seed germination (Schneider & Gupta, 1985; Shaw, 1977), influencing vegetation development and crop yields (Bollero et al., 1996). Similarly, soil temperatures have been linked to limited belowground plant (i.e., root) growth and development (Alvarez-Uria & Korner, 2007 DeLucia & Smith, 1987; Steinaker & Wilson, 2008;), which accounts for 50%–90% of all terrestrial plant growth (Bassirirad, 2000; Ruess et al., 2003).

Evaluations of temperature indices to estimate SOS have reported strong regional patterns (Walther & Linderholm, 2006). For example, Walther and Linderholm (2006) found that various climate metrics could produce differences in estimated SOS dates varying from less than six to more than 50 days at locations across the Baltic region. This reported regional variability in SOS dates seems to be linked to the selected threshold for SOS estimation. An earlier study by Suni, Berninger, Vesala, et al. (2003), identified region-specific thresholds for both 5- and 1-day averaged air temperature indices that best estimated SOS for that area and measure. The SOS thresholds for air temperature varied between 2.5°C and 5.0°C in their study for the 5- and 1-day mean air temperature measures, respectively. These results highlight the significance of selecting the appropriate threshold value when estimating SOS, which may be sensitive to variables such as

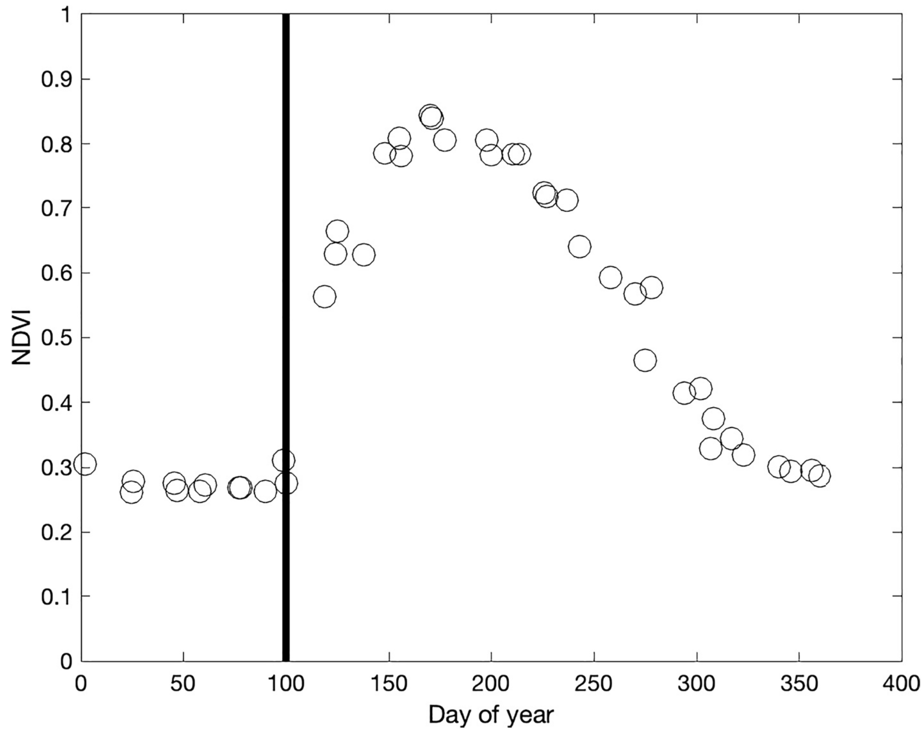

Figure 1. MODIS normalized difference vegetation index data (circles) for the pixel containing the Manhattan, Kansas U.S. Climate Reference Network station in 2010. The vertical line indicates our definition of onset of growing season.

type of vegetation cover, dominate soil characteristics, soil moisture, elevation, and latitude among others. While there are studies investigating the best thresholds to associate with air temperature to define the growing season (Linderholm, 2006; Suni et al., 2003a, 2003b), there are relatively few studies that have systematically evaluated thresholds for soil temperature based estimates of SOS over large spatial scales (Baldocchi et al., 2005) such as the continental U.S. or even comparisons of SOS estimates between air and soil temperatures by threshold. Sizable differences in air and soil temperature-based SOS are likely given the soil's higher measures of heat capacity and thermal conductivity (Hillel, 2005), which would dampen the soil's temperature response to incoming shortwave radiation as compared to air temperature. This is further complicated by transitory changes in atmospheric conditions (i.e., precipitation, cloud cover) brought on by extra tropical cyclones that are responsible for abrupt changes in temperature conditions (i.e., warm and cold fronts) during the spring season.

Due to the strong physiological relationship between belowground temperatures and aboveground phenology identified in the literature, soil temperature indices may provide useful estimates of plant growth. While Suni, Berninger, Vesala, et al. (2003) showed that using a threshold of 0°C with soil temperatures resulted in poor correlations with SOS, other soil temperature thresholds beyond 0°C were not considered. In this study, 0, 5 and 10°C thresholds will be used to estimate SOS dates from air, surface, and soil temperature observations from the U.S. Climate Reference Network (USCRN). The USCRN is an automated high-quality reference network with stations located across the U.S. (Bell et al., 2013; Diamond et al., 2013). Due to the lack of available plant phenology data at individual USCRN sites, MODIS normalized difference vegetation index (NDVI) data were used to evaluate temperature based estimates of SOS in this study. Given the differing definitions of SOS in the literature (de Beurs & Henebry, 2010; White et al., 2009; Cai et al., 2017), SOS dates were defined as the initial point where green-up begins (as indicated in Figure 1) (Pettorelli et al., 2005). Evaluations of SOS dates will not only provide information on which temperature measures (e.g., air, surface and soil) and threshold more closely align with NDVI-based SOS, but also how variable these measures are across the U.S. This is particularly important for studies exploring

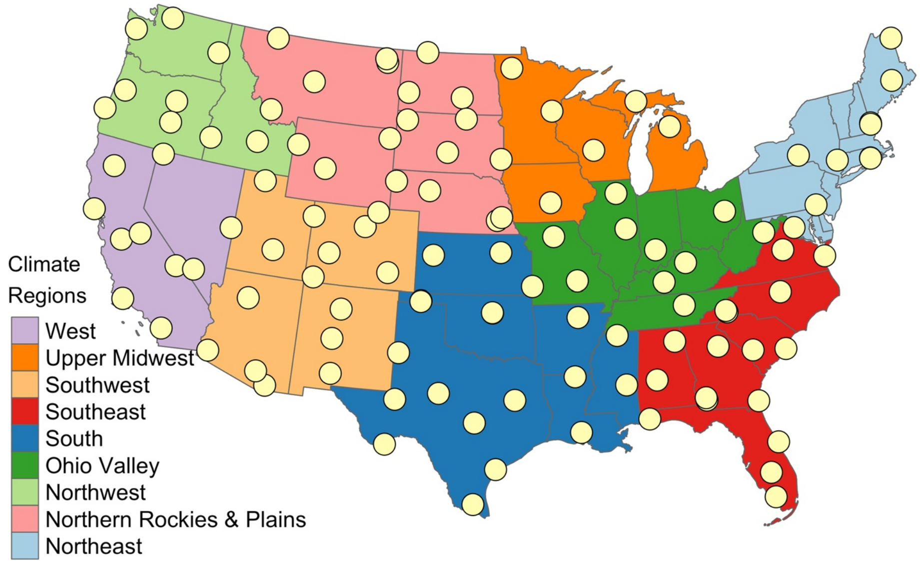

Figure 2. Location of U.S. Climate Reference Network stations by climate region.

The impacts of climate change on phenological outcomes or the determination of planting dates (Abendroth et al., 2017; Bollero et al., 1996), which focus on determing the earliest planting date to maximumize agricultural yields.

2. Materials and Methods

2.1. Data

2.1.1. USCRN

The USCRN currently comprises of 153 (114 Contiguous, 2 HI, and 39 AK) climate-monitoring stations operated by the National Oceanic and Atmospheric Administration (NOAA; Diamond et al., 2013). These stations were purposely located on stable public land, mostly grassland environments, that are generally free of trees, bodies of water or artificial heating surfaces to monitor climate. Deployment of the network began in 2001 with an initial instrumentation set focused on atmospheric variables (e.g., air temperature and precipitation). Air temperature observations are monitored 1.5 meters above the surface using three platinum resistance thermometers (Thermometrics Corporation PT1000) placed within separate fan-aspirated Met One (Model 076B) radiation shields. The five-minute observations from the redundant sensors that are within 0.3°C are then averaged to derive hourly temperature observations at each station used in this study. Hourly surface temperature measurements are observed using the Apogee infrared sensor (Model SI-11, Apogee Instruments, Inc.) pointed at the ground. Soil moisture and temperature sensors were added to the network over the Contiguous U.S. (Figure 2) beginning in 2009 using the Steven Hydra II probe. The USCRN monitors hourly soil conditions in triplicate at either five (5, 10, 20, 50, and 100 cm) or two (5 and 10 cm) depth configurations depending on the soil profile (Bell et al., 2013). Like air temperature, soil temperature observations from each probe that pass automated and manual quality control are combined to derive hourly layer averages of soil temperature. Hourly observations from the network from 2010 through 2018 were used to evaluate daily minimum conditions and estimate SOS in this study. More information on USCRN stations, instrumentation and data can be found at www.ncdc.noaa.gov/crn.

2.1.2. NDVI

NDVI is defined as (NIR − RED)/(NIR + RED) where NIR is the near infrared reflectance and RED is the red reflectance as observed by a radiometric sensor. The chlorophyll in plants absorbs wavelengths of red light, while plant leaves reflect wavelengths of near-infrared light. As such, NDVI has been shown to correlate well with multiple biophysical parameters of plant development (White et al., 1997). Although multiple satellite data products (i.e., albedo, EVI, fPAR, LAI, NDVI) at varying spatial and temporal resolutions have been shown capable to identify springtime phenology metrics, MODIS NDVI demonstrates the ability to capture the onset of growing season as we have defined in Figure 1 (Garrity et al., 2011). Collection 6 MODIS 16-day NDVI data at 250-meter spatial resolution, from both Aqua and Terra, were used to calculate the onset of growing season for each of the USCRN stations in this study. Note that using both Aqua and Terra NDVI products yields a composite remotely sensed NDVI value every 8 days, and in Collection 6 for these data, actual acquisition time is available. We used the actual acquisition time instead of the composite time, since this has been shown to reduce error in subsequent analysis (Kross et al., 2011). Furthermore, using the actual acquisition time provides a time series with varying temporal resolution that can be as fine as a 1-day timestep although the mean timestep for the years, stations, and quality control conditions under this study is roughly 8 days.

MODIS NDVI data were obtained for each station shown in Figure 2 from 2010 to 2018. Given the 114 USCRN stations and 9 years of data, there were at most 1,026 (114 × 9) possible station-year SOS dates to estimate from NDVI. Only data with reliability flags of good or marginal data were used (MODIS NDVI QC flag values of 0 or 1), which mostly excluded cloud and or snow/ice covered pixels. Estimation of SOS was only performed if there were more than 10 NDVI data values available for a given year at a station location. After applying the MODIS NDVI QC flags and controlling for years with less than 10 data points, SOS estimates were evaluated for 105 stations for a total of 833 station-years.

2.2. Estimation of SOS

The analysis of estimated SOS dates was performed in two steps. In the first step, SOS date differences between the various temperature measurements (e.g., air, surface and soil temperature) and threshold values (e.g., 0, 5, and 10°C) were used to evaluate how the choice of temperature measure and threshold impact the estimation of SOS dates, and to determine if there were any regional factors that might influence the accuracy of threshold-based SOS estimation. In the second step, estimated SOS dates USCRN using station temperatures were compared against NDVI-based SOS estimates to determine which combination of measure and threshold most closely aligned with NDVI-based vegetation greenup dates.

2.2.1. Estimated USCRN Temperature-Based SOS

The temperature threshold-based estimation of SOS was computed as the first day when temperature values exceeded and remained above a given threshold value throughout the growing season (Robeson, 2002). This method was used in this study to examine the USCRN daily minimum temperature data from June 30 to January 1 and identify the date just before temperature values decreased below the specified threshold of interest. When the annual minimum temperature were greater than the threshold, SOS dates were not calculated, but were instead set to missing values for the particular station, year, and threshold. In particular, temperature thresholds of 0, 5, and 10°C, respectively, were used to calculate SOS dates across USCRN stations. By assessing these thresholds against daily minimum observations of air, surface, and soil (at 5, 10, and 20 cm depths) from 2010 to 2018, we estimated 15 SOS dates per station per year. The deeper 50 and 100 cm depths available at USCRN stations were excluded from this study since southerly located stations consistently had annual minimum temperatures at these depths greater than the thresholds used in this study.

2.2.2. Estimated NDVI-Based SOS

Although numerous methods to identify SOS from satellite vegetation indices exist (White et al., 2009), a total of four different data-smoothing methods with different sensitivities to noise and data variability were employed and compared. Each method was performed using the pixel containing the USCRN station. The four different methods attempted were asymmetric Gaussian (Eklundh & Jonsson, 2003), Whittaker smoother (Eilers, 2003; Kandasamy et al., 2013), Savitzky-Golay (Cai et al., 2017), and the exponential method (Zhang et al., 2003), which is described below. Ultimately the exponential method was chosen due to its reliability and accuracy in pinpointing the location in the NDVI time series where the increase in the slope of the data indicated the start of growing season. For each year and location, all four methods were employed and the start of growing season based on the slope of each curve-fitting method determined accordingly. It was found that the methods which were more sensitive to noise in the data, such as Savitzky-Golay and Whittaker smoother, tended to under-estimate the start of growing season, whereas methods such as asymmetric Gaussian tended to overly smooth the data and consequently over-estimate the SOS.

The exponential function that was fitted to the NDVI data is defined as

$$NDVI_{\exp}\left(t\right) = \frac{\alpha_1}{1 + e^{\alpha_2 + \alpha_3\left(t + \alpha_4\right)}} + \alpha_5 \quad (1)$$

where α_1–α_5 are the fitted parameters. This model is similar to a logistic model originally described in Zhang et al. (2003), where α_5 may be interpreted as the background value and $\alpha_1 + \alpha_5$ as the maximum expected value of $NDVI_{exp}(t)$. Time series data up until the peak annual maximum NDVI value is used for model fitting. The parameters of Equation 1 were calibrated using the minimization routine *fit* in Matlab R2020a with an initial guess of {$\alpha_1 = 0.2$, $\alpha_2 = -0.4$, $\alpha_3 = -0.1$, $\alpha_4 = -100$, $\alpha_5 = 0.5$}. After calibrating $NDVI_{exp}(t)$ to data, the derivative with respect to time in days is calculated for $k = 1, ..., N$, where $N = 365$, by

$$\frac{\partial NDVI_{\exp}\left(t\right)_k}{\partial t_k} = \frac{\alpha_1 \alpha_2 e^{\alpha_2 + \alpha_3\left(t + \alpha_4\right)}}{\left(1 + e^{\alpha_2 + \alpha_3\left(t + \alpha_4\right)}\right)^2}. \quad (2)$$

We then evaluate a threshold value

$$\gamma = \frac{1}{N} \sum_{k=1}^{N} \frac{\partial NDVI_{\exp}\left(t\right)_k}{\partial t_k}. \quad (3)$$

The NDVI-based SOS estimate is defined as the first day of the year which is greater than the threshold γ. Additionally, nonlinear regression prediction confidence intervals for SOS were estimated with Matlab's function *nlpredci* which uses the fitted parameters, residuals, and Jacobian to calculate 95% confidence intervals.

For the remainder of the paper, we define SOS_{NDVI} as the SOS estimate based on MODIS NDVI data, and $SOS_{X,Y}$ as the SOS estimate based on temperature at the X level (where X is AT = air temperature, ST = surface temperature, 5 = 5 cm, 10 = 10 cm, and 20 = 20 cm soil temperature) with the Y threshold (where 0 = 0°C, 5 = 5°C, and 10 = 10°C). For example, $SOS_{AT,5}$ represents the SOS estimate using air temperatures and the 5°C threshold.

3. Results

3.1. SOS Dates Estimated at USCRN Stations From Temperature Data

The air temperature estimated SOS dates across the USCRN network were 103 (±34), 130 (±33), and 153 (±26) days since January 1st (referred to as julian days from here on) for the 0, 5, and 10°C thresholds, respectively. In general, SOS dates estimated based on surface temperature data were slightly later than air temperature SOS dates. For the same thresholds, SOS estimates based on surface temperature data were 8.92, 8.37, and 4.53 Julian days later than air temperature SOS estimates (Table 1). While the switch from air to surface temperature resulted in subtle (about a week) differences in SOS date, estimated SOS dates based on soil temperature data occurred 1–2 months earlier than air temperature SOS estimates (Figure S1). The soil temperature SOS differences with air temperature were generally larger for the lower threshold (0°C) and deeper soil depths. For instance, the SOS dates based on soil temperature data at the 5-cm level were 57.10, 46.92, and 39.53 days earlier than air temperature SOS dates for the same 0, 5, and 10°C thresholds, respectively. The differences were slightly larger when the 10-cm (60.54, 53.55, and 47.86 days) and 20-cm (60.83, 60.44, and 54.11 days) temperature data was used to estimate SOS dates. Inter-annually, these offsets from air temperature-based SOS dates were consistent over time (Figure S1). In general, soil temperature estimated SOS dates were earliest followed by air and then surface temperature based SOS estimates. Similar results in the timing of SOS dates were also found regionally across the U.S. climate divisions (Table 1), albeit with varying averages in SOS date differences from air temperature. Some of the largest offsets between air and soil temperature based SOS dates were in the western and southern regions (West, North- and Southwest, South, and Southeast) of the U.S. with slightly smaller averages in SOS differences in the Upper Midwest, Northeast, and Northern Rockies and Plains (Table 1). The range in regional differences indicate

Table 1
Regionally Averaged Start of Season Differences by Surface, 5 cm, 10 cm, and 20 cm Soil Temperatures Compared to Air Temperature (Air Minus Soil) for the 0, 5, and 10°C Thresholds

Measure	National	West	South	Southeast	Southwest	Upper midwest	Northwest	Ohio valley	Northeast	Northern rockies & plains
Surface (0°C)	−8.92	−15.87	−3.13	−6.22	−9.96	−11.10	−19.51	−11.82	−11.49	−5.03
Surface (5°C)	−8.37	−20.64	−3.14	−8.26	−9.94	−7.10	−7.46	−10.47	−9.75	−5.32
Surface (10°C)	−4.53	−6.22	−2.82	−5.15	−6.38	−2.69	−1.46	−11.11	−2.14	−2.63
5 cm (0°C)	57.10	63.00	69.12	60.07	67.84	39.88	75.46	60.33	47.76	47.30
5 cm (5°C)	46.92	45.10	58.98	53.79	42.11	33.64	73.87	44.49	39.97	32.74
5 cm (10°C)	39.53	46.61	49.51	53.31	31.74	29.51	44.44	34.86	40.32	24.30
10 cm (0°C)	60.54	84.50	75.20	54.71	77.12	37.00	88.11	60.92	48.75	51.18
10 cm (5C)	53.55	52.33	66.46	60.30	55.54	36.94	84.09	49.21	42.59	38.28
10 cm (10°C)	47.86	67.54	57.22	59.40	46.40	32.81	54.80	40.21	44.56	29.82
20 cm (0°C)	60.83	NA	87.64	7.67	84.88	41.75	116.29	54.53	40.65	52.70
20 cm (5°C)	60.44	70.80	72.23	67.95	66.76	39.44	97.46	54.66	46.12	42.88
20 cm (10°C)	54.11	91.95	61.84	66.65	54.35	33.28	62.40	45.89	46.90	34.44

that the national average may not reasonably capture regional differences in SOS estimates between air, surface, and subsurface temperatures.

Detailed analysis of estimated SOS dates showed that the station latitude and elevation had some impact on the timing of temperature-based estimates of SOS dates (Figure 3). Stations located further north or at higher elevation tended to have later SOS dates compared to southerly located stations at lower elevations. However, SOS dates based on soil temperatures were found to be less sensitive to station elevation. Interestingly, the later start of season estimates for the higher latitude stations were also those that had some of the smallest regional difference between soil and air temperature SOS estimates, which is discernible in Figure 3a. This may help to explain some of the regional differences in SOS estimates from Table 1 where air and soil temperature SOS estimates were more similar in the Upper Midwest, Northeast, and Northern Rockies and Plains regions than in other regions.

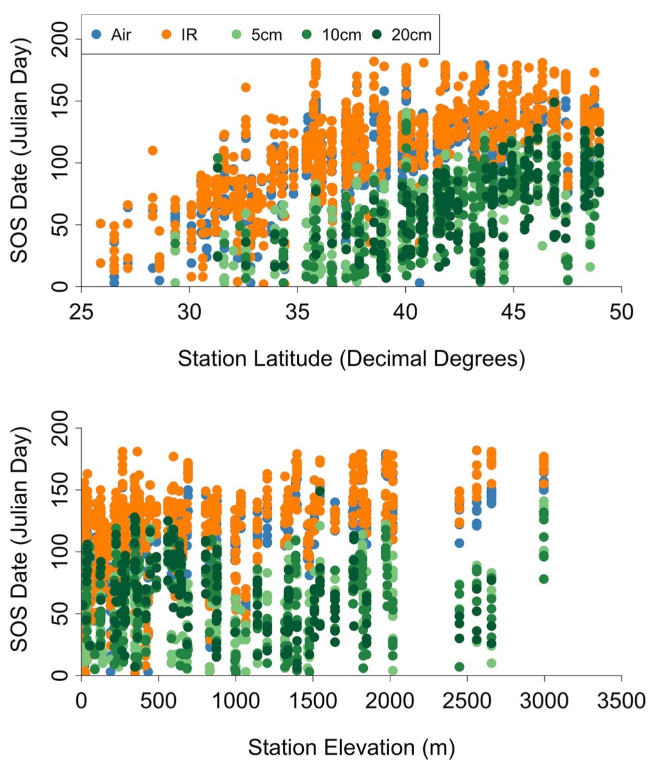

Figure 3. Start of season dates by station (a) latitude and (b) elevation for air (blue), surface IR (orange), 5-cm (light green), 10-cm (green), and 20-cm (dark green) temperatures at the 0°C threshold.

3.2. SOS Dates Estimated at USCRN Stations From MODIS NDVI Data

NDVI values and variability differed widely amongst the USCRN stations (not shown here). The MODIS NDVI data for many of the stations agreed with values estimated by Equation 1. However, some of the fits of Equation 1 did not match the NDVI data well for a particular station or year. We found that these instances of poor fitting often times had (at least) one of the following characteristics in the data time series:

1. There was little change in the magnitude of NDVI values throughout the year.
2. There was no early (i.e., winter) data available.
3. The maximum annual NDVI value was less than 0.3.

Data time series with the characteristics listed above were found to not match well with the assumed functional shape defined by Equation 1 and shown in Figure 1. However, these characteristics did not always cause poor fits to Equation 1, as there were stations that had some of these three features that were well characterized by fitting Equation 1. Given this,

Table 2
Temperature Measure and Threshold for Start of Season (SOS) Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Difference (Normalized Difference Vegetation Index (NDVI) Estimate–U.S. Climate Reference Network Estimate), Median Difference and Number of Comparisons With Respect to SOS_{NDVI}

Measure (threshold)	RMSE	MAE	Mean diff	Median diff	N
Air (0°C)	42.62	31.17	−10.37	−13	716
Air (5°C)	56.12	47.20	−38.21	−41	732
Air (10°C)	69.93	62.48	−58.91	−61	735
Surface (0°C)	46.14	35.61	−17.80	−20	724
Surface (5°C)	59.48	50.85	−44.27	−46	733
Surface (10°C)	73.11	65.71	−62.79	−64	735
5 cm (0°C)	55.73	43.95	39.87	36	443
5 cm (5°C)	42.01	29.75	6.51	2	680
5 cm (10°C)	45.27	35.96	−21.11	−23	725
10 cm (0°C)	56.19	45.44	42.17	39	354
10 cm (5°C)	42.78	29.52	11.92	7	639
10 cm (10°C)	42.68	33.23	−13.60	−19	714
20 cm (0°C)	54.03	45.33	42.48	40	203
20 cm (5°C)	41.51	28.93	18.25	13	512
20 cm (10°C)	40.82	30.66	−7.33	−12	591

we did not remove any cases based on these data characteristics and all 833 station years were included in the comparisons to USCRN temperature-based SOS estimates.

3.3. Comparison of USCRN Temperature-Based and NDVI-Based SOS Dates

The differences between SOS_{NDVI} dates and those estimated based on air or surface temperatures were found to be smallest for the 0°C threshold with root mean squared error (RMSE) ranging between 42.62 to 69.93 and 46.14–73.11 days for air and surface temperature, respectively (Table 2). Based on soil temperature, the choice of threshold that yielded the agreement with SOS_{NDVI} varied with soil depth. At the 5 cm level, SOS dates based on the 5°C threshold matched best (RMSE range of 42.01–55.73 days); however, the 10°C threshold was more similar to SOS_{NDVI} at the 10 and 20 cm depths. The sign of the mean and median differences in SOS dates revealed that above ground temperatures measures tended to detect SOS dates later than NDVI estimates (negative sign) while soil temperature estimates were generally earlier (positive sign). Overall, according to mean differences, $SOS_{5,5}$ best matched SOS_{NDVI} followed by $SOS_{20,10}$ and $SOS_{AT,0}$ (Figure 4); however, there was farily large variability in SOS_{NDVI} differences among the station years.

The regional analysis of estimated SOS dates also indicated that $SOS_{5,5}$ agreed better with SOS_{NDVI} than $SOS_{AT,0}$ for most northern regions including stations the Northeast, Ohio Valley, and the Upper Midwest (Figure 5). Conversely, $SOS_{AT,0}$ were found to be more similar to SOS_{NDVI} over the South and Southeast. However, both temperature-based estimates were earlier than SOS_{NDVI} in the Southeast, albeit slightly less so for soil temperatures, and later than SOS_{NDVI} in the Northern Rockies and Plains and Northwest regions. Over the Southwest and West regions, that are characterized by drier conditions and a mixture of low and high station elevations, the results were mixed as SOS_{NDVI} had a broad range in SOS dates. These regional results indicate that 5 cm soil temperature conditions can improve temperature-based estimates of SOS for most of the U.S.; however, differences with respect to SOS_{NDVI} remain.

To explore this further, 735 station years over the 104 stations where both values (NDVI and temperature estimate) were available for comparison were identified. Table 3 summarizes how frequently a particular measure, regardless of threshold, provided a temperature-based SOS date closest to SOS_{NDVI} when that measure produced an SOS estimate. For example, the first row indicates that there were 735 cases where both air temperature- and NDVI-based SOS estimates were available. Of those, 200 had air temperature-based SOS dates that were closest to SOS_{NDVI} than all other measures (e.g., Surface, 5 cm, 10 cm, 20 cm), indicating that 27.2% (200/735 = 27.2%) of the time air temperature-based SOS dates were available, it was considered the best choice. There were occasions when measures tied for "best measure" of choice. In these cases, the tied measures were all included, allowing the number of "best choice" to reach a total of 1,132 (the sum of elements in the second column of Table 3) and exceed the total number of station years compared (735). As depth increases, the total possible cases decrease due in part to not crossing required temperature thresholds or lack of observations. That said, Table 3 shows that SOS estimates based on 5 cm soil temperatures were more frequently closest to SOS_{NDVI} dates in both raw and normalized terms. From the temperature metrics considered, the 5 cm soil temperature estimates of SOS was closest to the SOS_{NDVI} 41.4% of the time when it was available followed by 20 cm (35.2%), 10 cm (35.2%), air (27.2%) and surface (23.5%) temperature.

4. Discussions

The SOS dates for a given temperature threshold displayed a stark difference between above- or below-ground temperature observations. For instance, soil temperature SOS estimates were found to be up to two months earlier than those based on air temperature conditions. In addition, the earlier soil temperature

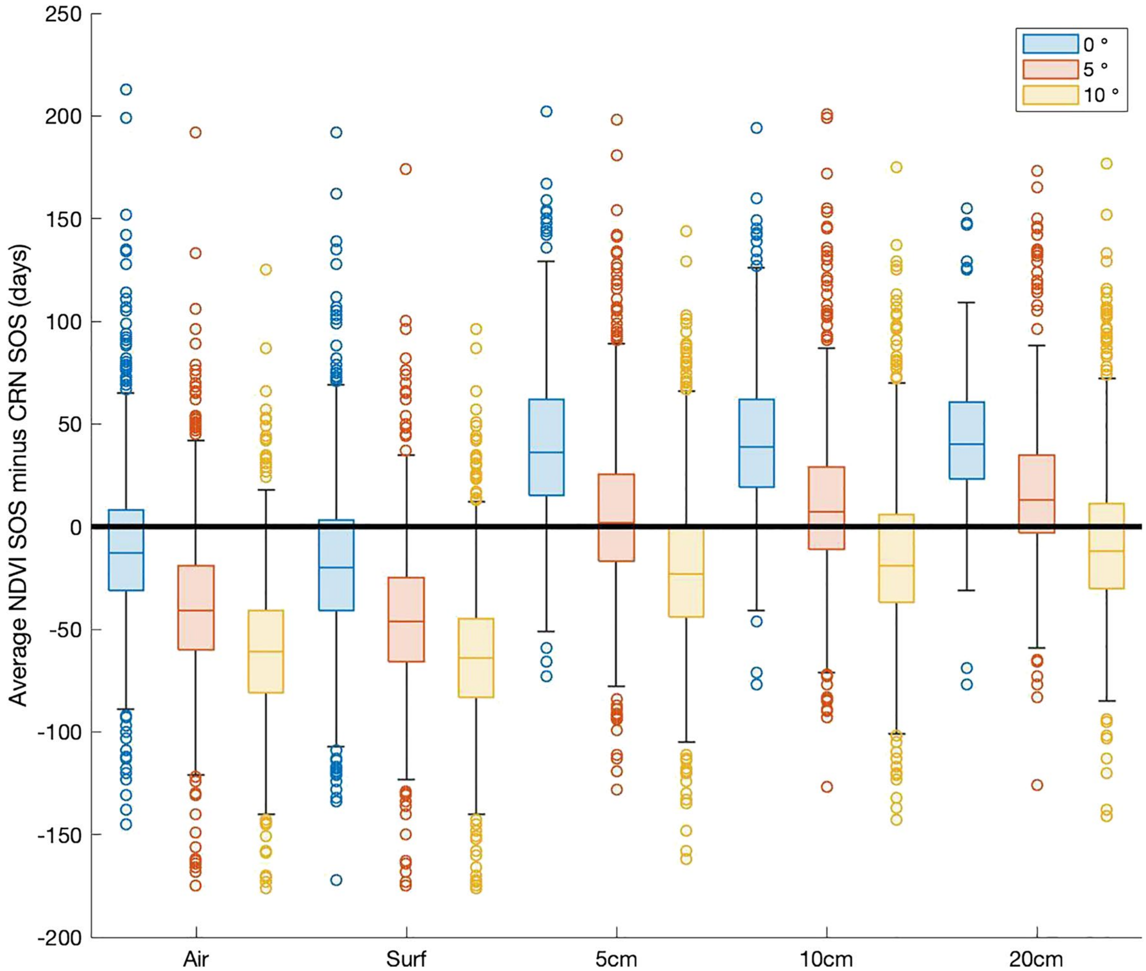

Figure 4. Boxplots of start of season differences (normalized difference vegetation index minus U.S. Climate Reference Network) for air, surface, 5 cm, 10cm, and 20 cm temperatures at the (blue) 0°C, (red) 5°C, and (yellow) 10°C thresholds.

SOS estimates were consistent over inter-annual timescales and regionally across the U.S. albeit with varying magnitudes of differences. These results are thought to be caused by the isolating properties (i.e., heat capacity and thermal conductivity) of the soil, which tends to dampen its response to changing conditions (Baldocchi et al., 2005; Hillel, 2005). To explore this further, plots of hourly 5 cm soil and air temperature observations revealed that air temperature had much larger diurnal swings in temperature (i.e., warmer maximums and cooler minimums) compared to soil temperature with periodic downward spikes that are thought to be caused by cold fronts. While soil temperatures were also impacted during downward swing in air temperature, the response was much more dampened. To explore a bit further, daily weather maps from NOAA were evaluated to determine the presence of cold frontal boundaries (https://www.wpc.ncep.noaa.gov/dailywxmap/) across Bronte, TX. One of the larger offsets between air and soil temperature estimated SOS dates (~1.5 months) was found to be related to the passage of a cold front between April 14th and April 15th, 2014 (https://www.wpc.ncep.noaa.gov/dailywxmap/index_20140415.html), which caused air temperature to dip below its 0°C threshold as soil temperatures remained above 5°C (Figure 6). While further analysis of cold front and their impacts on the offset between air and soil temperature based estimates of SOS dates is needed (particularly over the higher latitudes), frontal activity, which can be particularly active during the start of the growing season period (March–May) may partially explain some of the high variance found in temperature based SOS estimates between years. This also suggests that soil temperature conditions, given the reduced sensitivity to frontal boundaries, may provide a more stable measure of start of season than the air temperature of transient air masses.

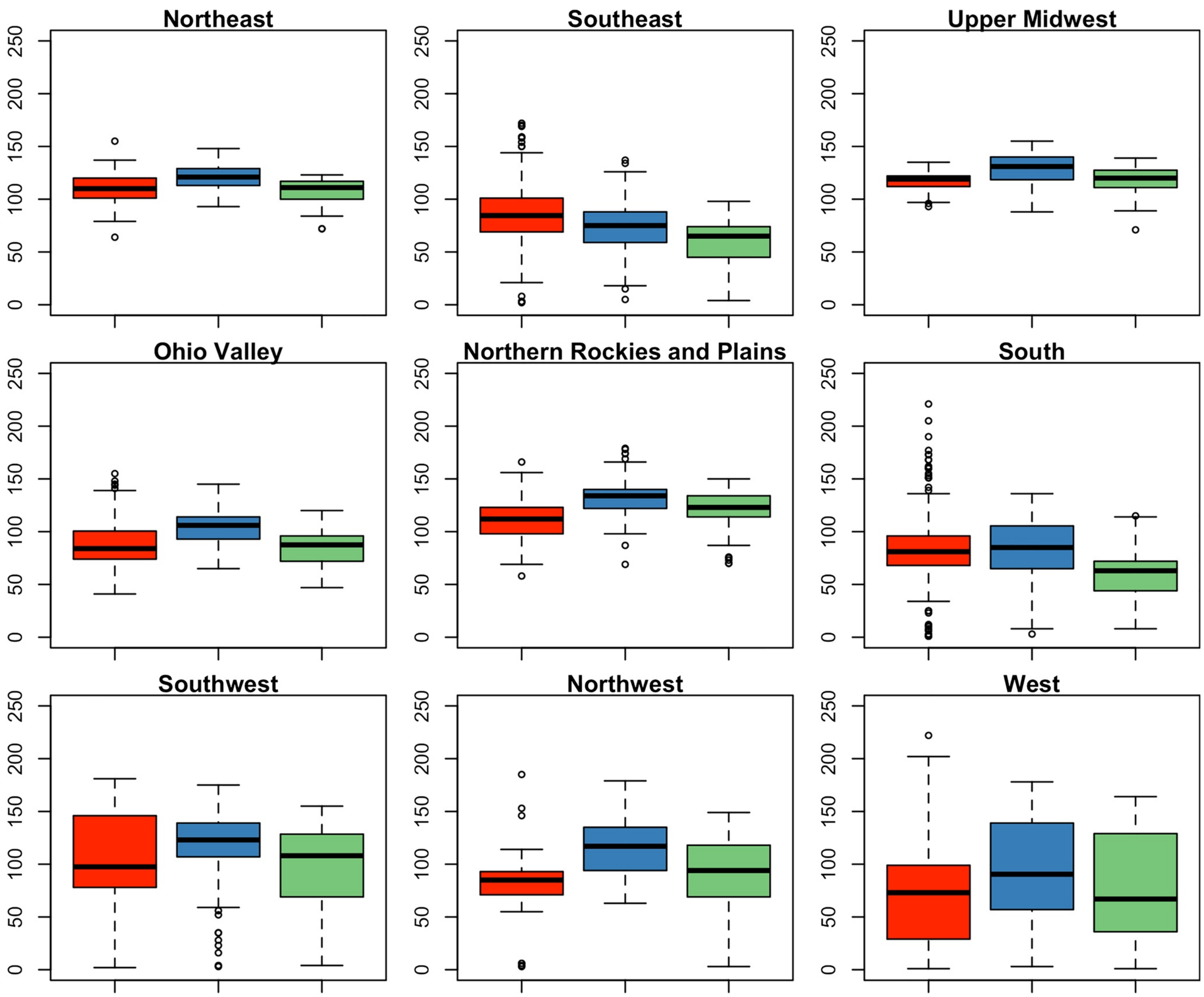

Figure 5. Boxplots of SOS_{NDVI} (red), $SOS_{AT,0}$ (blue) and $SOS_{5,5}$ (green) by region.

Overall, the SOS_{NDVI} estimates were strongly coupled to soil temperature based SOS dates. This was particularly true of the 5 cm soil temperature SOS estimates that not only had lower measures of error than the traditionally used $SOS_{AT,0}$ measure, but was also a better match with SOS_{NDVI} for 41.3% of stations years when 5 cm soil temperature measures were available compared to 27.2% for air temperature observations (Table 3). These results are consistent with previous studies that suggest biological activity for most plant species begins once soil temperatures surpass 5°C and peaks after 10°C (Alvarez-Uria & Korner, 2007; Day et al., 1989, 1990; DeLucia, 1986; Lippu & Puttonen, 1991). However, $SOS_{AT,0}$ estimates had only slightly larger measures of bias, and for some stations and years were a better match to SOS_{NDVI} dates (Table 3). This was more often the case for stations located in the South and Southeastern regions of the U.S. where $SOS_{5,5}$ estimates had an early bias compared to SOS_{NDVI} (Figure 7). In contrast, $SOS_{5,5}$ estimates had slightly lower measures of median error for stations located across the central and northern regions of the U.S. (New England, Ohio Valley, and parts of the Northern Rockies and Plains) despite slightly smaller differences in air and soil

Table 3
Counts of Cases Where Each Temperature-Based SOS Date was Closest to the NDVI-Based SOS Date Regardless of Threshold.

Measure	Best choice	Total cases	Best choice fraction
Air	200	735	0.2721
Surface	173	735	0.2354
5 cm	300	725	0.4138
10 cm	251	714	0.3515
20 cm	208	591	0.3519

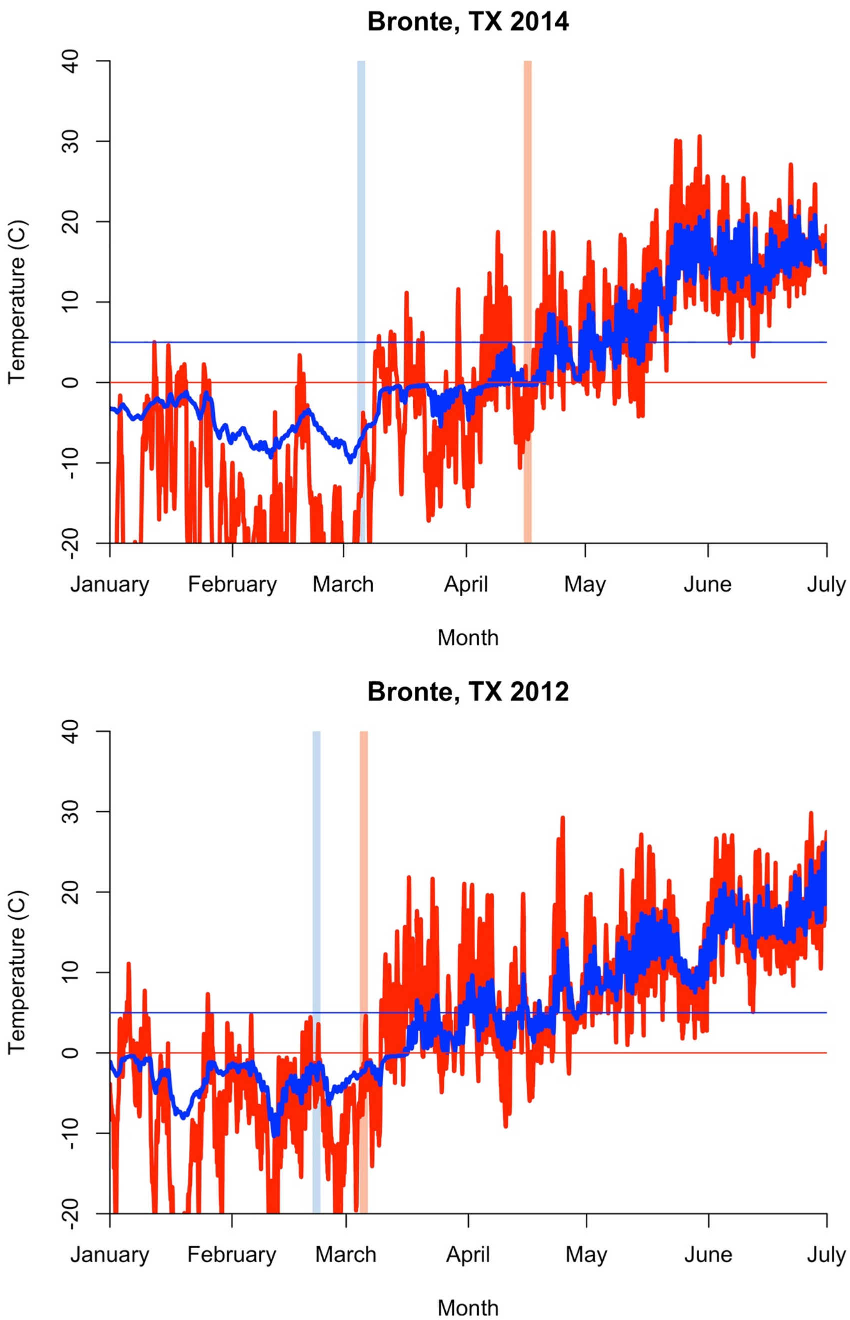

Figure 6. Hourly air (red) and 5 cm soil temperature (blue) observations from January to July for 2014 (top) and 2012 (bottom) at Bronte, TX. Start of season estimates for air (light red) and 5 cm soil (light blue) temperatures are the last day, since January, temperatures reached 0°C for air temperature and 5°C for 5 cm soil temperature.

temperature SOS estimates at higher latitudes. An exception to this were stations located over the Rockies where both air and soil temperatures had an early SOS bias with respect to SOS_{NDVI} for a number of stations. The spatial contrasts in median errors is not entirely understood and suggest that local factors (i.e., vegetation type and density) beyond temperature conditions may have a role in influencing SOS_{NDVI} as well as the quality of the remotely sensed NDVI measurements.

To evaluate the importance of soil moisture as a limiting factor on SOS_{NDVI}, daily averages of standardized soil moisture anomalies from the USCRN were analyzed for each station's annual SOS_{NDVI} date. The

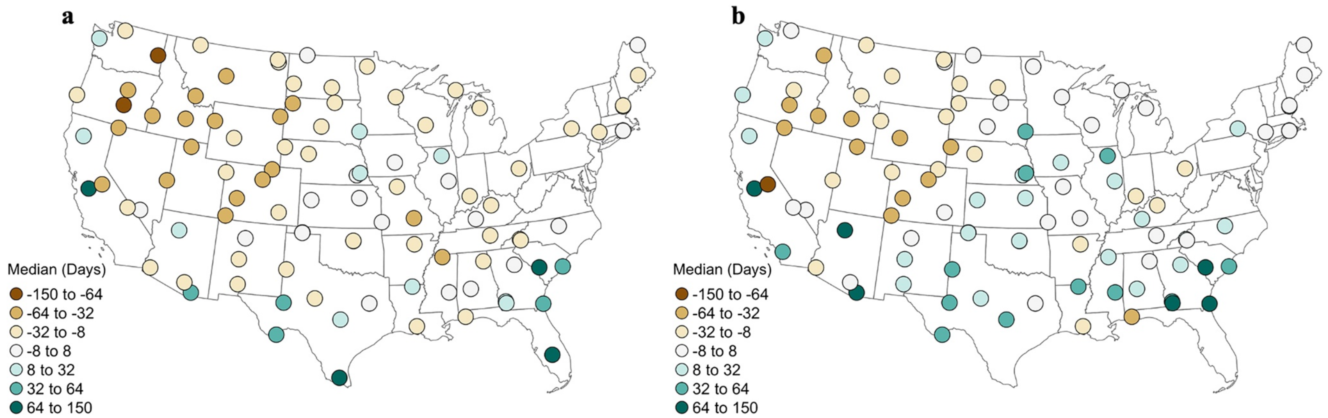

Figure 7. Median start of season (SOS) date differences computed as SOS_{NDVI} minus (left) $SOS_{AT,0}$ and (right) $SOS_{5,5}$.

standardized soil moisture anomalies, as described by Leeper et al. (2019), were evaluated using a centered 31-day moving window to provide monthly adjusted measures of soil moisture conditions. The standardized anomalies provide a relative measure of dry (negative values) or wet (positive values) conditions compared to normal soil moisture for that day of the year. Overall, the relationship between SOS_{NDVI} and standardized soil moisture conditions were relatively weak (Figure 8). For most regions, there was almost no relationship with an exception of the Northern Rockies and Plains and to a lesser extent the Northwest, which showed slightly later SOS_{NDVI} dates for drier soil moisture conditions. These results suggests that soil moisture recharge, which generally takes place over the fall to winter months when deciduous vegetation is dormant, is typically sufficient enough to support vegetation development even when soil moisture conditions are drier than usual (i.e., negative soil moisture anomalies may not imply there is no plant available water). This was also the case in the desert Southwest, indicating that the types of vegetation are well adapted for their respective region's moisture variability. Other factors that may influence green up include vegetation type (i.e., varieties with differing sensitivity to cold waves) and or density; however, these measures are not as widely available as temperature data sets when estimating SOS dates across broad regions in time.

Uncertainties in the SOS_{NDVI}, such as the health and heterogeneity of inter-pixel land cover, the timing of satellite over passes, and fitting method used to detect SOS date, should also be noted here as factors that likely impacted these results. Measures of NDVI are also likely impacted by the density of deciduous vegetation that have pronounced seasonal variations in greenness. This may partially explain some of the wider distributions of estimated SOS_{NDVI} in the Southwest and West regions of the U.S. that have sparse vegetation cover (Figure 5). This is particularly true in the desert Southwest regions of Southern California, New Mexico, Arizona, and Nevada. Even in some of the more densely vegetated areas of California and Colorado, the density of deciduous vegetation cover may be limited due to the predominance of evergreens. While efforts were taken to ensure the quality of the fits to Equation 1 used to estimate SOS_{NDVI} dates, there may be portions of the U.S. where sparse deciduous vegetation cover or sensitivity to other factors (i.e., high probability of cloud cover) make estimating SOS dates from NDVI data challenging (Beck et al., 2006). Future assessments of SOS dates using NDVI may be improved by incorporating other vegetation-related satellite data sets. For instance, the enhanced vegetation index or leaf area index when combined with NDVI may improve estimates of vegetative conditions in areas with sparse or dense vegetation cover (Pettorelli et al., 2005). This is particularly true if station photographs of the surrounding land-cover, which can allow for localized assessments of vegetation conditions with accompanying temperature data sets, are available and captured at a regularly frequency (i.e., hourly or daily).

5. Conclusions

The purpose of this study was to evaluate a combination of temperature measures and thresholds most often used to define start of season. While previous studies suggests that air temperature can serve as a good predictor for the start of plant greenup periods, determination of the climatic growing season across

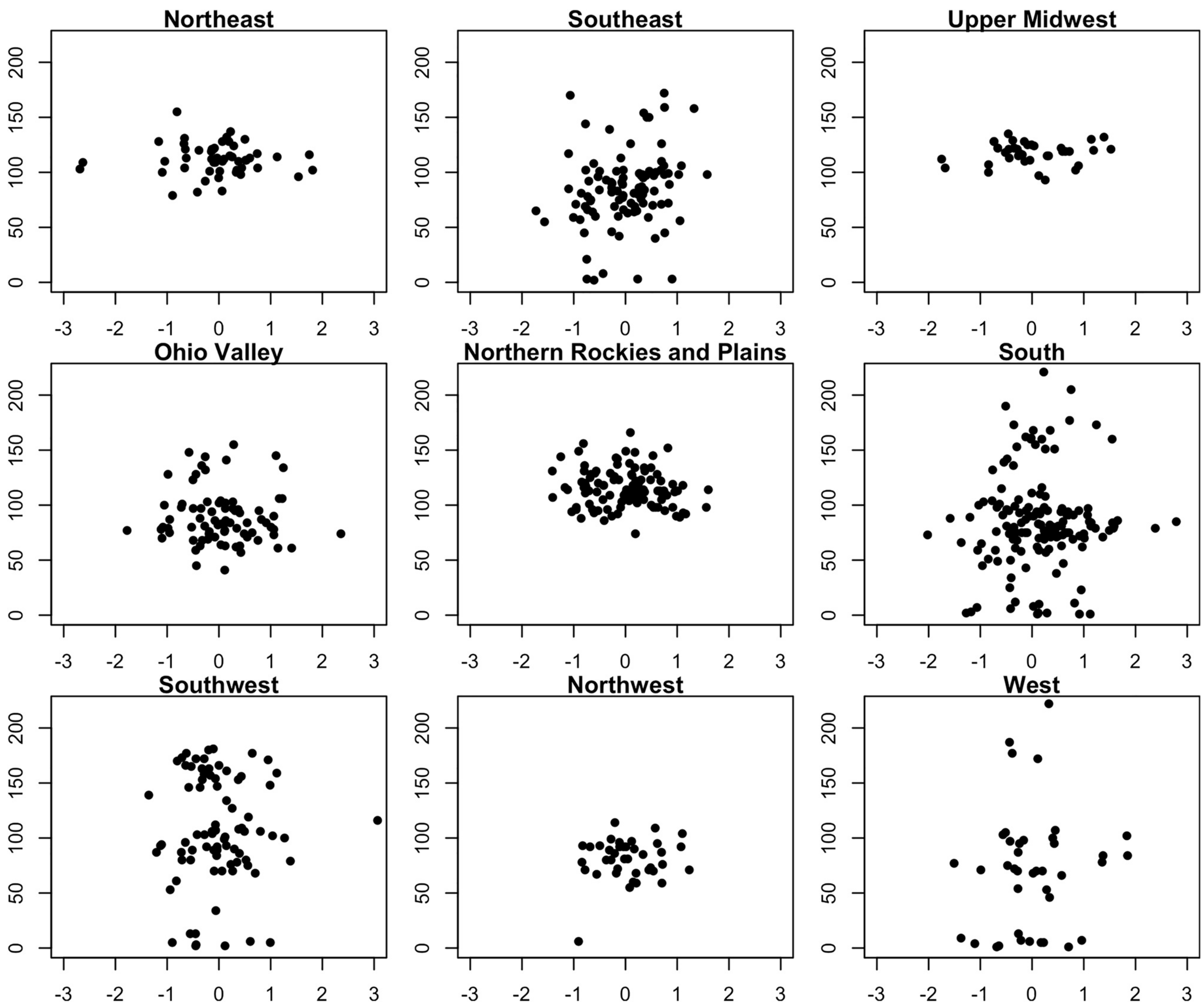

Figure 8. Regional scatter plots of standardized soil moisture anomalies (*x*-axis) with SOS_{NDVI} dates (*y*-axis). Negative standardized soil moisture anomalies indicate drier than usual while positive values represent wetter than usual soil moisture conditions at the time of SOS_{NDVI}.

the U.S. can be improved by using soil temperature. This was particularly true for more northern U.S. stations where the earlier soil temperature SOS estimates were better aligned with SOS_{NDVI}. Soil temperatures provided slightly better estimates of SOS than air temperature for many locations across the U.S., but there were considerable differences between SOS_{NDVI} and SOS estimates based on temperature (20 or 40 days). The magnitude of these differences were not all that surprising given the simplicity of the approach based solely on temperature conditions remaining above a critical threshold. In fact, these differences should inform which applications are best suited for such approximations of SOS dates. For instance, a climate study looking at shifting trends in SOS dates may have more relaxed requirements on uncertainty than an investigation on the timing of plant blooming dates. It may also be that a SOS date range, between $SOS_{5,5}$ and $SOS_{AT,0}$ estimates, provides a more reasonable reflection of the complex variations in localized green up caused by vegetation density and/or plant speciation rather than a single date. The range (between $SOS_{5,5}$ and $SOS_{AT,5}$) will also better reflect the year-to-year variability in SOS estimations caused by frontal (i.e., cold waves) activity that can result in sharp changes in atmospheric conditions. As a result, soil temperatures provide an additional measure, beyond air temperature, that has been found to be more skillful in estimating the start of season.

Data Availability Statement

The MODIS NDVI data were obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center, USGS/Earth Resources Observation and Science Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/tools/earthdata-search/). The Terra and Aqua doi numbers were 10.5067/MODIS/MOD13Q1.006 and 10.5067/MODIS/MYD13Q1.006 respectively. We appreciate NOAA's USCRN for data management and assistance (https://www1.ncdc.noaa.gov/pub/data/uscrn/products/hourly02/ doi: 10.7289/V5H13007).

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