3.3. Pheno-Climatology

Dates for the mid green-up and mid brown-down were empirically determined from the multi-year LSP curves shown in Figures 3 and 4; the NDVI periods ending 16 May and 31 October were chosen for comparison with three temperature and precipitation factors, as outlined below. The distributions of correlations that relate spring and autumn NDVI with GDD, CDD and PCP differ for deciduous and conifer-mixed vegetation types (Figure 6). Deciduous forests usually exhibit stronger positive or negative correlations than do their paired conifer-mixed forest counterparts.

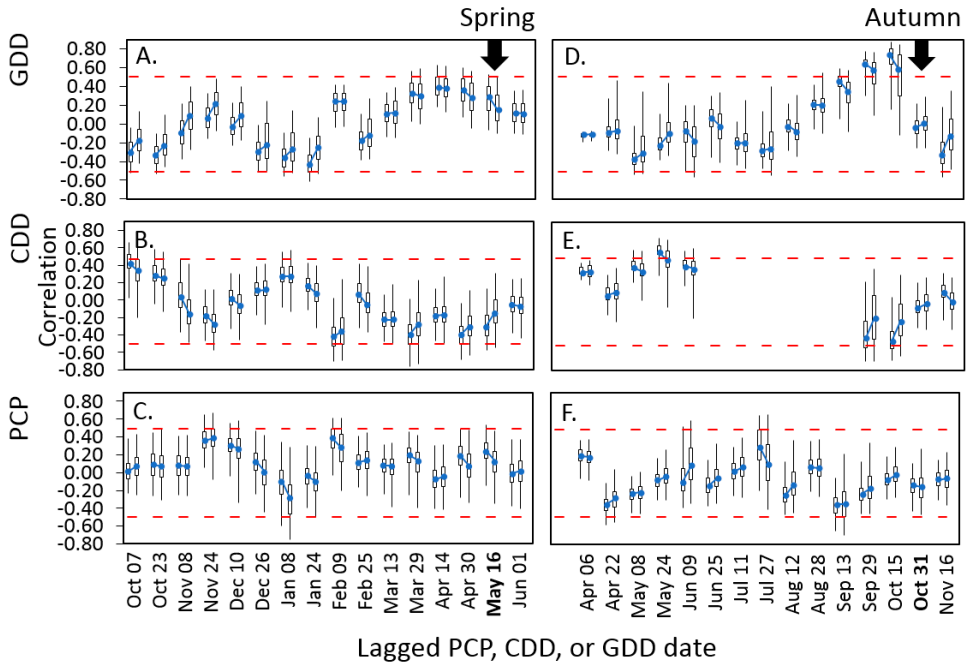

Figure 6. Distribution of 24-day time-lagged correlations of growing degree days (GDD; (**A**,**D**)), chilling degree days (CDD; (**B**,**E**)) and precipitation (PCP; (**C**,**F**)) with spring (**A**–**C**) and autumn (**D**–**F**) NDVI across the Park, 2000–2015. Arrows represent the fixed spring (16 May) and autumn NDVI (31 October) periods being correlated with antecedent weather that goes backward in time to the left. Two correlation box plots are shown for each date with medians that are connected by a blue line wherein the left member shows pure hardwood forests (N = 17,456 MODIS cells) and the right shows conifer and mixed forests (N = 15,876 MODIS cells). Box plots show the 99th, 75th, 50th, 25th and 1st percentiles for each date-cover type combination. For general guidance, dashed red lines show critical values for 95% confidence intervals with 15 degrees of freedom (years).

Correlations between mid-spring NDVI (for the period ending 16 May) and lagged GDD are positive for the lagged weather periods ending 29 March, 14 April and 30 April, meaning that greener mid-spring conditions are associated with warmer temperatures in the weeks prior to mid-spring (Figure 6A). This correlation becomes inverse for lagged GDD that accumulate for the periods ending 8 and 24 January, suggesting a possible association between years with earlier spring green-up and January coldness. Correlations with CDD are generally the reverse of those with GDD, with a colder early spring being associated with a delay in green-up (Figure 6B). Results also suggest a possible longer-reaching cross-seasonal relationship between early springs and coldness during the prior autumn (i.e., for the 24-day period ending 7 October) (Figure 6A,B). Correlations with spring NDVI and lagged PCP are weak, but positive for 24 November and 9 February (Figure 6C).

Correlations between mid-autumn NDVI (for the period ending 31 October) and lagged GDD are strongly positive for 29 September and 15 October, with a predictable inverse pattern with CDD (Figure 6D,E). A cross-seasonal association is suggested between late autumns (i.e., higher autumn

NDVI) and cool springs (i.e., more CDD) for the period ending 8 May. As seen with lagged PCP in the spring, fall PCP shows a weak relationship with autumn NDVI (Figure 6F).

When selected lagged correlations are mapped, the statistical distribution of Figure 6 exhibits coherent spatial structure in terms of correlation strength and sign. Correlations of mid-spring NDVI (16 May) and GDD accumulated from 7 April to 30 April show a stronger positive relationship for lower elevations, particularly to the south and west (Figure 7A). Similar spatial patterns occur with spring NDVI and lagged spring CDD, but correlations are reversed (Figure 7B), consistent with Figure 6A,B. Correlations of spring PCP with mid-spring NDVI show strong geographic differences. The northern and southern foothills are strongly positive, while low to mid-elevations of the west and east, and higher elevations more generally, exhibit weak to negative correlations (Figure 7C).

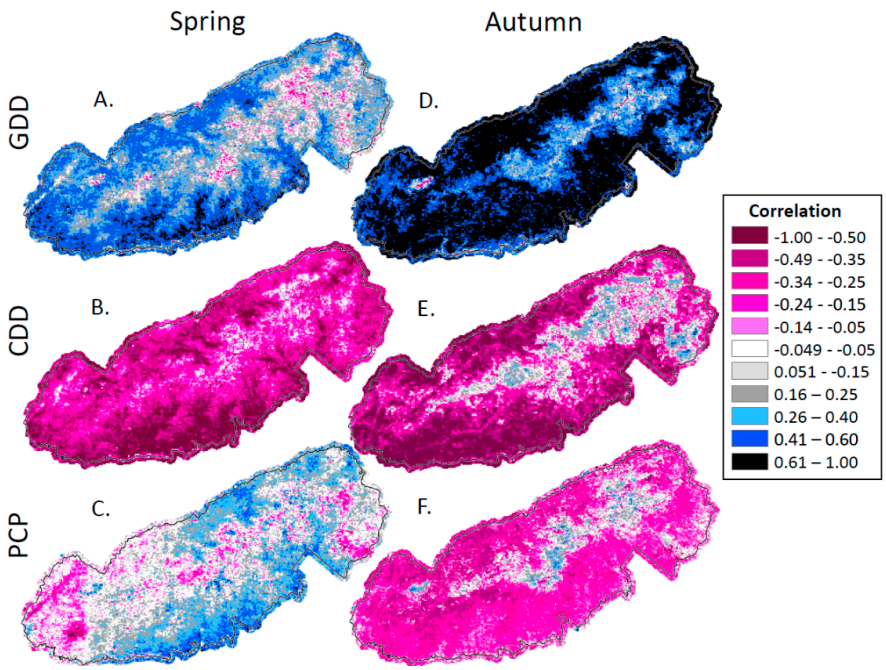

Figure 7. Correlations of mid-spring and mid-autumn NDVI with antecedent weather: (**A**) Correlation of spring NDVI with growing degree days (GDD); (**B**) spring NDVI with chilling degree days (CDD); (**C**) spring NDVI with precipitation (PCP); (**D**) autumn NDVI with autumn GDD; (**E**) autumn NDVI with autumn CDD; and (**F**) autumn NDVI with autumn PCP. Spring weather variables are lagged by two eight-day periods and the autumn variables are lagged by four periods compared to NDVI (see Figure 6 for context).

Mapped autumn correlations with mid-autumn NDVI (for the period ending 31 October) and GDD (accumulated from 6 to 29 September) are particularly strong and positive over nearly all of the Park (Figure 7D). Exceptions are the grass-dominated Cades Cove in the west, higher elevations to the east, and similar lower elevations in the east that were anomalous in spring. Autumn NDVI and autumn CDD largely mirror the pattern observed with GDD, though reversed (Figure 7E). Autumn NDVI and PCP correlations are weakly, but broadly negative across most lower and mid elevations, implying that drier conditions relate to delayed senescence. PCP correlations are consistently uncorrelated or only weakly correlated in many of the same locations as observed by other correlations (Figure 7F).

The combined influence of temperature and precipitation on spring and autumn NDVI are conveyed by Figure 8. Cool-dry springs are more likely to have a lower NDVI in May (represented by smaller diameter circles in Figure 8A) than are warm-wet springs, although moderately warm, but dry springs are occasionally abnormally green (2004 and 2010, at center-left of Figure 8A). Extreme

warm-wet or cool-dry conditions are not represented within this 2000–2015 measurement period in autumn, but late senescence (indicated by larger diameter circles in Figure 8B) is more likely when conditions are warm and dry rather than cool and wet.

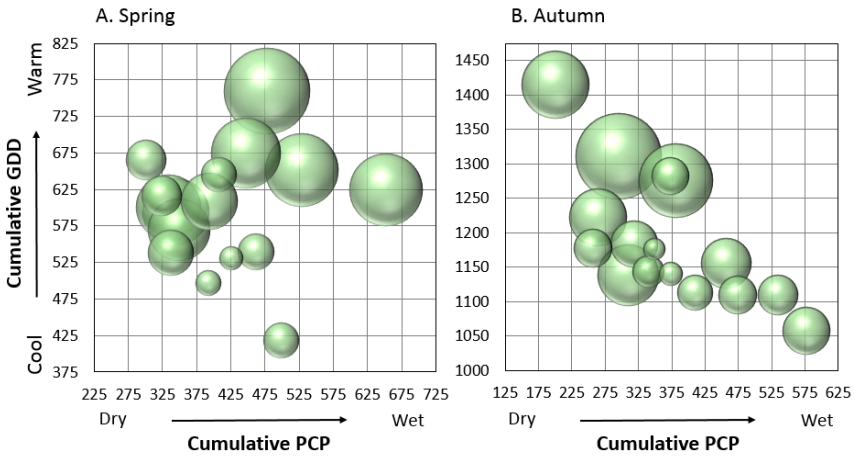

Figure 8. Relative mean spring and autumn NDVI for pure hardwood forests between 610 and 1220 m (2000–4000 ft.) elevation, 2000–2015, compared to cumulative growing degree days (GCC) and cumulative precipitation in mm (PCP). Larger diameter circles had higher mean NDVI for: 16 May (**A**); or 31 October (**B**). Weather measures accumulate from: 18 February to 16 May (**A**); or 28 July to 23 October (**B**).

In spring, the last frost date varied by 21 days with a Park-wide average date of 11 April (Table 1). The earliest frost date in autumn varied by 25 days, with a Park-wide average of 26 October. Growing season length, measured as the number of days between the last and first frost, ranged from 171 days (in 2015) to 206 days (in 2005).

Table 1. Average gridded first and last frost dates (<0 °C) for the Park, 2000–2015. Rank indicates position out of 16 years arranged in decreasing sorted order. Season is length in days.

Year	Spring	Rank	Autumn	Rank	Season	Rank
2000	16 April	13	13 October	1	198	6
2001	19 April	16	13 October	1	182	14
2002	16 April	12	3 November	13	191	8
2003	1 April	2	3 November	13	202	3
2004	15 April	11	7 November	16	190	10
2005	14 April	9	30 October	10	206	1
2006	5 April	3	17 October	3	189	11
2007	12 April	8	1 November	11	185	13
2008	18 April	15	26 October	8	199	5
2009	11 April	6	23 October	5	191	8
2010	29 March	1	1 November	11	192	7
2011	14 April	9	24 October	6	200	4
2012	10 April	5	4 November	15	203	2
2013	11 April	6	24 October	6	188	12
2014	16 April	12	22 October	4	174	15
2015	5 April	3	27 October	9	171	16
Mean	11 April	-	26 October	-	191	-

Places with anomalous correlations in Figure 7 usually occur where disturbance has occurred over the 2000–2015 era (Figure 9). A 2011 tornado scar shows up in the west in all three spring correlation maps (Figure 7A–C), but not in the autumn maps (Figure 7D–F). Wildfires show no discernable impact

on correlations, but most of the higher elevation and eastern forests with low or anomalous correlations are where hemlock is dominant or co-dominant and where the non-native hemlock woolly adelgid has led to widespread hemlock mortality. Mortality is widespread because treatment, where it occurs, targets only a fraction of the hemlock trees that are present.

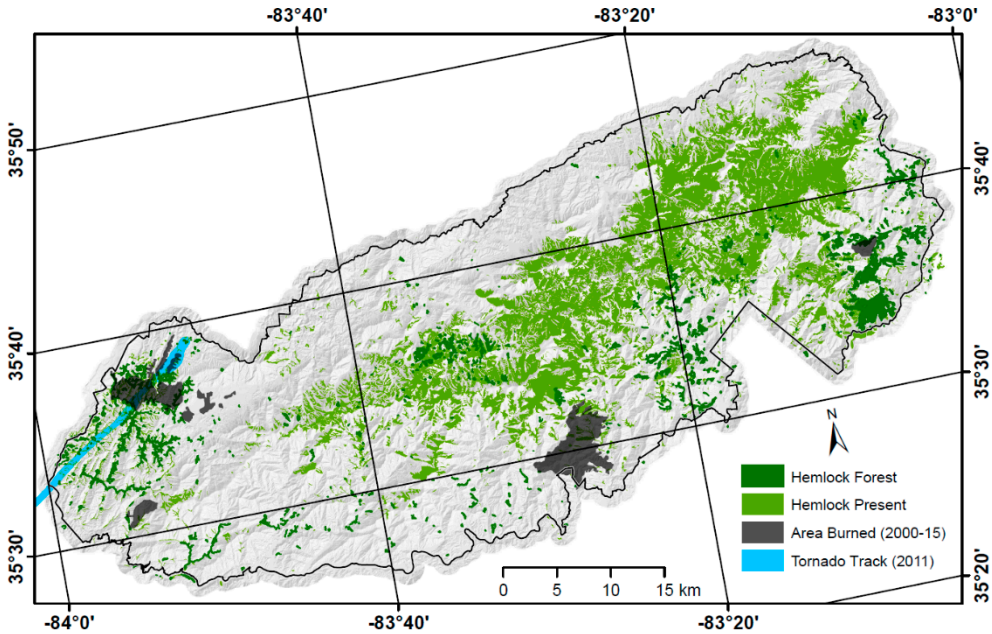

Figure 9. Areas of known blowdown, fire and insect-induced tree mortality within Great Smoky Mountains National Park, 2000–2015.

4. Discussion

The temporal and spatial resolution of MODIS LSP successfully conveys the influence of environmental gradients on spring and autumn land surface phenology across GRSM. Temperature and precipitation's fundamental influence on LSP is suggested by Figure 2, whereby the late winter and spring increase in day length and solar radiation drive changes in temperature, which, in turn, leads to an abrupt increase in NDVI in early April. NDVI persists through summer after GDD and DAYL decline, then the onset of autumn is associated with increased CDD in late September.

Topography provides a secondary influence on LSP across GRSM, with elevation, in particular, controlling the onset and progression of spring and autumn (Figure 3). The impacts of aspect are secondary, but it is difficult to know if aspect differences relate to microclimate or to differences in species composition that also conform to aspect. The importance of elevation in this research is consistent with results from prior research in mountainous terrain [22,68–73], but there is a clear need for more research regarding how topographic factors beyond elevation affect spring and autumn timing.

Our documented spring-to-autumn reversal in the order of seasonal change across slopes is notable, particularly because it represents the long-term average response over a large landscape (Figure 3). In spring, mesic slopes are first to advance, while in autumn they are the first to senesce. This pattern could be explained by microclimate or by the attributes of the dominant species that occur across this moisture gradient. While dry south-facing slopes warm relatively early in the spring, and may experience relatively early water stress in autumn, our observed LSP patterns do not show these expected LSP responses—sunny slopes advance after shaded slopes in spring, and water stress would be expected to be observed first on drier slopes. Instead, these patterns may relate to species' phenological attributes. Xerophytic species often leaf out weeks after mesic species in spring [27].

In autumn, a combination of differential species responses and microclimates having greater exposure to cooler autumn temperatures may explain these long-term average patterns.

Prior studies have measured spring and autumn using NDVI slopes or inflection points to estimate local dates of transitions, while in this research a less complex approach is used that relies on empirically selecting fixed dates for spring and autumn, in order to directly compare seasonality across climatic and topographic gradients. In Figure 3, comparability across sites within elevation bands is gained by calculating values as the Percent of Completion. This conversion reveals the extent of the summer reduction in NDVI from leaf aging, moisture stress or disturbance that occurs prior to the autumn season—a phenomenon that has been described in the northeastern US, but is not widely recognized [74]. In GRSM, neither low summer PCP nor warm summer temperatures (GDD) are strongly associated with delayed senescence (Figures 6 and 7), although they may increase drought stress in concert (Figure 8).

Lower elevation forests may be more vulnerable to drought-induced late-growing season stress than are forests at mid- and higher elevations, with implications for future forest productivity [22]. In general, autumn warmth delays senescence, while drought advances the onset of autumn [6,37]. While late-season hydrologic stress and productivity may not be consistently measured by autumn NDVI, here we find no strong support for summer or autumn drought-induced senescence (Figures 6F and 8B). While neither extreme warm-wet nor cool-dry autumns occurred during our 2000–2015 analysis period, warm-dry autumns were generally associated with delayed senescence and cool-wet autumns showed earlier brown-down, as expected (Figure 8B). The earliest autumns—2011 and 2012—appear as outliers to this trend, and they may have been caused by factors other than GDD or PCP as measured, but they are not explained by unusually early autumn frost dates (Table 1).

An early spring brings an increased hazard of frost damage, and growing season duration affects community productivity and competitive relationships. The extremely early spring of 2012 also experienced an early senescence. Compare the 2012 season with 2013, where both spring and autumn were late, and also with 2002, which experienced a particularly long growing season (Figure 4). LSP-based phenology results are often inconsistent with growing season expectations from the last and first frost dates alone (Table 1), and this highlights a need for better understanding the mechanisms that regulate the growing season in agricultural and wildland systems. The spring of 2000, 2001, 2007 and 2014 started early, but lost momentum (Figure 4A), and this helps explain their relative position in Figure 8A, since early green-up was caused by the early accumulation of GDD that then slowed. Each of these years had either a late-ranking frost (Table 1) or, in the case of 2007, a severe April freeze [20].

Our results are directionally consistent with a growing body of evidence regarding within-season and cross-seasonal temperature effects on spring and autumn LSP [24,36,45]. Recognition of within-season lags has long been acknowledged and captured through use of cumulative GDD and cumulative CDD to predict spring and autumn phenology [75]. Our strongest relationships are for within-season GDD in autumn, but we also show that on some sites, spring may be accelerated by cold winters and autumn may be delayed by cold springs. These cross-seasonal correlations do not, however, necessarily imply some causative physiological mechanism, since chance combinations of observed seasonal weather over the short 16-year period or some inherent cross-seasonal climate mechanisms could generate these results, with LSP only being responsive to shorter-term climatic factors. If, however, there are causal biological mechanisms at work, such cross-seasonal complexities may make it more difficult to accurately predict how LSP will respond to climate change.

Improved precision in monitoring provides an important path forward. By filtering our analysis according to cover type, we demonstrate that deciduous and conifer/mixed forest types respond differently to antecedent seasonal weather conditions (Figure 6). This filtering was particularly important in GRSM because dying evergreen hemlock trees and a tornado during the period of analysis likely reduced the statistical strength of correlations between LSP and climatic and topographic variables, although fire had no clear impact, presumably because severity was relatively low, with most mortality confined to the understory (Figures 7 and 9). In disturbed areas, the timing

of green-up may increasingly reflect the understory signal, which can differ from that of the overstory [31,32,76]. With improved understanding of where disturbances have occurred or how vegetational responses have changed because of disturbance, phenological observations can be refined to improve landscape monitoring.

5. Conclusions

In this study, we report on the behavior of MODIS LSP along environmental gradients among years having different combinations of seasonal weather. We document stronger effects from elevation than from slope or vegetation type. We found that deciduous hardwood forests exhibit a much stronger relationship with climatic variation than conifer and mixed-forest types. We also found a particularly weak 16-year temperature and precipitation relationship with LSP in areas of recent acute disturbance, including areas affected by the hemlock wooly adelgid and a recent tornado.

Across years, we found that spring NDVI was strongly correlated with accumulated warming, with up to a six-week lag at lower elevations, and that autumn NDVI was extended when autumn is warm more broadly. We also describe possible cross-seasonal relationships. Spring green-up was sometimes correlated with colder winters. Autumn greenness was correlated with colder prior-springs. The influence of precipitation on seasonal NDVI was weak. Wetter springs, but drier autumns, may extend the growing season, but this was dependent on the dominant influence of temperature.

Remote sensing provides an efficient all-landscape means for tracking growing season dynamics of vegetation. However, just as vegetation typologies do not perfectly convey the species assemblages within a given vegetation type, so the phenological responses of individual species may not be discernable from LSP gridded data, particularly in species-rich forests such as those of the Southern Appalachians. With numerous species and individuals contributing to the LSP behavior of a grid cell, observed LSP responses may not equate to ground-based phenological observations of particular species any more than characteristics of individuals relate to communities.

This research describes remarkable variation in spring and fall vegetational phenology among years and across environmental gradients. For the plant and animal species of these mountains, these spatial and temporal attributes constitute a rich diversity of phenological habitat that enriches the evolutionary environment of this place. Researchers have long-argued that the topographic and microclimatic complexity of the Great Smoky Mountains, and of the Southern Appalachian Mountains more broadly, have contributed to the region's rich biodiversity [50,77,78]. This research shows that, while vegetation phenology responds to those fixed environmental attributes, it also captures a dynamic year-to-year and cross-seasonal flux that is superimposed on those stable gradients. This flux includes the variable vegetative responses to spring and autumn weather across years, and the impacts of localized biotic and abiotic disturbances that alter phenological conditions at longer time scales. While such phenological complexity can be difficult to monitor, filtering observations with disturbance history and vegetation type can clarify how landscape vegetation responds to seasonal forcing.

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Conflicts of Interest: The authors declare no conflict of interest.

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