

Water Resources Research®



RESEARCH ARTICLE

10.1029/2022WR034125

Key Points:

- Topoclimate modulates coupling of precipitation and greenup with seasonal runoff dynamics
- Deciduous catchments show tighter coupling between greenup and seasonal runoff dynamics than paired evergreen ones
- Hillslope modulates coupling of precipitation and greenup with seasonal soil moisture dynamics

Supporting Information:

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

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Citation:

Hwang, T., Band, L. E., Oishi, A. C., & Kang, H. (2023). Greenup variability impact on seasonal streamflow and soil moisture dynamics in humid, temperate forests. *Water Resources Research*, 59, e2022WR034125. <https://doi.org/10.1029/2022WR034125>

Received 16 NOV 2022

Accepted 15 NOV 2023

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Greenup Variability Impact on Seasonal Streamflow and Soil Moisture Dynamics in Humid, Temperate Forests

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Abstract In this study, we investigate how seasonal streamflow and soil moisture patterns have responded to variability in vegetation phenology in humid, temperate forested watersheds without significant seasonal snowmelt over the last four decades. We characterize spring streamflow peaks using 50th percentiles of cumulative daily precipitation, streamflow, and soil moisture measurements, and investigate interactions with remotely sensed, greenup anomalies. After removing a dominant precipitation control, 1-day earlier greenup is usually associated with about 1-day early spring flow peak at four low-elevation deciduous catchments using both sequential and multiple linear regressions. This indicates that the strong dependency of seasonal flow regimes on precipitation is mediated by vegetation seasonality, especially by greenup variability. In contrast, we find less significant correlations of the greenup anomalies on flow percentiles from two paired evergreen and two high-elevation deciduous catchments. At a plot scale, similar correlations were found only at an upslope topographic position, where precipitation also showed tighter coupling with moisture seasonal patterns than downslope. Our study suggests that rainfall-runoff and rainfall-soil moisture relations have been closely mediated by vegetation seasonality in deciduous forests, especially by greenup anomalies, but patterned along topoclimate and hillslope gradients. This study emphasizes that it is important to understand phenological responses to ongoing climate change (in both long-term and interannual variability) for prediction of seasonal flow regimes especially in deciduous forested catchments.

1. Introduction

Vegetation phenology is a sensitive indicator of ecosystem responses to climate change. Ongoing warming has generally brought earlier greenup and extended growing season in deciduous forests at mid- and high-latitude regions (e.g., Menzel et al., 2006; Richardson et al., 2010). Many field studies in deciduous forests reported that vegetation phenology closely regulates the partitioning of net radiation between sensible and latent heat fluxes by the changes in leaf area, surface albedo and aerodynamic conductance (e.g., Moore et al., 1996; Schwartz & Crawford, 2001). Springtime greenup in mid-latitude regions is often accompanied by steep increases in canopy conductance and subsequent decreases in Bowen ratio due to plentiful available energy and soil water at the beginning of the growing season (Moon et al., 2020; Oishi et al., 2018; Wilson & Baldocchi, 2000). Recently, Denham et al. (2023) also showed that early greenup at deciduous forests led to high spring evapotranspiration (ET) to potential ET ratios from the flux tower data across the eastern US. These changes in canopy conductance and evapotranspiration (ET) during phenological transition periods (greenup and senescence) significantly affect surface soil moisture and catchment rainfall-runoff dynamics (Lian et al., 2020; Khodaei et al., 2021).

Many catchment studies reported nonlinear threshold behavior of stormflow generation by combined effect of gross precipitation and antecedent soil moisture conditions, which demonstrates subsurface storage controls on rainfall-runoff dynamics at the catchment scale (e.g., Detty & McGuire, 2010; Tromp-van Meerveld & McDonnell, 2006). However, recent studies in the eastern United States reported that this strong antecedent soil moisture control on stormflow generation was moderated by canopy conductance and transpiration capacity in forest headwater catchments. Scaife and Band (2017) reported that stormflow thresholds as a function of antecedent soil moisture were lower and more variable during dry growing seasons potentially due to water stress induced seasonal reductions in canopy conductance. Tashie et al. (2019) found that hydrograph recession behavior was significantly correlated with transpiration rates in the early growing season. These studies suggest a competition

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of tree water uptake and base flow drainage for root zone soil moisture particularly where shallow surface flow is a main pathway of streamflow generation (e.g., Hewlett & Hibbert, 1967).

Therefore, the interannual variability in leaf greenup timing and growing season length can manifest in plot-scale soil moisture, evapotranspiration, recharge, and eventually watershed-scale streamflow dynamics both in terms of water yield and seasonal patterns. For example, an early study by Czikowsk and Fitzjarrald (2004) showed that the recovery time to base flow levels after rainfall has shortened with earlier greenup onsets in the north-eastern United States. Creed et al. (2015) also reported that the timing of the Budyko evaporative index (the ratio of precipitation-runoff difference over precipitation) has shifted to earlier in spring and later in autumn due to lengthened growing season in temperate forest catchments in Canada. In our previous studies (Hwang et al., 2014; Hwang et al., 2018; Khodaei et al., 2021), we also examined the apparent correlations between phenology and rainfall-runoff dynamics across the eastern US where we showed that non-stationary behavior in precipitation and runoff deficit was significantly correlated with long-term and interannual variations in growing season length and subsequent vegetation growth. We also separated the net effect of lengthened growing season on water yield with a distributed ecohydrological modeling framework (Hwang et al., 2018; Kim et al., 2018). Specifically, Kim et al. (2018) suggested that early greenup usually increases annual ET and decreases water yield at the watershed scale in New England, while delayed senescence had a limited effect due to other factors, such as radiation, soil moisture stress and photoperiods.

However, there have been few studies that address the effect of phenological variations on both seasonal streamflow and soil moisture dynamics along the topoclimate and hillslope gradient, and their sensitivity to vegetation types, specifically in humid, non-snowmelt dominated regions. Furthermore, increased hydroclimate variability under ongoing climate change makes it difficult to separate the net effect of growing season variability and seasonal precipitation on seasonal flow regimes from emergent watershed-scale streamflow behavior. This indicates a critical knowledge gap in our understanding of how seasonal flow regime responds to variability of growing season and subsequent changes in ET seasonality at forested watersheds. In this study, we hypothesize that early greenup in humid, temperate deciduous forests leading to early ET increases, in turn result in early soil moisture dry-down and early seasonal streamflow declines given precipitation. However, we hypothesize that these correlations will be patterned along topoclimate and hillslope gradients, as well as vegetation types. Specifically, we test three specific hypotheses (Table 1).

- H 1.** Topoclimate will impart varying levels of coupling of precipitation and greenup with seasonal runoff dynamics. Specifically, we hypothesize that seasonal runoff dynamics at high elevations exhibit tighter temporal coupling with seasonal precipitation, but less coupling with greenup than low elevations, due to higher precipitation, lower temperature, shorter growing season, and subsequent lower ET demand.
- H 2.** Deciduous catchments will show tighter coupling between greenup (budburst) and seasonal runoff dynamics than evergreen catchments due to definite leaf seasonality.
- H 3.** Hillslope position will impart varying levels of coupling of precipitation and greenup with seasonal soil moisture dynamics. Specifically, we hypothesize that seasonal soil moisture dynamics at upslope would show tighter temporal coupling with seasonal precipitation and greenup than downslope due to active upslope subsidy to downslope topographic positions.

To test these three hypotheses, we combined long-term hydrologic datasets examining the correlation between remotely sensed leaf phenology and seasonal streamflow/soil moisture dynamics at different landscape positions and vegetation types in the southern Appalachian Mountains, USA.

2. Materials and Methods

2.1. Study Site

The study site is the Coweeta Hydrologic Laboratory, USDA Forest Service, located in North Carolina, USA (Figure 1). The area is characterized by complex topography with elevation ranging from 660 to 1,590 m, providing highly variable topoclimate patterns along the elevation gradient. This study site has among the longest hydrologic records comprising multiple gauged catchments over a substantial range of elevation, exposure, and landscape positions, making this area nearly unique for the goals of this study. This research was conducted at six deciduous broadleaf (WS02, WS14, WS18—low elevation, WS34—middle elevation, and WS27, WS36—high elevation) and two coniferous evergreen (WS01 and WS17) headwater catchments (Coweeta LTER &

Table 1
Three Key Hypotheses of This Study

	Conditions	Coupling with seasonal P	Coupling with greenup
Hypothesis I: Topoclimate will impart varying levels of coupling of precipitation and greenup with seasonal runoff dynamics			
High-elevation deciduous catchments	- higher P - lower T and potential ET - shorter growing season - shallower soil	Tighter	Less
Low-elevation deciduous catchments	- lower P - higher T and potential ET - longer growing season - deeper soil	Less	Tighter
Hypothesis II: Deciduous catchments will show tighter coupling between greenup (budburst) and seasonal runoff dynamics than evergreen catchments			
Deciduous broadleaf catchments	- similar topography - similar climate and soil - definite vegetation seasonality	NA	Tighter
Coniferous Evergreen catchments	- similar topography - similar climate and soil - leaves present year-round	NA	Less
Hypothesis III: Hillslope position will impart varying levels of coupling of precipitation and greenup with seasonal soil moisture dynamics			
Upslope topographic position	- less upslope subsidy - strong seasonality - xeric tree species	Tighter	Tighter
Downslope topographic position	- abundant upslope subsidy - relatively wet year-round - mesic tree species	Less	Less
<i>Note.</i> P, precipitation; T, temperature; ET, evapotranspiration.			

Miniat, 2019a, 2019b) (Table 2). These six reference deciduous catchments were undisturbed since 1920s, located at different combinations of elevation and aspects. Two coniferous evergreen catchments are located (WS01 and WS17) adjacent to two low-elevation deciduous catchments (WS02 and WS18), respectively, under paired catchment settings (Figure 1).

The climate is classified as a humid temperate region, where long-term mean annual temperature is 12.6°C at a base meteorological station (RG06; 685 m elevation; Figure 1). Precipitation is relatively evenly distributed throughout the year (Figure 2) with average annual precipitation of 1,870 mm at the base station, and 2,500 mm at 1,430 m (Laseter et al., 2012), about a 5% increase for every 100 m elevation increases (Swift et al., 1988). For example, WS27 (high-elevation deciduous) has about 23.4% more annual precipitation than the low-elevation catchments (Hwang et al., 2014), as well as lower temperature and subsequently lower potential ET (Miniat et al., 2017). On average, the high-elevation deciduous catchments have about a-month shorter growing season length than the low-elevation ones (Hwang, Song, Vose, & Band, 2011; Hwang, Song, Bolstad, & Band, 2011), while the evergreen catchments have leaves year round.

Typical southern Appalachian oak-hickory-pine community is dominant at low elevations in the study site with greater presence of tulip poplars downslope, while northern hardwood community types are dominant at high elevations (Hwang et al., 2020). The dominant canopy tree species at low elevations are *Quercus* spp. (oaks), *Acer rubrum* (red maple), *Liriodendron tulipifera* (yellow poplar), *Carya* spp. (hickory) and *Nyssa sylvatica* (black gum) (Day et al., 1988). Northern hardwood forests are dominated by *Acer saccharum* (sugar maple), *Betula alleghaniensis* (yellow birch), *Tilia heterophylla* (basswood) and *Aesculus flava* (yellow buckeye) (Day et al., 1988). *Pinus strobus* L. (white pine) was planted at WS17 and WS01 in 1956 and 1957, respectively, after

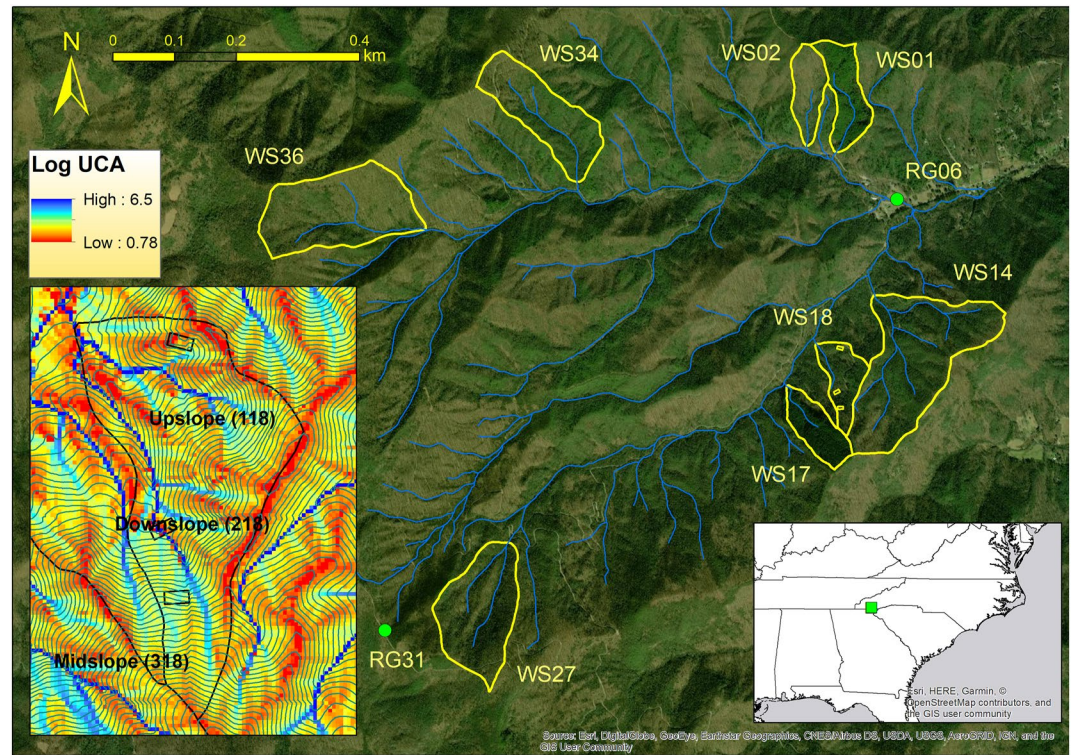


Figure 1. Eight study watersheds in the study site (Coweeta Hydrologic Lab., North Carolina, United States): six deciduous broadleaf (WS02, WS14, WS18—low elevation, WS34—middle elevation, and WS27, WS36—high elevation) and two coniferous evergreen (WS01 and WS17) catchments with a base (RG06) and a high-elevation climate station (RG31) (Table 2). Three soil moisture plots (upslope—118, midslope—318, and downslope—218) are located within WS18. A winter aerial image shows clear differences between deciduous and evergreen watersheds. Zoom-in map shows log-transformed upslope contributing area (UCA) with 5-m contour intervals, generated from 6.1-m (20-ft) LiDAR elevation data. See Table 2 for more information.

Table 2
Detailed Information on Study Watersheds, Climate Stations, and Soil Moisture Plots

Site ID	Elevation (m)	Topographic position	Explanation
WS01	832	Low-elevation S facing	Planted white pines in 1957 (evergreen coniferous)
WS02	856	Low-elevation S facing	Oak-hickory mixed hardwood forest, undisturbed since 1927 (deciduous broadleaf)
WS17	895	Low-elevation NW facing	Planted white pines in 1956 (evergreen coniferous)
WS14	878	Low-elevation NW facing	Oak-hickory mixed hardwood forest, undisturbed since 1927 (deciduous broadleaf)
WS18	823	Low-elevation NW facing	Oak-hickory mixed hardwood forest, undisturbed since 1927 (deciduous broadleaf)
WS27	1,256	High-elevation NE facing	Northern hardwood forest, undisturbed since 1927 (deciduous broadleaf)
WS34	1019	Mid-elevation SE facing	Oak-hickory mixed hardwood forest, undisturbed since 1927 (deciduous broadleaf)
WS36	1289	High-elevation SE facing	Northern hardwood forest, undisturbed since 1927 (deciduous broadleaf)
RG06	685	valley bottom	Long-term rain gauge at low (RG06) and high elevations (RG31) (Coweeta Research Data ID 1011)
RG31	1,363	ridge	
118	782	upslope	Terrestrial gradient soil moisture plots within WS18 (1999–2016) (Coweeta Research Data ID 1013)
318	865	midslope	
218	795	downslope	

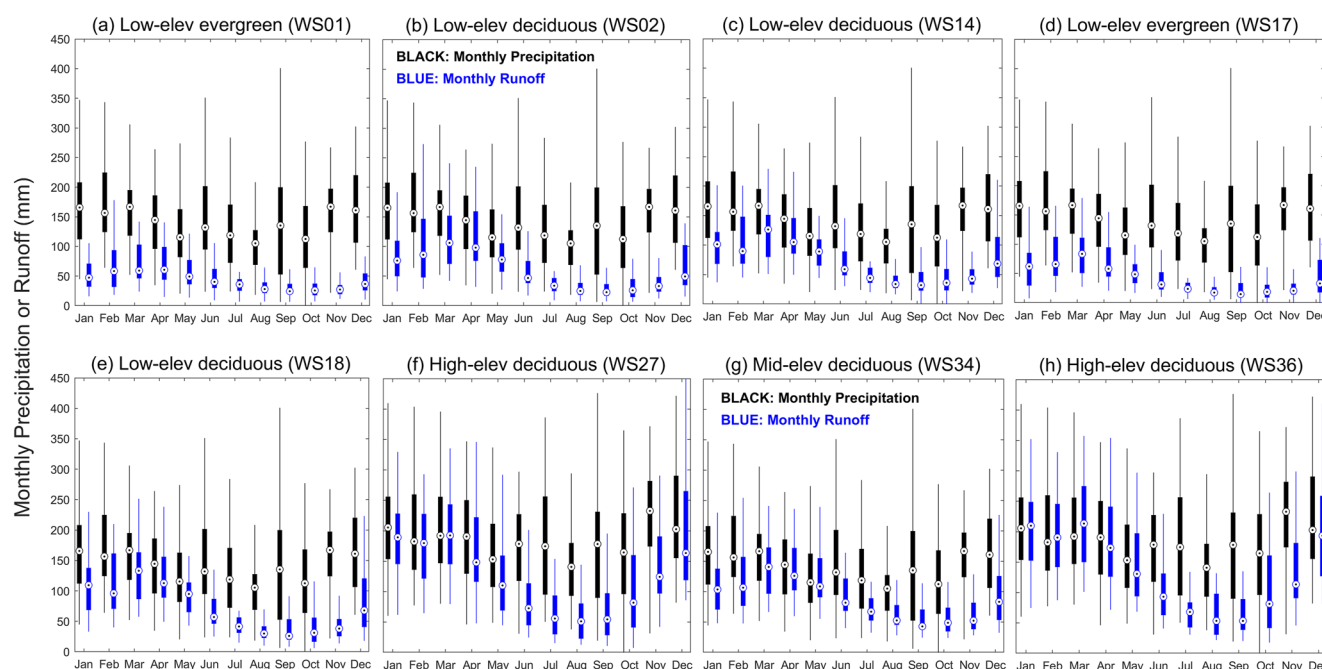


Figure 2. Boxplots of total monthly precipitation (black) and runoff generation (blue) for eight study catchments in the study site between 1982 and 2015. (a) WS01 and (d) WS17—low-elevation evergreen, (b) WS02, (c) WS14, and (e) WS18—low-elevation deciduous, (g) WS34—mid-elevation deciduous, and (f) WS27 and (h) WS36—high-elevation deciduous catchments. Note that low- and mid-elevation catchments share the same rain gauge at low elevation (RG06), while precipitation data for high elevation catchments were from the high-elevation rain gauge (RG31). Boxes have lines at the lower and upper quartiles and points at the medians, with the whiskers extended to 1.5 times the interquartile ranges. See Figure 1 and Table 2 for more information for the study watersheds and gauge locations.

about 15-year clear cut periods, with the closed canopy achieved in the early 1970s (Swank & Douglass, 1974). Soils are relatively uniform, described as coarse sandy loam Ultisols and Inceptisols, with typical colluvial materials in coves and more organic rich soils in ridge positions (Knoepp & Swank, 1998; Knoepp et al., 2018).

2.2. Long-Term Hydrologic Records

In addition to daily streamflow data from the eight study watersheds, we used long-term hydrologic records at the base (RG06) and high-elevation (RG31) climate stations (Miniat et al., 2017) and long-term daily volumetric soil water, measured at different landscape positions from ridge to valley bottom in WS18 (upslope, midslope, and downslope; Figure 1) (Coweeta LTER & Knoepp, 2019). Streamflow has been measured with either 90- or 120-degree notch weirs every five minutes. Rain gauges are tipping-bucket types, located at the open areas. Soil moisture data have been collected at four locations at two different depths (0–30 and 30–60 cm) of each plot using Time Domain Reflectometer (TDR) sensors (CS615 or CS616 Water Content Reflectometer, Campbell Scientific Inc., Logan, UT, USA) every 15 min (Table 2). The 60-cm measurements are roughly comparable with observed rooting depths at low elevations (Hales et al., 2009; Hwang et al., 2015).

2.3. Vegetation Phenology From Long-Term Remote Sensing Data

We use two sources of long-term remote sensing datasets to extract vegetation phenology at different scales. First, we use the MODerate-resolution Imaging Spectro-radiometer (MODIS) Normalized Difference Vegetation Index (NDVI) data (MOD13Q1) to derive fine-resolution (about 250 m) phenological information at the landscape scale, sufficient to resolve elevation differences between sites (Figure S1 in Supporting Information S1). We extracted the MODIS NDVI products since 2000 using a MODIS web service, provided by the Oak Ridge National Lab (ORNL, 2018). Original data were initially quality controlled using the pixel reliability parameter, post-processed, and linear interpolated into daily NDVI values. The composite day of the year variables were also retrieved to get exact acquisition dates during the composite periods. In our previous study (Hwang et al., 2014), we showed that the ground phenological observations (greenup, coloration, and abscission) at two walk-up towers

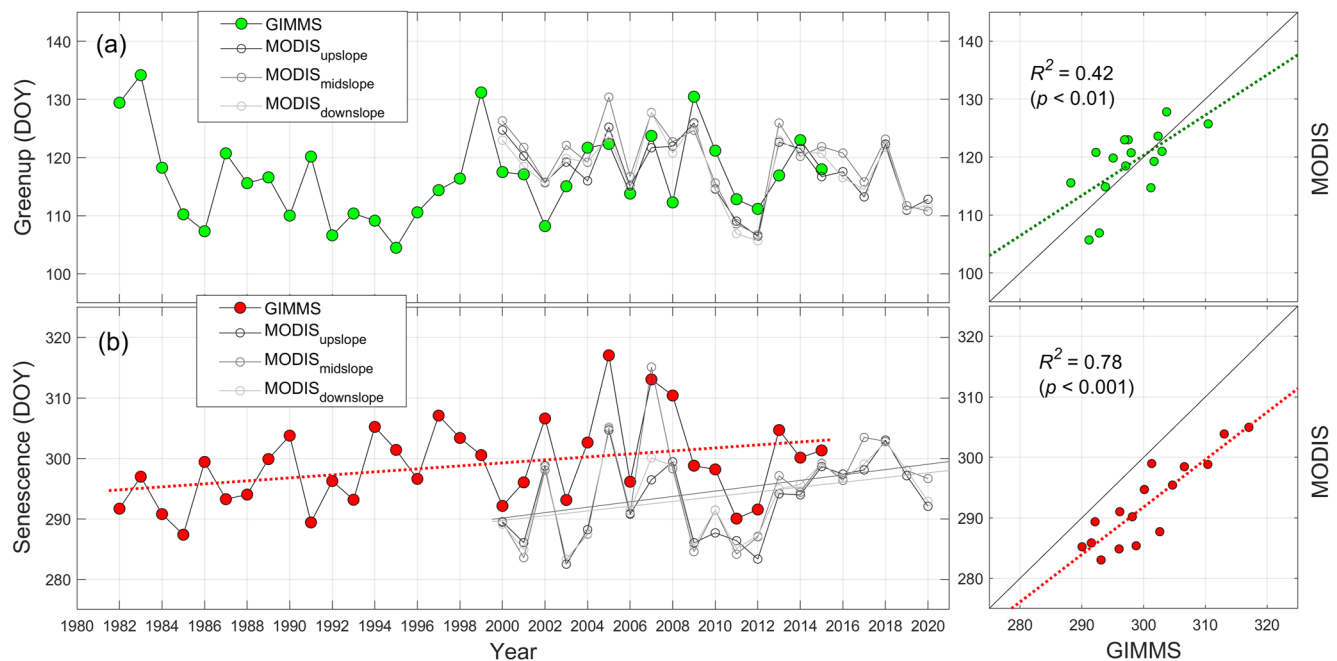


Figure 3. Leaf greenup (a: green, DOY) and senescence (b: red, DOY) from the time series of GIMMS and MODIS NDVI data at the study site (Figure S1 and S2 in Supporting Information S1). GIMMS-derived phenology values (filled) were from one 8-km pixel which includes most of the study site, while three lines of MODIS-derived phenology values (blank) were from three 250-m pixels which includes three soil moisture plots (upslope, midslope, and downslope; Table 2) within the low-elevation deciduous catchment (WS18; Figure 1). Trend lines are shown only when time series data show significant trends ($p < 0.1$) from the Mann-Kendall trend analyses. Scatter plots at the right panel show the correlations of GIMMS phenology (x-axes) with the means from the MODIS-derived ones (y-axes).

in the study site (Coweeta LTER & Bolstad, 2019) were well correlated with the MODIS-derived phenological products.

We also use the bi-monthly 8-km Global Inventory Modeling and Mapping Studies (GIMMS) NDVI3g (third generation) data (version 2), which span the period from July 1981 to December 2015 (Fensholt & Proud, 2012). GIMMS NDVI3g product was derived from a series of the Advanced Very High Resolution Radiometer (AVHRR) imagery by reducing the variation due to view geometry, sensor degradation, and volcanic activity (Tucker et al., 2005). We extract the time series of NDVI values from one (about 8-km) GIMMS pixel, which includes most of the study site (Figure S2 in Supporting Information S1) using *gimms* R software package (<https://cran.r-project.org/web/packages/gimms/>). It is important to note that the GIMMS-derived NDVI and vegetation phenology have limited ability to characterize landscape-scale phenology information due to its coarse spatial resolution. However, phenology patterns in complex terrain are usually dependent on topography. For example, greenup is delayed about a day with every 30-m elevation increase, often known as Hopkins' law (Hopkins, 1918). In our previous studies (Hwang, Song, Vose, & Band, 2011; Hwang et al., 2014), we also demonstrated that greenup in the study site showed predictable spatial patterns along the elevation gradient reflecting the dominant controls of temperature on the onset of spring. This means that the GIMMS NDVI at coarse resolution still provide reliable interannual anomalies especially in interannual greenup values.

Both MODIS and GIMMS NDVI datasets were post-filtered and fitted to multi-year NDVI values using a difference logistic function to get the mid-point NDVI value at each pixel (Hwang, Song, Vose, & Band, 2011; Hwang, Song, Bolstad, & Band, 2011). The timing of annual greenup and senescence timing were extracted from the intersections between mid-NDVI values (horizontal line) and linearly interpolated time-series NDVI values as DOY each year (White et al., 2009) (Figure 3; Figures S1 and S2 in Supporting Information S1). Annual anomalies in greenup and senescence are calculated as the difference between annual values and the long-term mean, such that a positive anomaly represents a later than the normal phenology dates (Figure 3). We also performed the Mann-Kendall tests for both greenup and senescence variables from MODIS and GIMMS NDVI dataset with a null hypothesis of trend absence. Note that growing season is defined as the periods between greenup and senescence each year in this study.

2.3.1. Timing of 50th Percentiles of Cumulative Daily Precipitation and Streamflow

Boxplots from monthly total precipitation and streamflow from the study catchments are shown in Figure 2. Monthly precipitation shows relatively uniform seasonal distributions with higher interannual variation in September at both low and high elevations (RG06 and RG31, respectively), probably due to occasional tropical storms (Laseter et al., 2012). However, there exists strong seasonality in the monthly streamflow records in all the catchments (Figure 2): the highest monthly water yield in February or March and the lowest in August or September. Earlier seasonal flow peaks were usually found in the high-elevation deciduous catchments (WS27 and WS36) than other low-elevation catchments, as well as higher water yield throughout the year.

To investigate the changes in timing of the spring seasonal peaks over the full time series, we calculated the timing of 50th percentiles of cumulative daily streamflow and precipitation as DOY (QD_{50} and PD_{50} hereinafter). These cumulative daily hydrologic records were calculated starting at the lowest flow period (mid-August; Figure 2), which makes seasonal patterns close to a unimodal normal distribution (Figure 4; Figure S3 in Supporting Information S1). In this study, the seasonal flow and soil moisture dynamics indicate the timing of seasonal peaks and lows from these normalized cumulative distributions. The cumulative distribution lines were normalized by total precipitation and streamflow amounts for each 1-year period to facilitate interannual comparison.

We related these yearly QD_{50} values with the PD_{50} and greenup anomalies using linear regressions both sequentially and simultaneously (multiple linear regression: $QD_{50} \sim 1 + PD_{50} + \text{greenup}$). In sequential linear regressions, we first applied linear regressions between PD_{50} and QD_{50} metrics at each watershed, and then their residuals were regressed with the greenup anomalies. Similarly, we also related these yearly QD_{50} values with the PD_{50} and previous-year senescence anomalies using both linear regressions. We also include an interaction term between PD_{50} and greenup metrics in the multiple regression analyses to examine possible rainfall-phenology interactions. We note the similarity of QD_{50} with a center of mass metric, usually used to extract snowmelt timing from daily streamflow data in the western US (Stewart et al., 2005). In this study, we use these QD_{50} values as a key indicator to separate net effect of greenup variability on seasonal flow regimes under the dominant precipitation controls.

To test the first hypothesis (H1), we compare the correlations of QD_{50} with PD_{50} and greenup variables between two groups: the low-to-mid elevation (WS02, WS14, WS18, and WS34) and the high-elevation (WS27 and WS36) catchments (Figure 1; Table 2). For the second hypothesis (H2), we explicitly compare the correlations between greenup and QD_{50} values between two adjacent paired catchments with different vegetation types: WS01 versus WS02 and WS17 versus WS18 (Figure 1). Considering that topography, climate, and soil conditions are similar in these paired catchments, we can attribute the apparent difference in the greenup- QD_{50} correlations mainly to different vegetation types: deciduous versus evergreen (Table 1) (Hewlett et al., 1969).

2.4. Timing of 50th Percentiles of Cumulative Soil Moisture Days

We applied a similar method to daily soil moisture measurements. However, there were two main differences mostly due to the nature of daily soil moisture (state variable), compared to daily precipitation and streamflow data (flux variables). In this respect, our use of a cumulative soil moisture metric is analogous to the use of growing degree days (GDD) in phenology models (e.g., Richardson et al., 2006). First, we applied a low pass filter (11-day moving average) to extract seasonal signals, suppressing noisy daily fluctuations. Second, we separately calculated cumulative soil moisture and saturation deficit days for both original soil moisture data and saturation deficit (depth below an approximate saturation), respectively. Deficit values were calculated from the difference between original soil moisture and multi-year maximum soil moisture values at each plot. The use of saturation deficit was to isolate the timing of seasonal lows timing prior to onsets of seasonal recharge.

To facilitate the comparisons between different daily time series data, we also calculated timing of 50th percentiles from the cumulative soil moisture days ($CSMD_{50}$ hereinafter) as DOY starting mid-August (same with PD_{50} and QD_{50}). We also calculated the timing of 50th percentiles from the cumulative saturation deficit days ($CSDD_{50}$ hereinafter) as DOY starting January 31st as a datum with approximately the highest moisture values of the year (Figure S5 in Supporting Information S1). The percentiles of cumulative daily precipitation were also calculated starting the January 31st (iPD_{50} hereinafter) when comparing $CSDD_{50}$ values. Because of maintenance issues in the soil moisture data, there were several missing years both in $CSMD_{50}$ and $CSDD_{50}$ values, when a few blank daily measurements lead to yearly missing values.

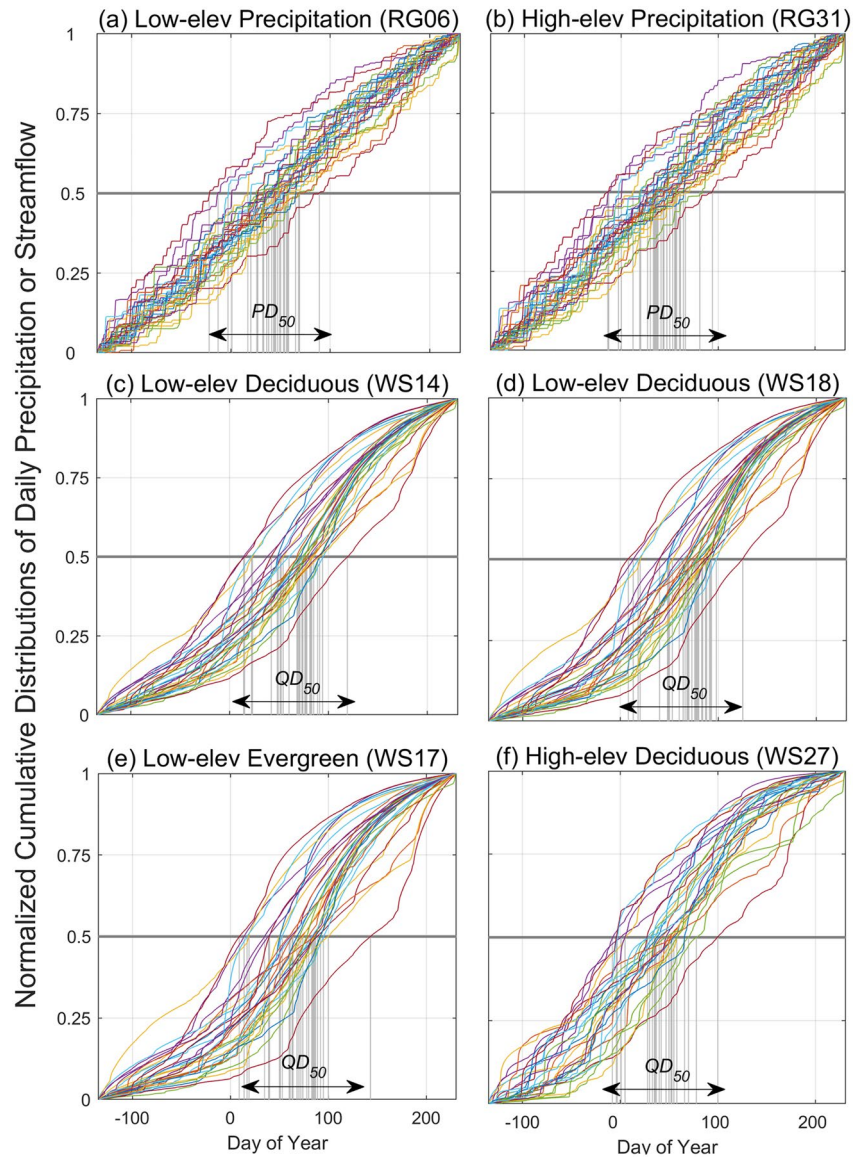


Figure 4. Normalized cumulative distributions for daily precipitation from (a) low-elevation (RG06) and (b) high-elevation (RG31), and daily streamflow from (c) and (d) low-elevation deciduous (WS14 and WS18), (e) low-elevation evergreen (WS17), and (f) high-elevation deciduous (WS27) catchments between 1982 and 2015. Daily values are cumulated starting August 16 each year when there is usually lowest water yield for most watersheds. Timings of 50th percentiles (PD_{50} and QD_{50}) are calculated as day of year, where each line meets with 0.5 horizontal lines. While precipitation values show typical uniform distributions throughout the most years, streamflow data exhibit normal distributions, where tangential slopes of the cumulative flow distributions are steepest around the 0.5 line (especially at low elevations). Different colored lines represent years between 1982 and 2015. Negative DOY values mean the previous calendar year. Similar graphs for other four study catchments (WS01, WS02, WS34, and WS36) are available in Figure S3 in Supporting Information S1. See Figure 1 and Table 2 for more information for the study watersheds and gauge locations.

To test the third hypothesis (H3), we related yearly $CSDD_{50}$ values (timing of summer lows as DOY) to iPD_{50} and MODIS-derived greenup variables along the hillslope gradient (downslope, midslope, and upslope) using both sequential and multiple linear regressions ($CSDD_{50} \sim 1 + iPD_{50} + \text{greenup}$). Similarly, the yearly $CSMD_{50}$ values (timing of spring peaks as DOY) were related to PD_{50} and MODIS-derived senescence variables at each soil moisture plot ($CSMD_{50} \sim 1 + PD_{50} + \text{senescence}$). Specifically, we examine how both seasonal soil moisture metrics ($CSDD_{50}$ and $CSMD_{50}$) are correlated to two phenology metrics (greenup and senescence) along the hillslope gradient. All yearly variables used in this study are summarized in Table 3.

Table 3
Summary of Yearly Variables Used in This Study

Symbols	Explanation	Meaning
PD_{50}	Timing of 50th percentiles of cumulative daily precipitation starting August 16	
QD_{50}	Timing of 50th percentiles of cumulative daily streamflow starting August 16	Spring streamflow peak day
$CSMD_{50}$	Timing of 50th percentiles of cumulative soil moisture days starting August 16	Seasonal soil moisture peak day
iPD_{50}	Timing of 50th percentiles of cumulative daily precipitation starting January 31	
$CSDD_{50}$	Timing of 50th percentiles of cumulative saturation deficit days starting January 31	Seasonal soil moisture low day

Note. All units are day of year.

3. Results

3.1. Vegetation Phenology From MODIS and GIMMS NDVI

Time-series of MODIS and GIMMS NDVI values demonstrate that the adopted methods effectively captured greenup and senescence timing of the deciduous forest in the study site (Figures S1 and S2 in Supporting Information S1), when NDVI values show steep increases or decreases, respectively (White et al., 2009). The summer and winter NDVI ranges show typical values for deciduous forests in this region (Hwang, Song, Bolstad, & Band, 2011) with filtered NDVI values largely deviating from the normal trajectories of typical seasonal patterns. Summer NDVI values were much more stable in MODIS than GIMMS probably due to improved cloud filtering and sensor stability (Huete et al., 2002). Sudden decreases of NDVI values during the winter periods are mostly driven by occasional snowfall in the study site, while those during the summer by frequent cloud contaminations.

Greenup and senescence timings center around April and October, respectively, where both show about a-month interannual variations (Figure 3). Only senescence shows significant long-term delayed trends ($p < 0.1$) both in GIMMS and MODIS (midslope and downslope). Inter-comparisons between the MODIS- and GIMMS-derived greenup and senescence values show very similar year-to-year variations during the overlapping period (2000–2015) despite some shifts (Figure 3), where R^2 values are 0.42 and 0.78 for greenup and senescence, respectively. This might be attributed to the differences in the spatial scales (about 250-m vs. 8-km) and band designations (red and near-infrared) between MODIS and AVHRR sensors. However, this still indicates that the GIMMS NDVI time series can provide reliable interannual anomalies in long-term greenup and senescence patterns at the watershed scale.

3.1.1. 50th Percentiles of Daily Cumulative Precipitation and Streamflow

Daily precipitation data show typical uniform distributions (close to straight lines) in most years (Figure 4), indicating relatively evenly distributed precipitation seasonal patterns throughout the year with several years exhibiting either substantially high proportions of either early or late annual precipitation. For the study period, PD_{50} ranged from DOY 343 to DOY 89 at the low elevation (RG06) and from DOY 351 to DOY 94 at the high elevation (RG31). Years with early PD_{50} values are related to occasional heavy rainfalls around September due to tropical storms (Figure 2) (e.g., Hurricanes Frances and Ivan in 2004). However, daily streamflow data show typical normal distributions with much smoother lines than cumulative daily precipitation (Figure 4; Figure S3 in Supporting Information S1), which exhibit the steepest increases in cumulative functions around the 50th percentile lines. These seasonal patterns are much clearer in the low-elevation catchments, compared to the high-elevation. This suggests that the 50th percentile metrics were able to effectively capture seasonal (springtime) peak timing in streamflow. Most QD_{50} values are scattered around mid-February to March at the low-elevation catchments while earlier at high elevations (WS36 and WS27), which is consistent with long-term monthly seasonal streamflow patterns (Figure 2).

In all study catchments, QD_{50} increased linearly with PD_{50} values ($p < 1 \times 10^{-5}$) with slope values close to one in both sequential (Figure 5; Figure S4 in Supporting Information S1) and multiple regressions (Table 4). These correlations are more statistically significant (higher R^2 values) at the north-facing catchments (WS14, WS17, WS18, and WS27; Figure 5), compared to the south-facing ones (WS01, WS02, WS34, and WS36; Figure S4 in

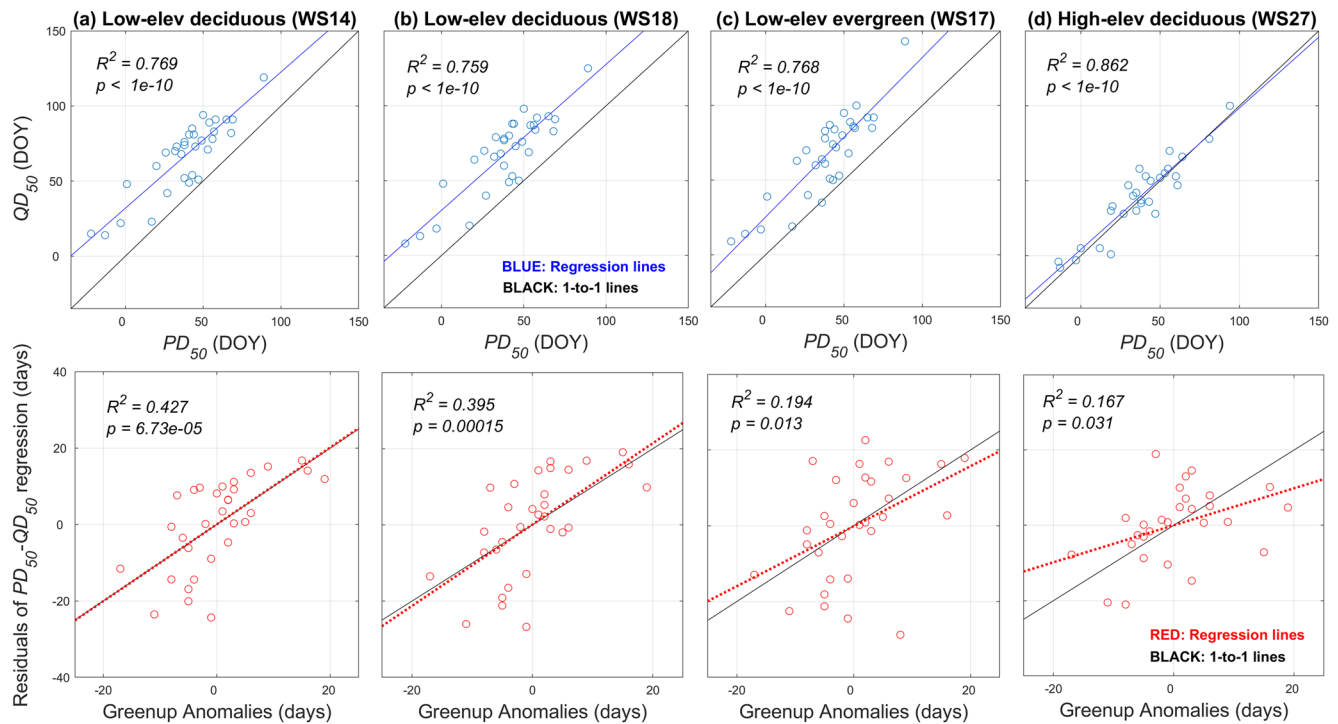


Figure 5. Linear regressions between the timings of 50th percentiles of cumulative daily precipitation (PD_{50}) and streamflow (QD_{50}) (upper panel), and between greenup anomalies and residuals of PD_{50} - QD_{50} linear regressions (lower panel) at (a) and (b) low-elevation deciduous (WS14 and WS18), (c) low-elevation evergreen (WS17), and (d) high-elevation deciduous (WS27) catchments. See Figures 3 and 4 for more information how to calculate greenup and PD_{50} / QD_{50} timing, respectively. Solid lines represent 1-to-1 lines. More information of all variables is available in Table 3. Similar graphs for other four study catchments (WS01, WS02, WS34, and WS36) are available in Figure S4 in Supporting Information S1.

Table 4
Coefficient Estimates and R^2 Values From Multiple Linear Regressions for the Timing of 50th Percentile of Cumulative Daily Streamflow (QD_{50}) With That of Cumulative Daily Precipitation (PD_{50}) and Greenup Anomalies ($QD_{50} \sim 1 + PD_{50} + \text{Greenup}$) at the Eight Study Catchments (Figure 1; Table 2)

	Intercept	PD_{50}	Greenup anomalies	R^2
Low- to mid-elevation deciduous catchments				
WS02	43.4*	0.987***	1.28***	0.806***
WS14	30.1**	0.948***	1.03***	0.855***
WS18	27.4*	1.01***	1.09***	0.839***
WS34	42.6**	0.880***	1.22***	0.810***
High-elevation deciduous catchments				
WS27	7.96	0.967***	0.505*	0.874***
WS36	12.1	0.915***	0.772**	0.811***
Low-elevation evergreen catchments				
WS01	38.4	0.982***	1.04*	0.687***
WS17	29.4	1.10***	0.810*	0.795***

Note. Greenup anomalies were calculated from the GIMMS NDVI data (Figure 3; Figure S2 in Supporting Information S1). P values are from t -stats (coefficients) and F -stats (R^2). Detailed explanations of all variables are available in Table 2. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Supporting Information S1). The residuals of the linear regression between PD_{50} and QD_{50} (variability of seasonal flow dynamics which cannot be explained by precipitation) show significant positive relationships with the greenup anomalies at all study catchments ($p < 0.05$; Figure 5; Figure S4 in Supporting Information S1). However, these correlations are more statistically significant (higher R^2 values) at the south-facing catchments (WS01, WS02, WS34, and WS36; Figure S4 in Supporting Information S1), compared to the north-facing ones (WS14, WS17, WS18, and WS27; Figure 5). The greenup anomalies also hold statistical significance (t -stat $p < 0.05$) in multiple linear regression models for QD_{50} (F -stat $p < 1 \times 10^{-5}$) at all the study watersheds under the dominant precipitation control (PD_{50} ; t -stat $p < 1 \times 10^{-5}$) (Table 4). No significant relationship was found for both the previous-year leaf senescence anomalies and interaction terms between the PD_{50} and greenup anomalies in all study catchments. This indicates that in years with early greenup, there were earlier seasonal streamflow peaks than expected based on precipitation across all the study catchments.

However, these correlations show distinct patterns along the elevation gradient, as well as between deciduous and evergreen vegetation types. First, QD_{50} values are aligned much more closely along the one-to-one lines at high elevations (WS27 and WS36; Figure 5; Figure S4 in Supporting Information S1), while delayed about a month compared to PD_{50} values at the other catchments (i.e., positive intercepts). These intercept values are statistically significant ($p < 0.05$) only at low- and mid-elevation deciduous catchments (WS02, WS14, WS18, and WS34) in the multiple regressions (Table 4). Second, each day of early greenup usually leads to about 1-day early QD_{50} values at both in

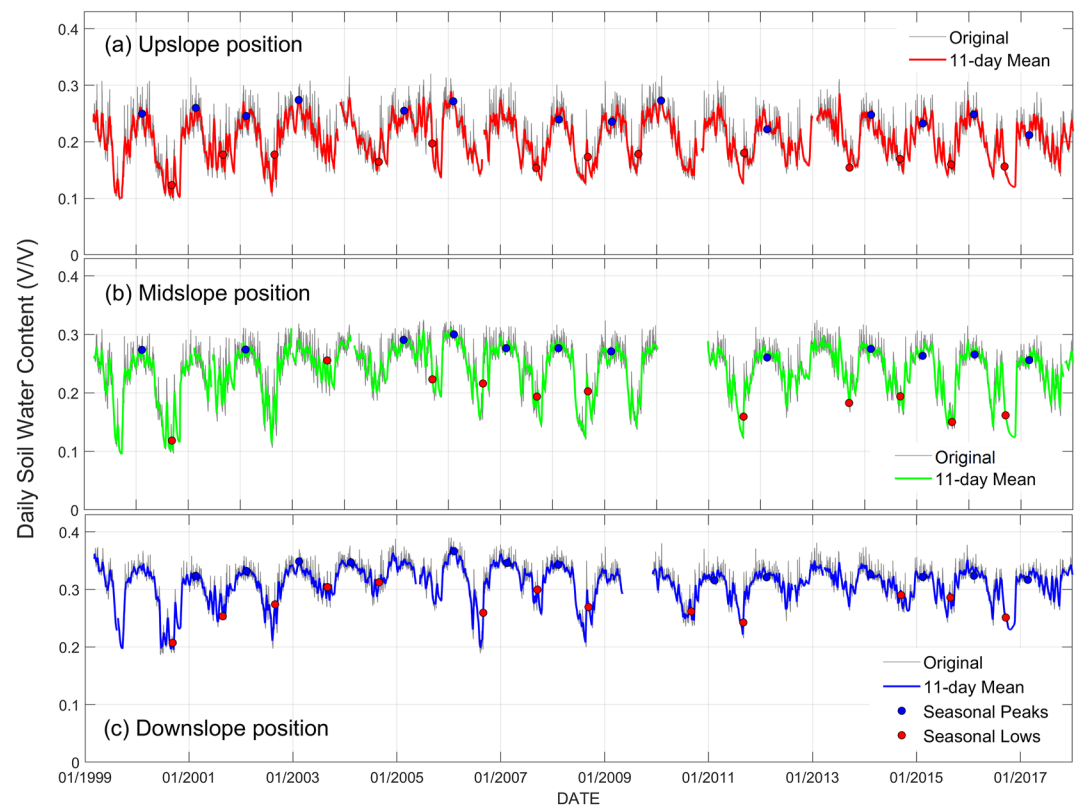


Figure 6. Time series of original (gray lines) and 11-day moving average (colored lines) daily soil moisture at (a) upslope (118), (b) midslope (318), and (c) downslope (218) topographic positions within the low-elevation deciduous catchment (WS18). Blue and red dots are $CSMD_{50}$ and $CSDD_{50}$ each year, respectively, which represent the timings of 1 seasonal peaks and lows (Table 3). See Figure S6 in Supporting Information S1 to see how the $CSMD_{50}$ and $CSDD_{50}$ variables are calculated from cumulative distributions of daily soil moisture and saturation deficit values, respectively. Geographical locations and more information of these sites are available in Figure 1 and Table 2.

sequential and multiple regressions at low- and mid-elevation deciduous catchments ($p < 0.0005$). However, the greenup anomalies show much reduced responses with less significant levels ($p < 0.05$) at high elevations (WS27 and WS36) in both regressions. These results suggest that we accept H1 that topoclimate will impart varying levels of coupling of precipitation and greenup with seasonal runoff dynamics.

The distinct correlations between the greenup anomalies and QD_{50} values can be also observed between the paired deciduous and evergreen catchments (WS01 vs. WS02 and WS17 vs. WS18). Although these two pairs showed similar 1-month lag-correlations between PD_{50} and QD_{50} values (Figure 5; Figure S4 in Supporting Information S1; Table 4), the greenup anomalies show much less significance levels at two evergreen catchments ($p < 0.05$; WS01 and WS17) compared to their deciduous pairs ($p < 0.0005$; WS02 and WS18). These different levels of correlations between greenup and seasonal flow dynamics (QD_{50}) can be attributed mainly to the different vegetation types: deciduous broadleaf versus coniferous evergreen forests. These results suggest we accept H2 that deciduous catchments will show tighter coupling between greenup and seasonal runoff dynamics than evergreen catchments.

3.1.1.1. 50th Percentiles of Cumulative Precipitation and Soil Moisture

Soil moisture values at the three topographic positions within WS18 reached annual minimums during the growing season but showed interannual variability in the timing and magnitudes of these minima (Figure 6; Figure S5 in Supporting Information S1). In contrast, soil moisture increased at the end of each growing season and reached fairly consistent peaks typically around December and remained wet throughout the dormant season (Figure S5 in Supporting Information S1). This results in much less interannual variations in $CSMD_{50}$ values (Figure 6; Figure S6 in Supporting Information S1), compared to PD_{50} and QD_{50} values. The timing of soil moisture peaks after each growing season was well-coupled with precipitation seasonal patterns, such that $CSMD_{50}$ values

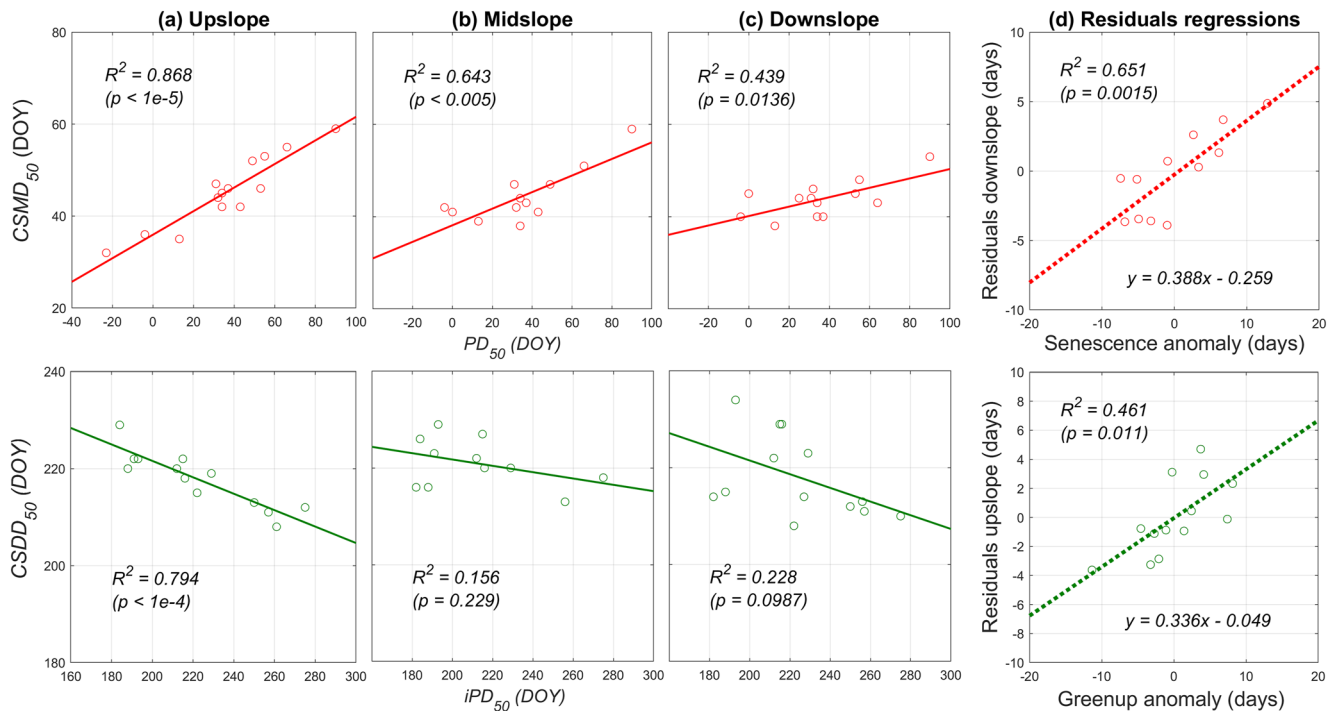


Figure 7. Linear regressions between timings of 50th percentiles of cumulative daily precipitation (PD_{50}) and soil moisture ($CSMD_{50}$) (upper panel), and between timings of 50th percentiles of cumulative daily precipitation (iPD_{50}) and soil moisture deficit ($CSDD_{50}$) (lower panel) at (a) upslope (118), (b) midslope (318), and (c) downslope (218) within the low-elevation deciduous catchment (WS18; Figure 1). Graphs at the right column (d) represent the linear regressions between senescence and the residuals of the PD_{50} - $CSMD_{50}$ regression at downslope (218) (upper panel), and between greenup and the residuals of the iPD_{50} - $CSDD_{50}$ regression at upslope (118) (lower panel). Negative DOY values mean the previous calendar year. Note that starting days of cumulative calculations are different between PD_{50} (August 15) and iPD_{50} (January 31). See Figures 3, 4 and 6 for the details for greenup/senescence, PD_{50} , and $CSMD_{50}$ / $CSDD_{50}$ timing, respectively. Detailed explanations of all variables are available in Table 3.

increased linearly with PD_{50} in most sites although they are patterned along the landscape positions (Figure 7). In the upslope position, the correlation between PD_{50} and $CSMD_{50}$ was the strongest with the steepest slope ($p < 1 \times 10^{-5}$), indicating tight coupling between seasonal precipitation and soil moisture recharge patterns. However, these correlations get progressively weaker at midslope ($p < 0.005$) and downslope ($p < 0.05$) positions, indicating less coupling than upslope.

We could not find any significant relationship between the residuals of the linear PD_{50} - $CSMD_{50}$ regressions and the plot-scale senescence anomalies from MODIS NDVI at midslope and upslope topographic positions (Table S1 in Supporting Information S1). Thus, for most of the basin, fall soil moisture recharge is not affected by timing of leaf senescence but is primarily driven by the timing of precipitation. The exception to this is the downslope topographic position, where years with later senescence resulted in later seasonal soil moisture recharge than those expected from precipitation. After accounting for PD_{50} , much of the residual variability in $CSMD_{50}$ was explained by timing of leaf senescence at the downslope position ($p < 0.005$; Figure 7d). Similarly, both PD_{50} and senescence variables showed statistical significance with $CSMD_{50}$ in a multiple linear regression ($p < 0.005$) only at downslope (Table S1 in Supporting Information S1).

Meanwhile, $CSDD_{50}$ was negatively correlated with the 50th percentiles of the cumulative daily precipitation (iPD_{50}) over the same period (Figure 7). This indicates that earlier seasonal precipitation often correlates with later dry-down of soil moisture. Similar to PD_{50} and $CSMD_{50}$, they also showed the highest significance upslope (118; $p < 1 \times 10^{-4}$), compared to the midslope (318; $p > 0.05$) and downslope (218; $p > 0.05$) positions (Figure 7). Interestingly, we found a significant relationship of the residuals of the iPD_{50} and $CSDD_{50}$ regression with the MODIS greenup anomalies only at upslope ($p = 0.011$; Figure 7d). Similarly, both iPD_{50} and greenup variables exhibited statistical significance for $CSDD_{50}$ in a multiple linear regression only at upslope ($p < 0.01$; Table S2 in Supporting Information S1). This indicates that years with earlier greenup experienced earlier seasonal soil moisture dry-down than expected solely from precipitation only at the upslope topographic position. These

results suggest that we accept H3 that hillslope position will impart varying levels of coupling of precipitation and greenup with seasonal soil moisture dynamics.

4. Discussion

4.1. Topoclimate Modulates Coupling of Precipitation and Greenup With Seasonal Runoff Dynamics (H1)

In this study, we characterized the timing of seasonal streamflow peaks around springtime using the 50th percentiles of the cumulative daily streamflow (QD_{50}) and precipitation data (PD_{50}) from 34-year hydrologic records in the southern Appalachians. Then, we compared seasonal streamflow and precipitation timing in six deciduous and two evergreen headwater catchments along an elevation gradient. Cumulative daily streamflow over a year showed typical normal distributions, while those of daily precipitation displayed uniform distributions in most years (Figure 4). This asynchrony between seasonal precipitation and flow dynamics effectively represents lagged responses of ET seasonality. However, these normal distribution patterns of the cumulative daily streamflow better manifested in the low- and mid-elevation catchments, compared to the high-elevation. Meanwhile, there were significant linear correlations between PD_{50} and QD_{50} at all study watersheds (Figure 5; Figure S4 in Supporting Information S1), where regression slopes are close to one (Table 4). This demonstrates a dominant precipitation control on seasonal streamflow peaks across all the study catchments. However, we found about 1-month lag-correlations between PD_{50} and QD_{50} only at low elevations. This suggests tighter coupling between seasonal patterns of precipitation and runoff generation at high elevations and a stronger ET control at low elevations.

The differences in PD_{50} - QD_{50} relations along the elevation gradient may be explained by decreased storage capacity due to shallow soils at high elevations in the study site, where Hewlett and Hibbert (1967) reported quick stormflow responses. Additionally, higher potential ET, longer growing seasons and lower precipitation at low elevations (Hwang, Song, Vose, & Band, 2011; Hwang et al., 2014) result in lower antecedent soil moisture and groundwater conditions given precipitation, compared to high elevations. This eventually leads to less tight coupling between seasonal precipitation and flow patterns due to the combined antecedent soil moisture controls on stormflow generation with gross precipitation (Scaife & Band, 2017). Similarly, we found the tighter PD_{50} - QD_{50} coupling at the north-facing catchments, compared the south-facing ones, which suggests stronger ET controls at the south-facing catchments. Previous studies also found that topoclimate variations in the study site led to very different ET and water storage estimates between the low- and high-elevation catchments (Hwang et al., 2014; Nippgen et al., 2016). Specifically, Nippgen et al. (2016) also reported roughly 1-month lag-correlations between monthly precipitation and runoff ratios across five catchments in the study site, very similar to the delayed responses of QD_{50} to PD_{50} in this study. They also reported that these lag-correlations were less prominent at a high-elevation catchment (WS36), explained by stronger memory (storage) effect on runoff behavior at the low-elevation catchments along the topoclimate gradient.

Greenup anomalies showed the most significant correlation with the residuals of PD_{50} - QD_{50} regressions ($p < 0.0005$) at four low-to-mid elevation deciduous catchments (Figure 5; Figure S4 in Supporting Information S1). The multiple linear regression also indicates that 1-day early greenup led to about 1-day early spring flow peaks (QD_{50}) after accounting the dominant effect of seasonal precipitation patterns (PD_{50}) (Table 4). However, the greenup anomalies show much less significant correlations ($p < 0.05$) at the two high-elevation deciduous catchments. This generally implies a secondary control of greenup on spring streamflow peaks through the accelerated onset of ET around greenup, the variability which is not explained by seasonal precipitation patterns. However, this effect is suppressed by less memory (storage) effect due to the relatively wet conditions, low ET demand (due to low temperature and shorter growing seasons), and shallow soils at high elevations.

4.2. Deciduous Catchments Show Tighter Coupling Between Greenup and Seasonal Runoff Dynamics than Evergreen (H2)

While there exist similar lag correlations between seasonal precipitation and runoff dynamics (PD_{50} and QD_{50}) at the paired deciduous and evergreen catchments (Figure 5; Figure S4 in Supporting Information S1; Table 4), greenup anomalies showed much less significant influence on spring flow peaks (QD_{50}) at the two evergreen catchments compared to the paired deciduous ones, respectively. We note that the long-term remotely sensed phenology signals were largely from deciduous forests which occupy most forested landscapes in the study site

(Figure 1) as evergreen white pines in WS01 and WS17 have much less definite leaf seasonality than the deciduous trees (Vose & Swank, 1990; Vose et al., 1994). Less definite leaf seasonality might also result in the lower seasonal differences (amplitudes) in its monthly runoff values between summer and winter seasons, compared to the paired deciduous catchments (Figure 2). This might lead to the less significant correlations between the greenup and spring peak timings at two evergreen catchments.

However, warmer spring temperature than usual alone (in years with early greenup at the adjacent deciduous catchments) could lead to early onsets of ET at the evergreen catchments. However, the warm temperature signal would be amplified by accompanying early greenup onsets in the adjacent deciduous forests. Recently, Moon et al. (2020) showed that the decreases in Bowen ratios before and after springtime phenology were about three times greater in deciduous broadleaf than evergreen needleleaf forests using *AmeriFlux* tower data. This suggests that the effect of warm spring on the accelerated onset of ET and subsequent streamflow declines can be amplified by ecophysiological responses (such as early greenup) especially in deciduous forests, compared to evergreen ones.

In this study, we could not find any significant relations between leaf senescence and seasonal flow peaks at the watershed scale. Frequent drought stress toward the end of growing season easily decouples shallow soil moisture dynamics with leaf senescence timing. Soil moisture dynamics downslope showed tight coupling of the recharge timing ($CSMD_{50}$) with leaf senescence, likely to be hydrologically connected to riparian zones and stream channels throughout the year (Jencso & McGlynn, 2011; Jencso et al., 2009). However, when scaled up to the entire watershed, this soil moisture signal coupled with leaf senescence might weaken due to a relatively small proportion of downslope positions. This suggests that later senescence does not necessarily correspond with more ET and later recharge at the watershed scale, contrary to earlier greenup. Previous studies in southern Appalachians also showed that severe droughts toward the end of growing season resulted in early senescence for drought deciduous trees especially at low elevations (Gunderson et al., 2012; Warren et al., 2011; Wulschleger & Hanson, 2006), which might effectively desynchronize emergent leaf, soil moisture, and flow seasonality especially toward the end of growing season (Hwang et al., 2014; Kim et al., 2018).

4.3. Hillslope Modulates Coupling of Precipitation and Greenup With Seasonal Soil Moisture Dynamics (H3)

We found significant correlations of $CSMD_{50}$ (seasonal soil moisture peaks timing) and $CSDD_{50}$ (seasonal lows timing) with PD_{50} and iPD_{50} , respectively. $CSMD_{50}$ values generally exhibit more significant correlations with the 50th precipitation percentiles than $CSDD_{50}$ across the landscapes. This suggests the dominant precipitation controls on plot-scale soil moisture seasonality, especially recharge onset of the shallow soils after the growing season. Precipitation usually infiltrates shallow soils first, which remain above or near field capacity throughout the dormant season without active transpiration uptake (Figure 6). More significant correlations at the upslope positions indicate tighter coupling between the seasonal precipitation and soil moisture patterns in general (Figure 7), compared to mid- and downslope. This decoupling between seasonal precipitation and soil moisture patterns at mid- and downslope positions might be due to active upslope subsidy to downslope topographic positions especially during springtime (Hawthorne & Miniati, 2018; Hwang et al., 2012), which may be more related to the total amount of precipitation than its seasonal pattern.

Apparent phenological controls on seasonal soil moisture dynamics were patterned along the hillslope gradient. Greenup anomalies from the 250-m MODIS NDVI data were positively correlated with the residuals of the linear regression between iPD_{50} and $CSDD_{50}$ only at upslope, consistent with the multiple linear regression (Table S2 in Supporting Information S1). This indicates that greenup provides a secondary explanation for the timing of seasonal soil moisture low, the variability which is not explained by seasonal precipitation patterns. However, we could not find similar phenological controls on $CSDD_{50}$ at mid- and downslope positions. This also might be attributed to significant upslope subsidy to the downslope topographic position, which usually remains relatively wet throughout the year (Figure S5 in Supporting Information S1) despite high leaf/sapwood area and transpiration rates (Ford et al., 2011; Hwang et al., 2020). Upslope subsidy to downslope may be linked to less tight coupling between seasonal precipitation and soil moisture dynamics downslope. This suggests that steep increases in canopy conductance and ET due to early greenup result in early soil dry-down upslope, while soil moisture downslope is still replenished by upslope subsidy (Hawthorne & Miniati, 2018).

Similarly, leaf senescence anomalies from the 250-m MODIS NDVI data were positively correlated with the residuals of the linear regression between PD_{50} and $CSMD_{50}$ only at the downslope topographic position (Figure 7d),

also consistent with the multiple regression analysis (Table S1 in Supporting Information S1). This indicates that senescence provides a secondary explanation for the timing of seasonal soil moisture peak, the variability which is not explained by seasonal precipitation patterns. We did not find similar senescence controls on $CSMD_{50}$ at mid- and upslope positions. Conditions of low soil moisture are common at the upslope plot especially toward the end of growing season (Figure 6a) which contributes to reductions in transpiration, but not early leaf cessation (Ford et al., 2011; Hwang et al., 2020). A large proportion of upslope tree species (mostly oaks) are well suited to cope with frequent soil moisture stress through hydraulic traits including xylem anatomy and stomatal behavior (Hwang et al., 2017). Thus, under moderate water stress conditions, late senescence upslope may only result in a small contribution to total growing season ET. This may help to explain the decoupling between soil recharge timing ($CSMD_{50}$) and senescence at the upslope and midslope positions.

In contrast, sap flux measurements confirm that trees downslope can maintain consistent transpiration at the end of growing season even during moderate droughts (Ford et al., 2011; Hwang et al., 2020). This further indicates that the downslope regions are relatively resilient to moderate droughts and buffer catchment responses to drought in terms of evapotranspiration. Hawthorne and Miniati (2018) reported that shallow soils remained consistently wetter downslope (218) than upslope at the end of growing season even in moderately dry years due to high nighttime recharge rates. Furthermore, there are more drought deciduous tree species (*Acer rubrum*, *Liriodendron tulipifera* and *Nyssa sylvatica*, etc.) downslope compared to upslope (Hwang et al., 2020), suggesting that remotely sensed phenology may be better able to identify drought effect on ET in downslope locations. Only under severe drought conditions, early senescence downslope is expected (Hwang et al., 2014) when upslope subsidy is too low to support high transpiration rates downslope. Relatively wet soil condition and greater presence of drought deciduous trees downslope may lead to tight coupling between leaf senescence and soil recharge timing ($CSMD_{50}$).

5. Conclusions

In this study, we identify the secondary control of greenup variability on spring flow peak and soil moisture dry-down under the dominant precipitation controls. This demonstrates that strong dependency of seasonal flow and soil moisture regimes on precipitation is mediated by vegetation seasonality, especially by greenup variability, and that these correlations were modulated by elevation, vegetation types and hillslope positions.

For the three posted hypotheses (Table 1).

1. Topoclimate modulates the coupling of precipitation and greenup with seasonal runoff dynamics. Specifically, the greenup controls on spring flow peaks are mitigated by shallow soils and wet conditions (low saturation deficits) at high elevations, where there exists a tight coupling between seasonal precipitation and runoff dynamics.
2. Given climate and soil conditions, deciduous catchments show tighter coupling between greenup and seasonal runoff dynamics than evergreen ones. This suggests that the accelerated onset of ET and subsequent streamflow declines in spring can be amplified by accompanying greenup (budburst) in deciduous forests.
3. Hillslope position modulates coupling of precipitation and greenup with seasonal soil moisture dynamics. Specifically, early greenup leads to early soil moisture dry-down only at the upslope topographic position, where seasonal soil moisture dynamics are tightly coupled with precipitation.

This is the first study examining how both seasonal flow and soil moisture patterns vary with interannual greenup in snow-free regions as modulated locally by topoclimate and hillslope gradients and vegetation type. Our findings also highlight the need to incorporate the dependency of seasonal flow regime on vegetation phenology to develop long- and short-term water management plans in this region.

Data Availability Statement

Long-term daily streamflow, soil moisture, and field phenology data are publicly available on the Environmental Data Initiative Archive. (WS18: <https://doi.org/10.6073/pasta/be7e01d7c339220d948aef54e982443f>, WS27: <https://doi.org/10.6073/pasta/75fc67212f315c52cfe14b29627315df>, soil moisture: <https://doi.org/10.6073/pasta/94e5a3203dc10ce1497813191a3e9f25>, and phenology: <https://doi.org/10.6073/pasta/cb73d325a7c89e32d050d1d11c3e4aac>). Long-term daily rain gauge data are publicly available the Research Data Archive in USDA

Forest Service (<https://www.fs.usda.gov/rds/archive/catalog/RDS-2017-0031>). MODIS NDVI data are publicly available on Oak Ridge National Lab, Web Service (https://modis.ornl.gov/data/modis_webservice.html). GIMMS NDVI data available through *R gimms* software package (<https://cran.r-project.org/web/packages/gimms/gimms.pdf>). Daily streamflow data for WS01, WS02, WS14, WS17, WS34, and WS36 are now undergoing the submission process for publication at Research Data Archive of the Forest Service.

Acknowledgments

This research was supported by the Brain Pool program from the National Research Foundation of Korea (NRF) (Grant: 2021H1D3A2A01042250) to Yonsei University. H. Kang is also grateful to ME (2022003640002) and NRF (2020M1A5A1110494). Long-term datasets were collected by the USDA Forest Service Southern Research Station, and the National Science Foundation (NSF) awards, DEB-0218001, DEB-0823293, DEB-1226983, DEB-1440485, DEB-1637522 from the Long-Term Ecological Research (LTER) Program to the Coweeta LTER. Any opinions, findings, conclusions, or recommendations expressed in the material are those of the authors and do not necessarily reflect the views of the USDA or NRF of South Korea.

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