# Environmental controls on the terrestrial water cycle in forested mountain ecosystems.

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# Abstract

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Water is a key resource to natural ecosystems and human societies alike, and the water cycle is fundamentally linked to the climate and the characteristics of catchments. However, the challenges posed by environmental change makes it imperative to understand how the water cycle is affected by biotic and abiotic factors, in particular, in areas that are crucial sources of water like forested headwater catchments. Therefore, this doctoral dissertation aims to advance the knowledge on the dynamics between climate, vegetation and landscape that determine the water balance of forested mountain ecosystems. This document presents five chapters, an introductory chapter, three standalone scientific manuscripts and a concluding chapter. The research follows the common theme of evaporation controls, going from long-term and large scales, to the study of daily variations and the forest stand scale, showing the critical importance of scale on studying the relationships between forests, climate and the water balance.

The first manuscript tests the assumption of stability in reference catchments of classic US experimental catchments by investigating stability in long-term hydroclimatology records. Two methods are used: trend and break-point analyses, and a Budyko-based energy model to quantify the sensitivity of partitioning to changes in precipitation, potential evaporation and catchment properties. Several catchments presented instability in the partitioning of precipitation, yet most were hydrologically stable. Lower stability was linked to larger changes in the catchment characteristics, than to the changes in long-term precipitation and potential evaporation. This research is relevant to improve paired catchment studies and for understanding fundamental questions about the dynamics between long-term climate variables, climate controls, seasonality, and vegetation dynamics. The second investigation studies the precipitation partitioning controls in the central Appalachian mountain regions (US). The Budyko framework was applied to study the relative importance of overall climate regimes, partial correlation analysis and multivariate regressions were used to find the principal partitioning controls. Mean annual temperature and fraction of precipitation falling in the form of snow exerted a higher influence on partitioning than landscape controls (e.g. forest cover, Normalized Difference Vegetation Index, slope). Moreover, the study found that partitioning controls are scale dependent and could differ between basins in the same climate region, especially in a complex, mountainous topography setting. The third investigation quantified the degree to which the sap velocities of two dominant broadleaved species (*Acer saccharum* L. (sugar maple) and *Quercus velutina* Lam. (black oak)) in the central Appalachian mountain region, responded to ambient and experimentally altered soil moisture conditions using a throughfall displacement experiment. Also, future climates under two emissions scenarios were used to predict hypothetical forest evapotranspiration rates. Sap velocity in maples was higher and had a more plastic response to vapor pressure deficit than sap velocity in oaks. Increased vapor pressure deficits could increase transpiration, and potentially reduce the water available to the heavily populated areas downstream. This dissertation highlights the importance of studying ecohydrological processes at different temporal and spatial scales, as they reveal the complexity of tree-soil-water-atmosphere relationships.

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I could not have achieved this arduous goal without the help of supporting, kind and motivating people that I had by my side during five years at WVU. I will briefly mention some of them, probably missing someone, even if a whole chapter could be devoted to recognizing their help.

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**List of Abbreviations**

| | |
|---|---|
| °C | Degree Celsius |
| AIC | Akaike Information Criteria |
| ASD | Average Storm Depth |
| CTI | Compound Topographic Index |
| DI | Dryness Index |
| E | Evaporation |
| EI | Evaporative Index |
| Ep / PE | Potential Evaporation |
| EV | Explained Variance |
| FSNOW | Fraction of Precipitation Falling as Snow |
| GCM | Global Circulation Model |
| LOS | Length of the Growing Season |
| MAMS | Maximum Accumulation Monthly Surplus |
| MAP | Mean Annual Precipitation |
| MAT | Mean Annual Temperature |
| n | Budyko's n |
| NDVI | Normalized Difference Vegetation Index |
| NOAA | National Oceanic and Atmospheric Administration |
| P | Precipitation |
| PS | Phase shift of the seasonal cycle |
| Q | Runoff |
| RCP | Representative Concentration Pathway |
| RD | Redundant Variance |
| RI | Relative Importance |
| SAR | Storm Arrival Rate |
| SD | Standard deviation |
| SEAS | Relative amplitude of the seasonal cycle |
| SM | Soil Moisture |
| SSI | Seasonal Surplus Index |
| Sv | Sap velocity |
| T | Transpiration |
| USDA FS | United States Department of Agriculture Forest Service |
| VPD | Vapor Pressure Deficit |
| VWC | Volumetric Water Content |

# Chapter 1 Introduction

The water cycle is the process in which water molecules circulate between different water storages (e.g. the atmosphere, the land and the oceans), through different processes (e.g. precipitation, evaporation, runoff). Understanding and assessing the water cycle is a key question for water resources sciences (Oki, 2006). The water cycle has suffered important modification due to human activities (Abbott et al., 2019), and is predicted to be increasingly affected by climate change (Huntington, 2006). Warming of the atmosphere can increase evaporation intensifying the water cycle (Katul & Novick, 2009), that can lead to greater instances of flooding and droughts that can affect societies and ecosystems. Consequently, special focus should be given to water towers (Viviroli et al., 2007): i.e. high elevation regions that provide water to larger surrounding areas. A prime example is the heavily forested central Appalachian mountains, constituting the headwaters to important rivers across the eastern US. This doctoral dissertation centers on the study of the evaporative processes that occur in forested headwater catchments and seeks to advance forest hydrology, as well as, the knowledge on the ecohydrological processes dominant in the headwaters and forest of the central Appalachian mountains.

The water balance of headwater catchments, described by the long-term water inputs (precipitation) minus the water outputs (runoff and evaporation) is a crucial concept to water management (Brooks et al., 2012) and to explain vegetation’s geographic distribution (Stephenson, 1990). The water balance is affected by two main climatic factors: precipitation (and its characteristics, e.g. the form, magnitude, intensity and seasonality) and potential evaporation, or in other words, the atmospheric water demand. The seasonal dynamics of precipitation and potential evaporation create conditions of water surplus or scarcity, that are modulated by landscape conditions (e.g. soils, topography). Land cover is also influential to the water balance as it affects evaporation (Zhang et al., 2001), which represents the part of the precipitation that will not reach streams or fill aquifers since it is partitioned back into the atmosphere through phase change.

Evaporation over land includes transpiration, i.e. the release and evaporation of water that is stored in soils through the plant’s stomata. Transpiration is also important since it is one of the Earth’s main energy transformation processes (Budyko, 1974), converting, through photosynthesis, solar energy into glucose which sustains terrestrial life and create the terrestrial carbon (C) sinks in biomass and soil organic C, ultimately contributing to balancing the Earth’s climate (Asbjornsen et al., 2011; Berry et al., 2006; Ellison et al., 2017).  The relationships between forests water use and runoff is studied ucan be studiedwith hydrologic models (e.g. Budyko, 1974; L. Zhang et al., 2004); land cover experiments, as the pair catchment design (Andréassian, 2004; Bosch & Hewlett, 1982; Brown et al., 2005); measuring pan evaporation (Katul & Novick, 2009), estimation of water vapor fluxes (Williams et al., 2012); sapflow methods (Poyatos et al., 2020) or lysimeters (Teuling, 2018).

Due to the critical role that forest play in partitioning precipitation into either runoff or evaporation, studying the effects of atmospheric warming on forest ecosystem and hydrological processes is even more important to fill current knowledge gaps and uncertainty around evaporation's future (Fisher et al., 2017). Moreover, devoting resources to study the water cycle dynamics and its relation to forests has practical importance for several reasons. First, comprehending the controlling factors of the water balance allows for improved assessments of climate and land use change impacts on water resources. Second, advancing the state of knowledge on forest-water dynamics can inform the hydrological community on what variables and processes should be considered to improve climate and ecological models. Finally, more information, at the appropriate scales, can serve land managers to better decision making.

Therefore, the aim of this dissertation is to advance the knowledge on the dynamics between climate, vegetation and landscape that determine the water balance of forested mountain ecosystems. Three main research questions guided my investigation:

a) Are long-term reference catchments in the US hydrologically stable and how sensitive are precipitation partitioning processes to long-term changes in potential evaporation, precipitation and catchment characteristics?

b) What are important precipitation partitioning controls in the central Appalachian mountains that are dominated by broadleaf temperate forests?

c) What controls tree-scale sap velocity and transpiration of two common tree species in central Appalachia?

Studying the controls of the terrestrial water cycle on mountain ecosystems is a complex task that calls for a variety of theoretical frameworks and methods. In order to select the appropriate investigative approach, not only the research questions and objectives should be taken into account, but also the spatial and temporal scale of the study should be considered (Asbjornsen et al., 2011). In this investigation, two main approaches were used to answer the three main research questions that had large distinctions in temporal and spatial scales. First, the Budyko framework (Budyko, 1974) was applied to study ecohydrological dynamic at either long-term time scales or intra-regional scales. Secondly, an empirical field based approach was used to study the tree-soil-atmosphere dynamics that determined transpiration at small scales and within one vegetative growing season.

The Budyko framework consists on a simple energy balance model in which long-term evaporation is a function of three components precipitation, potential evaporation and the characteristics of the particular watershed where evaporation is occurring (Budyko, 1974; Sposito, 2017). Despite its simplicity, the prediction potential of the Budyko framework has made it well known to the hydrological community. They have applied it to understand how the three components influence the partitioning of precipitation (Donohue et al., 2012; Padrón et al., 2017), how terrestrials controls, particularly, vegetation influence partitioning (Donohue et al., 2007; Zhang et al., 2017), and, another important application has been the attribution and/or the sensitivity to changes in water yield to either climatic or landscape changes (Patterson et al., 2013; Roderick et al., 2014; Wang & Hejazi, 2011; Young et al., 2019). I used the Budyko framework in two different ways: to study temporal changes and to contrast spatial differences. The first application focused on the changes in precipitation partitioning in reference catchments that have been monitored for long periods of time. The stability of reference catchments is imperative to their use as a baseline of hydrologic behavior when they are compared to experimental catchments where treatments have modified their land cover. The second application was to understand what factors (e.g. climate, vegetation, LULC) are more important at catchments that belong to different basins in the central Appalachian mountain region.

An empirical approach was used to study how tree sap velocity, soil moisture and atmospheric conditions were associated at the forest stand and plot level during one vegetative growing season. The temporal resolution for the analysis was the daily rates, while the measurements in the field occurred at even shorter durations. The ecological study was designed around a throughfall exclusion experiment that purposively aimed at simulating drought conditions. The empirical information obtained in the field was analyzed with the help of different statistical procedures and mathematical models that aided in determining patterns and correlations. The evidence allowed to advance the knowledge about the sap velocity rates of common tree species in the central Appalachian mountains.

A short description of each chapter in the dissertation is presented below, chapters 2 - 4 represent three standalone scientific manuscripts, and chapter 5 summarizes the main conclusion of the dissertation and provides future research directions.

**Dissertation organization**

Chapter 2 is an inquiry on the hydrologic stability of reference catchments in the US. The study scale in this chapter is represented by small experimental catchments, but their distribution is across the contiguous US and Puerto Rico. The main outcomes of the study are insights into the dynamics of precipitation partitioning in catchments that have low human disturbance. This study is scientifically relevant given that statistical relationships at experimental pair catchment studies assume that the reference catchments do not experience important changes in their partitioning, an assumption that could lead to erroneous conclusions.

Chapter 3 determines the most important precipitation partitioning controls in the central Appalachian mountain region. This regional study uses gridded long-term datasets from climate reanalysis, land cover, vegetation and topography to determine what are the most influential factors to evaporation in a set of relatively undisturbed catchments. We used catchments from 5 different basins draining from the central Appalachian mountains (Potomac, Monongahela, Ohio, Kanawha and Tennessee) which provide important water resources to surrounding lowlands and metropolitan areas. We show the importance of taking an intraregional approach to understanding the most important controls of the water balance and highlight the influence of the eastern continental divide in determining precipitation partitioning in the region.

Chapter 4 looks at sapflow rates of *Acer saccharum* and *Quercus velutina*, two common tree species in the central Appalachian region. The study was empirical and set at the forest stand scale, and we look at the tree - atmosphere – soil interactions during a year of abundant precipitation (2018). We investigate the sensitivity of sap velocity to variations in vapor pressure deficit and soil moisture. Moreover, we contrasted the differences of sap velocity rates between tree species and modeled how such difference could influence transpiration within future scenarios of climate change and future species abundance.

Chapter 5 summarizes the main conclusions from the three investigations presented in chapters 2-4 and presents future research directions stemming from their discussions.

# Chapter 2 Hydrologic stability in reference catchments.

Formatted for Hydrological Processes as Guillén, L.A. and Zegre, N.P. *Hydrologic stability of long-term headwater reference catchments in experimental forests across the U.S.*

**Abstract**

Reference catchments are experimental catchments where direct human activities have been reduced or completely eliminated and serve as a baseline to understand the effects of change (land use, climate) on hydrology in pair catchment studies. Such long-term catchment studies have contributed greatly to the advancement of hydrology since the first half of the twentieth century. A key assumption of reference catchments is that they are hydrologically stable: i.e. hydrological processes and the partitioning of precipitation into runoff and evaporation are stationary. Yet, first order controls such as climate and land cover properties are dynamic over time and potentially undermine the efficacy of this widely applied assumption. We test this assumption in reference catchments of classic US experimental catchments, by investigating stability in long-term hydroclimatologic records using trend and break-point analyses, and a Budyko-based energy model to quantify the sensitivity of partitioning to changes in precipitation, potential evaporation and catchment properties. We also identify which climate controls contribute to changes in the partitioning processes across the diverse geographies and climates represented in our sample. We found that several catchments presented instability in partitioning, even if most reference catchments are hydrologically stable. Lower stability was more linked to larger changes in the catchment characteristics, than to changes in long-term precipitation and potential evaporation. Providing insight into the hydrologic instability of reference catchment is important for paired catchment studies and for understanding fundamental questions about the relationships between long-term climate variables, climate controls, seasonality, and vegetation dynamics.

**Keywords**: Budyko framework, evaporative index, hydrological processes, experimental catchments, disturbance, pair-watershed design.

### 2.1. Introduction

Experimental catchments play a critical role in understanding how precipitation (P) is partitioned into runoff (Q) and evaporation (E) and are key to furthering the knowledge about catchment scale water cycle and hydrology (Tetzlaff et al. 2017). Many long-term experimental catchment studies include a reference catchment (RC), or “control” catchment, that serves as a baseline from which to compare changes in nearby “treatment” catchments due to experimental disturbance (e.g., forest harvesting) (Amatya et al. 2016; Zegre et al. 2010). This experimental design, known as the pair catchment approach (Bosch and Hewlett 1982), consists on establishing statistical relationships between two or more small catchments with similar size, climate, topography and land cover (Andréassian 2004). Paired catchment studies have provided unparalleled insight about the catchment water balance, hydrologic processes, and the hydrological effects of management and land cover disturbance (Bosch and Hewlett 1982; Brown et al. 2005; Hornbeck et al. 1993; Andréassian 2004). In theory, the RC is used to account for the effects of climate variability imposed on both catchments (Zegre et al. 2010). A critical and long-standing assumption is that reference catchments and their statistical relationship to treatment catchments, are hydrologically stable. Notwithstanding, first order controls on water balance partitioning (e.g. climate, land cover) are known to be dynamic over time (Berghuijs et al. 2017; Caldwell et al. 2016; Donohue, Roderick, and McVicar 2007; Gudmundsson, Greve, and Seneviratne 2016; Young et al. 2019). Despite the use of the RCs since the first paired catchment study in the US, Wagon Wheel Gap, Colorado in 1910 (Bates, 1921 in Zegre et al. 2010), hydrologic stability is nearly always assumed. Yet the question "Are RCs hydrologically stable?" largely remains unanswered (Andréassian 2004; Andréassian, Parent, and Michel 2003). Here, we explore this question by analyzing precipitation partitioning characteristics for ten US classic long-term reference catchments.

While forested RCs are, by design, absent of experimental disturbance during the study period, they can be subjected to natural disturbances that create forest change, such as insect outbreaks, wildfires, hurricanes, droughts (e.g. Rodman et al. 2019; Negron and Cain 2019; Yeakley et al. 2003), which can alter rainfall-runoff relationships (see e.g. Mirus et al. 2017 and references within). Furthermore, stability can be affected by climate change and legacy disturbances that define the trajectory of forest productivity, composition, structure, and age (Amatya et al. 2016; Creed et al. 2014; Jones et al. 2012; Jones 2011). Although, these disturbances might be considered marginal, progressive changes in partitioning could result in large departures from stability, conflating Type I and Type II errors and confidence in change detection (Zegre et al. 2010).

Changes in a catchment's P partitioning are understood as changes in the long-term evaporative index (EI=E/P) (Figure 2.1). Hence, a modification in P partitioning between two time periods occurs only when the ratio between the difference in E and the difference in P is not equal to the EI from the initial period calibration (Equation 1a). Changes in the magnitudes of P and E can still occur, but if they are proportional, P partitioning could be considered in a steady state (Equation 1b). Hydrologic stability can be equated to hydrologic resilience, i.e. the capacity of a catchment to be elastic to changes, adapting to them but always returning to the initial state (in our case the average partition of P into Q and E) (Creed et al. 2014).

Change in P partitioning: $\frac{\Delta E}{\Delta P} \neq EI$ (Equation 1a)

Steady state $\frac{\Delta E}{\Delta P} = EI$ (Equation 1b)

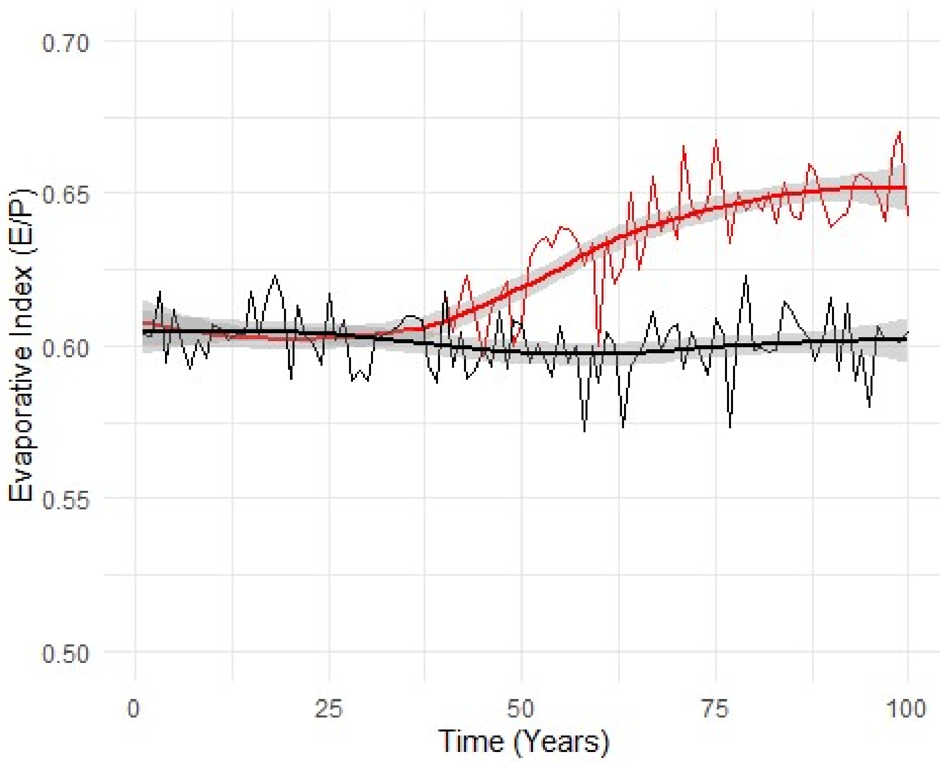


*Figure 2.1 Theoretical change in reference catchment hydrologic stability: A reference catchment's evaporative index has annual variations, yet over time it is stable (black lines). Climate and landscape changes could modify a reference catchment's evaporative index has annual variations, yet over time it is stable (black lines). Climate and landscape changes could modify a reference catchment's evaporative index creating a new steady state (red lines).*

Although studying P partitioning in RC is complex, given the variety of climatic and ecological characteristics, and record length, previous authors have initiated the discussion on P partitioning in RC. Namely, Jones et al. (2012) focused on the influence of climate change on Q, concluding that ecosystem and human influence mediate the effects of climate change on Q by either masking, exacerbating, mimicking or counteracting them. Vadeboncoeur et al. (2018) found that E in several undisturbed catchments in the eastern US have distinct trends of change which are dependent on a latitudinal gradient, and Creed et al. (2014) determined that forest type influences water yield resilience to changes between warm and cold periods across RC in North America. Despite this critical literature, a research gap on the hydrologic stability of long-term RC is still present.

Consequently, we aim to assess the hydrologic stability of headwater catchments that are undisturbed by human activities through three objectives: i) determine the hydrologic stability of classic RC in the US; ii) evaluate the sensitivity of partitioning to changes in P, Ep and catchments characteristics utilizing the Budyko framework, a simple water and energy balance model; and iii) discuss possible drivers of change within climate controls. Our research contributes to the discussion on controls over long-term hydrological processes and underlines the importance of continuing long-term experimental catchment studies.

### 2.2. Methods

#### 2.2.1. Study sites and data.

We selected a set of long-term RC across the US to represent different climates and ecosystems (Figure 2.2), from needle evergreen forests on the Pacific coast to tropical mountain forests in Puerto Rico. A list of the selected RC and their general characteristics of the catchments are summarized in Table 2.1, and more information can be found in e.g. Amatya et al. (2016) and Sun et al. (2011). The catchments form part of the USDA Forest Service Experimental Forests Network and data is available at the Climate and Hydrology Database CLIMDB/HYDRODB [*https://climhy.lternet.edu/*] and experimental sites data bases (see Data Availability Statement). Data on daily discharge and/or Q, P and temperature (T) were downloaded from the aforementioned databases, transformed and pre-processed to obtain annual time series according to water years. The USGS water year was used when we did not have information available about a water year period that was more appropriate to close the water balance (Table 2.1). We used the longest available shared record of P, Q and T for each individual RC. Thus, each RC presents a different record length and starting year. Temperature data was used to calculate potential evaporation (Ep) using the Priestly-Taylor equation (Priestley and Taylor 1972). Short data gaps (< 5 days) were filled using splines; longer data gaps of temperature data were filled by estimating values through linear regression between RC weather station and nearby weather stations.

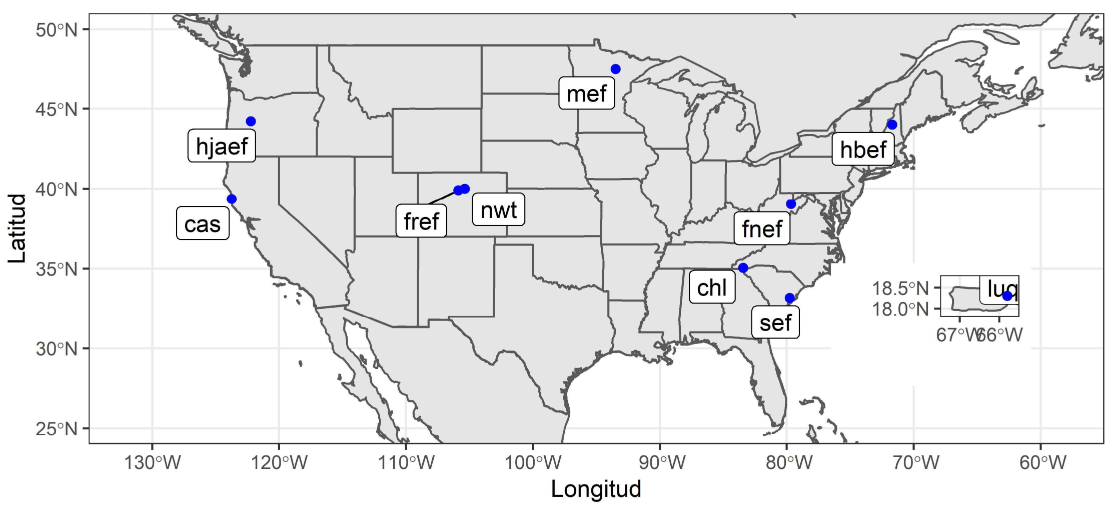


*Figure 2.2 Location of the reference catchments used in this study.*

*Table 2.1 Reference catchments included. Modified from Amatya et al. (2016), Jones et al. (2012), Harris et al. (2012).*

| Reference catchment | Watershed id | State | Ecosystem | Area (ha) | Elevation range (masl) | Slope (%) | Time period | Record length (years) |
|---|---|---|---|---|---|---|---|---|
| Caspar creek experimental forest (CAS) | North Fork | CA | Needle evergreen forest | 473 | 30-322 | 49 | 1964-2004 | 41 |
| Coweeta hydrologic laboratory (CHL) | WS18 | NC | Mixed broadleaf deciduous forest | 12.5 | 726-993 | 52 | 1945-2018 | 74 |
| Fernow experimental forest (FNEF) | WS4 | WV | Mixed broadleaf deciduous forest | 38.7 | 670-866 | 20 | 1953-2013 | 61 |
| Fraser experimental forest (FREF) | East St Louis | CO | Needle evergreen forest | 803 | 2907-3719 | 16 | 1977-2005 | 29 |
| Hubbard Brook experimental forest (HBEF) | WS3 | NH | Mixed broadleaf deciduous and needle leaf evergreen forest | 42.4 | 527-732 | 21 | 1959-2014 | 56 |
| HJ Andrews experimental forest (HJAEF) | WS02 | CA | Needle evergreen forest | 61 | 572-1079 | 41 | 1959-2017 | 59 |
| Luquillo experimental forest (LUQ) | Río Espíritu Santo | PR | Tropical evergreen broadleaf forest | 2333 | (150-1075) | 10-20 | 1976-2011 | 36 |
| Marcell experimental forest (MEF) | S2 | MN | Mixed broadleaf deciduous and needle leaf evergreen forest | 9.7 | 420-430 | 3 | 1962-2006 | 45 |
| Niwot ridge LTER (NWT) | Upper Green Lakes | CO | Alpine tundra | 225 | 3515-4084 | - | 1982-2013 | 32 |
| Santee experimental forest (SEF) | WS80 | SC | Mixed needle leaf evergreen and broadleaf deciduous forest | 160 | 3.7-10 | <3 | 1969-1980 | 12 |

### 2.2.2. Trend analysis

We started the analysis of the water balance time series by looking for trends. We carried out the non-parametric Mann-Kendall test for each hydrologic variable at each RC. Next, we calculated their Sen's slope in order to find out the magnitude of change in the variables that could have monotonic trends. We used the Pettit Test (Pettitt 1979), the Buishand U and Range tests (Buishand 1982, 1984) to find possible breaking points in each of the reference catchments EI and dryness index (DI) (DI = Ep/P) The information obtained from the breaking point analysis was used to determine the first and second time periods used in the Budyko analysis. The breaking point year would determine the last year of the first period. If a reference catchment had no conclusive breaking points in their EI, the time series was divided into two periods of equal or approximately equal length.

A p-value < 0.05 was considered significant in our statistical analysis. We used the programming language *R* (R Core Team 2019) to carry out the analysis. Specifically, we used the packages *tidyverse* (Wickham et al. 2019) for data management and visualization, *trend* (Pohlert 2018) for statistical analysis, and *EcoHydRology* (Fuka et al. 2018) to estimate Ep.

### 2.2.3. Budyko Analysis

The Budyko framework (Budyko 1974) is a well-known theory used to study the dynamics of P partitioning, building on how energy and water availability determine P partitioning over the long-term in a catchment. Budyko (1974) looked at the relationship between EI and the DI and found that over long time periods EI is mainly driven by DI, but also conditioned by the catchment's characteristics, described as a partitioning parameter *n* (Table 2.2) (Choudhury 1999). The aforementioned relationship has several mathematical derivations (e.g. Fu 1981; Pike 1964; Sposito 2017; Turc 1954; Zhang, Dawes, and Walker 2001). The framework is visually represented as the Budyko curve (Figure 2.3) which is given by EI, DI and *n*. A catchment's Budyko curve is bounded by two asymptotes representing the theoretical limits of water (E cannot be higher than P) and energy (E cannot be higher than Ep) that exist in the ecosystem. Budyko's partitioning parameter are associated with catchment characteristics such as vegetation and soils (Donohue, Roderick, and McVicar 2007, 2012) and specific climate characteristics (e.g. fraction of P falling as snow, seasonality, storminess) (Padrón et al. 2017; Williams et al. 2012). The Budyko framework has been useful to several studies related to P partitioning in experimental catchments (Creed et al. 2014; Jones et al. 2012; Vadeboncoeur et al. 2018; Young et al. 2019). For our inquiry, the Budyko framework is useful as it theorizes that changes in partitioning processes would be represented by a change in the partitioning parameter *n*, visualized as a new Budyko curve. Hence, studying changes in Budyko's *n* serves as proxy to understanding hydrologic stability.

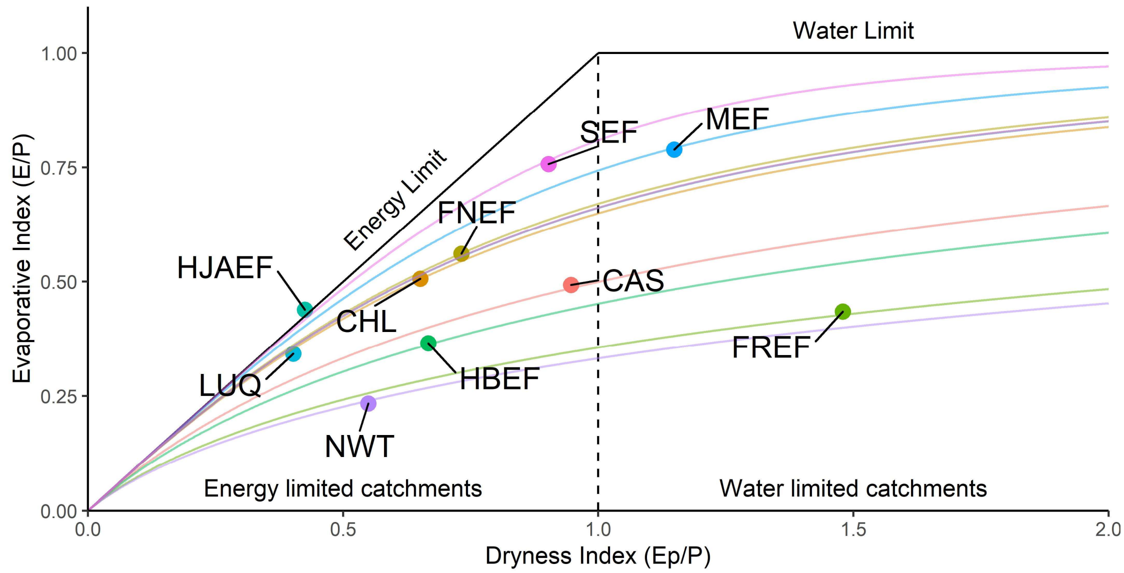


*Figure 2.3 Reference catchments of the US and Budyko curves based on their n value plotted in the Budyko Framework. The evaporative index is a function of dryness index and theoretical limits are given by water and energy availability; as in natural catchments under long periods, evaporation cannot be higher than precipitation (horizontal line), nor can it exceed the atmospheric water demand or potential evaporation (identity line).*

We followed the sensitivity analysis developed by Roderick and Farquhar (2011) to understand how changes in either P, Ep or *n* are reflected in E for each catchment. A comprehensive explanation of the framework is found in their original work and the equations used in this analysis are presented in Table 2.2. First, we calibrated Budyko's *n* based on the long-term P, Ep and E using the R package *rootSolve* (Soetaert and Herman 2009). Next, we calculated the changes in E using the partial differentials for P, Ep and *n* (Roderick and Farquhar 2011). Then, we computed sensitivity coefficients indicating the degree of influence that a relative change in either P, Ep or *n* have on modifying  partitioning. Further, we utilized the observed changes in P and Ep to estimate the E difference (dE) between the time periods determined in the trend analysis. These differences are used to make two estimations of E for the second period (E2 = E1 + dE). In the first, E calculated (Ec) is estimated with the assumption that the RC are in steady state and therefore, *n* does not experience change, i.e. dn= 0. In the second, E is calculated for a non-steady system (Ec'), in which we utilize the difference between the *n* parameter calibrated for each time period. Both E estimations were then compared to the observed change in E between periods, allowing to contrast assumptions of hydrologic stability to observed changes. According to the framework, relative changes in E can be attributed to a combination of the relative changes in P, Ep, *n*, whose effect on E is given by the multiplication of the sensitivity coefficients and the relative change in the variables.

*Table 2.2 Budyko framework and sensitivity analysis equations (Roderick and Farquhar 2011).*

| Equations |
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| | |
|---|---|
| Budyko equation for E estimation (Choudhury 1999) | $E = \frac{PEp}{[P^n + Ep^n]^{\frac{1}{n}}}$ |
| Partial differentials of E with respect to P | $\frac{\delta E}{\delta P} = \frac{E}{P}(\frac{Ep^n}{P^n + Ep^n})$ |
| Partial differential of E with respect to Ep | $\frac{\delta E}{\delta Ep} = \frac{E}{Ep}(\frac{P^n}{P^n + Ep^n})$ |
| Partial differential of E with respect to *n* | $\frac{\delta E}{\delta n} = \frac{E}{n}(\frac{ln(P^n + Ep^n)}{n} - \frac{(P^n lnP + Ep^n lnEp)}{P^n + Ep^n})$ |
| Sensitivity of E to changes in P | $S_{\frac{dP}{P}} = \frac{P}{E}\frac{\delta E}{\delta P}$ |
| Sensitivity of E to changes in Ep | $S_{\frac{dEp}{Ep}} = \frac{Ep}{E}\frac{\delta E}{\delta Ep}$ |
| Sensitivity of E to changes in *n* | $S_{\frac{dn}{n}} = \frac{n}{E}\frac{\delta E}{\delta n}$ |
| E change in steady state | $dEc = \frac{\delta E}{\delta P}dP + \frac{\delta E}{\delta Ep}dEp + 0$ |
| E change in non-steady state | $dEc' = \frac{\delta E}{\delta P}dP + \frac{\delta E}{\delta Ep}dEp + \frac{\delta E}{\delta n}dn$ |
| Relative effect of dP on dE | $P_{effect} = S_{\frac{dP}{P}}\frac{dP}{P}$ |
| Relative effect of dEp on dE | $Ep_{effect} = S_{\frac{dEp}{Ep}}\frac{dEp}{Ep}$ |
| Relative effect of dEp on dE | $n_{effect} = S_{\frac{dn}{n}}\frac{dn}{n}$ |

In order to exemplify our framework, we have artificially created two time series of annual water balance for two catchments: defined as “stable” and “unstable”. Hypothetical results of the hydrologic stability framework are visualized in Figure 2.4. The stable catchment presents stationarity in all the water balance components, while, the unstable catchments has increasing Q and decreasing E (Figure 2.4a). Thus, the unstable catchment has a decreasing trend in the EI, or a change in partitioning (Figure 2.4b). Further, the Budyko sensitivity analysis shows that when we assume a non-steady state in both catchments and *n* is calibrated, the predicted E is close to the observed E for both catchments; yet, when steady state is assumed the differences between the predictions and observation are importantly higher for the unstable catchment (Figure 2.4c). Lastly, the effect of *n* on the change in E is evidently larger for the unstable catchment than for the stable catchment (Figure 2.4d).

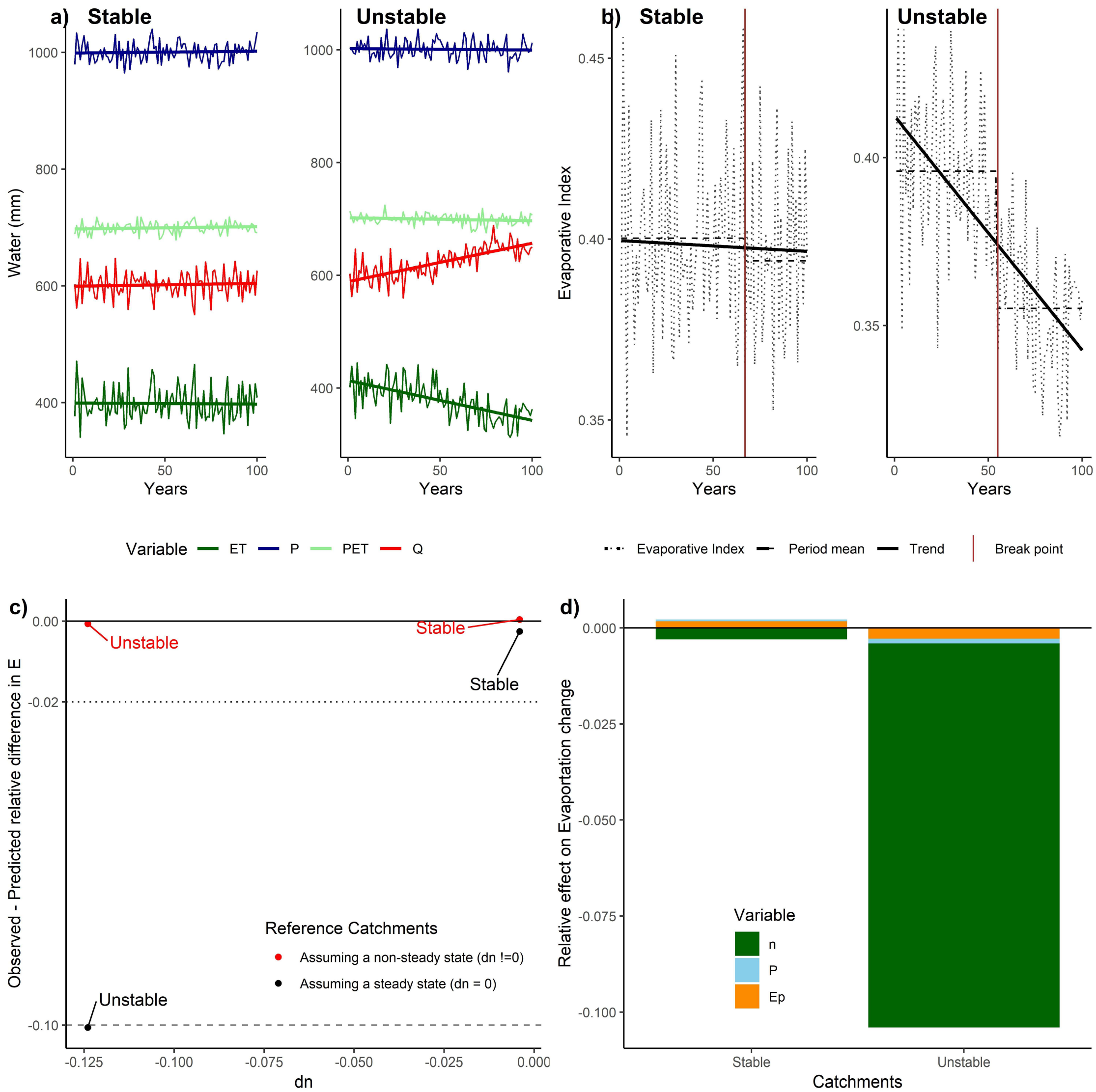


*Figure 2.4 Applying hydrologic stability framework to two hypothetical catchments. a)Water balance time series (E: evaporation, P: precipitation, Ep: potential evaporation, Q: runoff); b) Breaking points and trend of evaporative index; c) Observed - Predicted differences in E (dn= difference in Budyko's n); d) Relative effects of variables on E (n: Budyko's n).*

We conclude our analysis by computing a set of climate controls to contrast their changes between periods, and qualitatively discuss how those changes could influence the hydrologic stability and explain changes in Budyko's *n*, and consequently theoretically favor either E or Q (Table 2.3). Climatic controls have been described as important to determining Budyko's *n* (Padrón et al. 2017), and, within the time scales of our study, are likely to experience larger changes than other factors in undisturbed ecosystems (topography, soils, vegetation). Hence, the study of climate controls, such as seasonality of P and Ep, frequency and intensity of P, temperature influence on snow precipitation and melting are integrated by Budyko's *n*, provide valuable information of hydrological processes that occur in the RC that is not reflected by long-term DI. Moreover, the influence of climate controls over Budyko's *n* should be contextualized to the RC main climate type (Padrón et al. 2017), as they would have different effects on water limited or energy limited catchments. For instance, increases in the frequency of low magnitude precipitation events in water limited catchment could increase E if the timing is during the warmest months of the year.

*Table 2.3 Theoretical effects of changes in climate control on Budyko's n, E and Q. + indicates increase, - indicates decrease. Source: Modified from Roderick and Farquhar (2011) and Padrón et al. (2017).*

| Theoretical factors leading to change | n | E | Q |
|---|---|---|---|
| *Change in P related controls* | | | |
| Increase of P | - | - | + |
| Increase in storm arrival rate (SAR) | - | - | + |
| Increase in average storm depth (ASD) | - | - | + |
| *Change in storage related controls* | | | |
| Increase in maximum accumulation of monthly surplus (MAMS) | - | - | + |
| Increase in seasonal surplus index(SSI) | - | - | + |
| *Change in temperature related controls* | | | |
| Increase in mean annual temperature (MAT) | + | + | - |
| Increase in the fraction of P falling as snow (FSNOW) | - | - | + |
| *Change in temporal distribution of P* | | | |
| Increased in summer and decreased in winter | + | + | - |
| Decreased in summer and increased in winter | - | - | - |
| *Change in temporal distribution of Ep:* | | | |
| Increased in summer and decreased in winter | + | + | - |
| Decreased in summer and increased in winter | - | - | + |

## 2.3. Results

### 2.3.1. Time series and breaking points.

According to the Mann-Kendal trend test, annual P was stationary in all the catchments except for HBEF (p-value = 0.002), increasing by 5.07 mm/yr (Table 2.4). Although, significant trends of P were not found in other RCs, several catchments had increases of > 1 mm/yr (CAS, CHL, LUQ, MEF, TCEF) while other had decreases of < 1 mm/yr (NWT, SEF). Similarly, Q had the small magnitude of trends that were only significant in HBEF (5.49 mm/yr, p-value < 0.001) and in NWT (10.8 mm/yr, p-value = 0.004). Moreover, Q did not follow the patterns of P in all the catchments; in CAS, CHL and FREF, Q decreased while P increased; and in FNEF Q increased while P decreased (Table 2.4, Figure 2.5). Trends in E were more salient than Q, with two catchments presenting significant increases: CAS (3.8 mm/yr, p-value = 0.004) and CHL (3.7 mm/yr, p-value < 0.001), while E significantly decreased in three catchments FNEF (-1.2 mm/yr, p-value = 0.004), HBEF (-1.6 mm/yr, p-value = 0.022) and NWT (-10.8 mm/yr, p-value < 0.001). Other catchments with not significant E trends but with high Sen's slopes were LUQ (6.9 mm/yr, p-value = 0.674) and FREF (2 mm/yr, p-value = 0.069)(Table 2.4). Potential evaporation had generally stronger trends than E: five catchments had significant increases CHL (0.7 mm/yr, p-value < 0.001), FREF (1.9 mm/yr, p-value = 0.001), HBEF (0.5 mm/yr, p-value = 0.036), MEF (1.4 mm/yr, p-value < 0.001), NWT (2.7 mm/yr, p-value = 0.031), while HJAEF (-0.5 mm/yr, p-value = 0.019) significantly decreased (Table 2.4). The differences in magnitudes of trends of Ep and E are reflected in the DI and EI indexes, with DI generally changing more than EI. The EI had significant trends in CHL (p-value = 0.011), HBEF (p-value < 0.001) and NWT (p-value < 0.001); while four RC had significant changes in DI: CAS (p-value = 0.001), CHL (p-value < 0.001), FNEF (p-value = 0.013), HBEF (p-value = 0.003). Overall, HBEF was the only catchment with significant trends across all the water balance components, while LUQ and SEF did not have any significant trends in any of the studied components (Table 2.4, Figure 2.5).

The breaking points analysis over the time series of indexes resulted in three RC with statistically significant breaking points for EI and only HBEF with a significant breaking point in DI (Table 2.5). Two catchments (CHL and NWT) had significant breaking point on EI according to all the tests, where NWT had two significant breaking points at years 1995 and 1997; while EI breaking points in CHL were at year 1980. A significant breaking point at year 1971 was found for both EI and DI at the FNEF according to the Pettitt test. The EI in HBEF had significant breaking points at year 2003 and year 1989 according to the Pettitt test and Buishand Range respectively (Figure 2.5 and Table 2.5). Consequently, we used specific breaking points for CHL (year 1980), FNEF (year 1971) and NWT (year 1996) as guidance to divide their time series, while the time series of the remaining RC was divided into equal lengths.

*Table 2.4 Annual mean, standard deviation, Mann Kendall test and Sen's slope results for water balance components in reference catchments of the US. Bold text indicates significant at p-value < 0.05.*

| | | CAS | CHL | FNEF | FREF | HBEF | HJAEF | LUQ | MEF | NWT | SEF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **P** | Mean (mm) | 1164 | 1978 | 1449 | 598 | **1357** | 2264 | 3658 | 778 | 1213 | 1450 |
| | Sd (mm) | 344 | 321 | 162 | 94 | **195** | 418 | 696 | 117 | 180 | 177 |
| | Z | 0.371 | 1.335 | -0.081 | 0.356 | **3.06** | 0 | 1.022 | 0.284 | 0.114 | -0.48 |
| | S | 34 | 287 | -14 | 20 | **434** | -1 | 76 | 30 | 8 | -8 |
| | Sen's Slope (mm/yr) | 1.721 | 2.674 | -0.102 | 0.925 | **5.072** | -0.008 | 8.146 | 0.321 | 0.615 | -7.508 |
| | p-value | 0.711 | 0.182 | 0.936 | 0.722 | **0.002** | 1 | 0.307 | 0.777 | 0.91 | 0.631 |
| **Q** | Mean (mm) | 628 | 997 | 642 | 345 | **872** | 1295 | 2405 | 168 | **927** | 349 |
| | Sd (mm) | 315 | 319 | 134 | 112 | **211** | 375 | 606 | 65 | **193** | 126 |
| | Z | -0.416 | -0.737 | 0.741 | -0.469 | **3.626** | -0.379 | 0.341 | 1.027 | **2.903** | -0.069 |
| | S | -38 | -159 | 120 | -26 | **514** | -59 | 26 | 106 | **180** | -2 |
| | Sen's Slope (mm/yr) | -1.089 | -1.545 | 0.933 | -1.152 | **5.488** | -1.027 | 3.806 | 0.757 | **10.834** | -1.206 |
| | p-value | 0.678 | 0.461 | 0.459 | 0.639 | **0** | 0.704 | 0.733 | 0.304 | **0.004** | 0.945 |
| **Ep** | Mean (mm) | 996 | **1252** | 1046 | **861** | **886** | **925** | 1396 | **872** | **650** | 1292 |
| | Sd (mm) | 49 | **36** | 37 | **25** | **34** | **31** | 197 | **34** | **52** | 33 |
| | Z | -1.674 | **3.575** | 0.081 | **3.433** | **2.099** | **-2.341** | 1.73 | **3.492** | **2.157** | 0.55 |
| | S | -150 | **767** | 14 | **184** | **298** | **-359** | 128 | **358** | **134** | 9 |
| | Sen's Slope (mm/yr) | -1.325 | **0.656** | 0.021 | **1.926** | **0.524** | **-0.491** | 5.662 | **1.373** | **2.742** | 1.792 |
| | p-value | 0.094 | **0** | 0.936 | **0.001** | **0.036** | **0.019** | 0.084 | **0** | **0.031** | 0.582 |
| **E** | Mean (mm) | **536** | **981** | **807** | 252 | **485** | 969 | 1253 | 610 | **286** | 1101 |
| | Sd (mm) | **111** | **139** | **54** | 46 | **73** | 121 | 474 | 75 | **164** | 206 |
| | Z | **2.842** | **6.141** | **-2.856** | 1.82 | **-2.297** | 1.229 | 0.913 | -0.421 | **-3.584** | 0 |
| | S | **254** | **1317** | **-460** | 98 | **-326** | 189 | 68 | -44 | **-222** | 0 |
| | Sen's Slope (mm/yr) | **3.841** | **3.687** | **-1.204** | 2.089 | **-1.587** | 1.031 | 6.851 | -0.374 | **-10.786** | -1.083 |
| | p-value | **0.004** | **0** | **0.004** | 0.069 | **0.022** | 0.219 | 0.361 | 0.674 | **0** | 1 |
| **EI** | Mean | 0.49 | **0.51** | 0.56 | 0.43 | **0.37** | 0.44 | 0.34 | 0.79 | **0.23** | 0.76 |
| | Sd | 0.15 | **0.09** | 0.05 | 0.11 | **0.08** | 0.08 | 0.12 | 0.06 | **0.13** | 0.08 |
| | Z | 1.179 | **2.557** | -1.699 | 1.032 | **-3.541** | 1.007 | 0.368 | -1.184 | **-3.714** | 0.069 |
| | S | 106 | **549** | -274 | 56 | **-502** | 155 | 28 | -122 | **-230** | 2 |
| | Sen's Slope | 0.002 | **0.001** | -0.001 | 0.003 | **-0.002** | 0.001 | 0.001 | -0.001 | **-0.009** | 0 |
| | p-value | 0.238 | **0.011** | 0.089 | 0.302 | **0** | 0.314 | 0.713 | 0.237 | **0** | 0.945 |
| **DI** | Mean | **0.95** | **0.65** | **0.73** | 1.48 | **0.67** | 0.42 | 0.4 | 1.15 | 0.55 | 0.9 |
| | Sd | **0.40** | **0.12** | **0.10** | 0.26 | **0.10** | 0.09 | 0.14 | 0.21 | 0.10 | 0.11 |
| | Z | **3.291** | **4.993** | **-2.47** | 0.094 | **-2.933** | 1.726 | -0.123 | -1.418 | 1.054 | -0.069 |
| | S | **294** | **1071** | **-398** | 6 | **-416** | 265 | -10 | -146 | 66 | -2 |
| | Sen's Slope | **0.005** | **0.002** | **-0.001** | 0.002 | **-0.002** | 0.002 | -0.001 | -0.001 | 0.001 | -0.005 |
| | p-value | **0.001** | **0** | **0.013** | 0.925 | **0.003** | 0.084 | 0.902 | 0.156 | 0.292 | 0.945 |

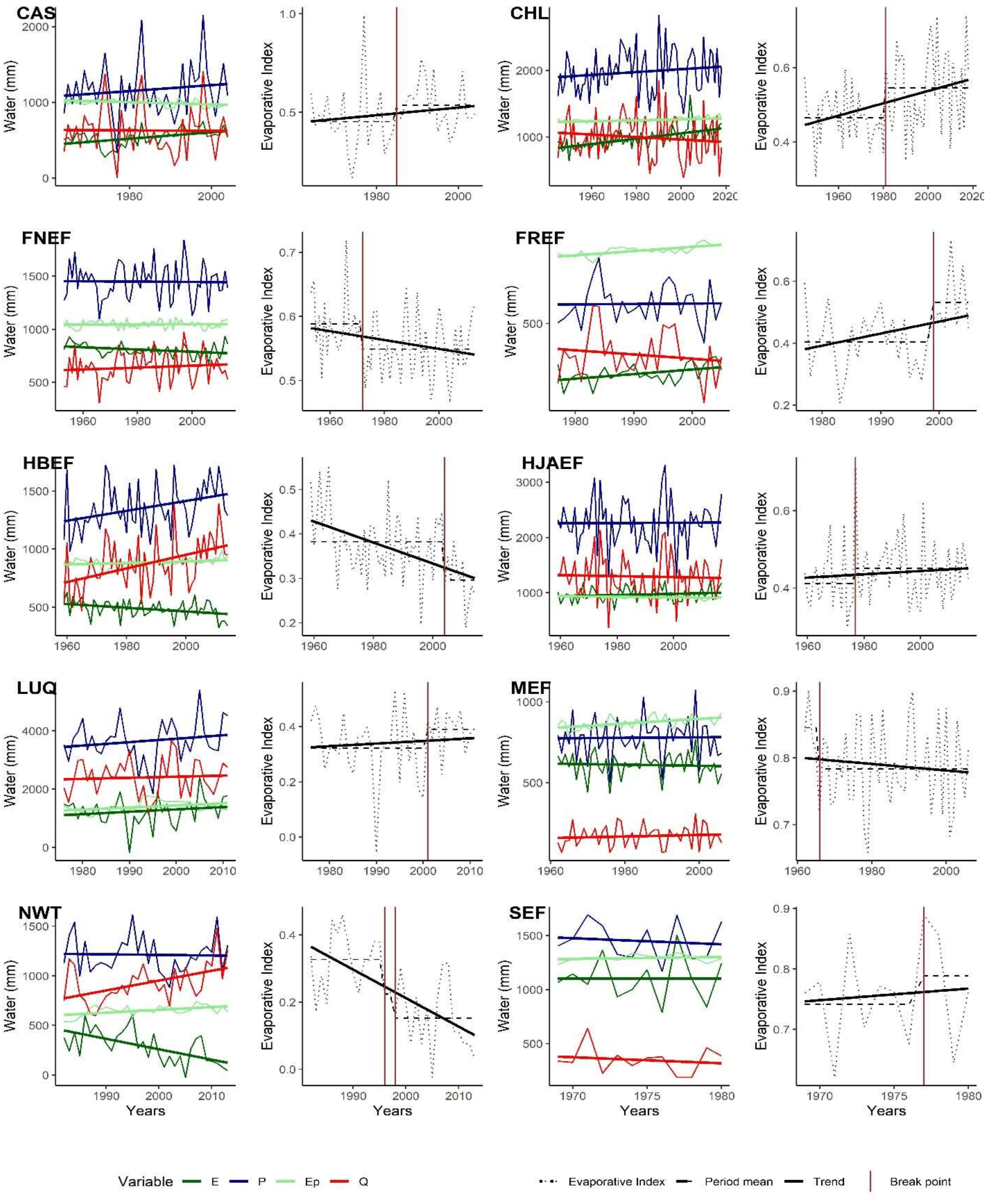


*Figure 2.5 Annual time series of water balance components, and evaporative index trend with Pettit test break points for reference catchments of the US.*

*Table 2.5 Breaking point water years according to three tests.*

| | Evaporative Index | | | Dryness Index | | |
|---|---|---|---|---|---|---|
| | Pettit Test | Buishand Range | Buishand U | Pettit Test | Buishand Range | Buishand U |
| CAS | 1984 | 1984 | 1984 | 1994 | 1992 | 1992 |
| CHL | **1980*** | **1980*** | **1980*** | 1967 | 1998 | 1998 |
| FNEF | 1971 | **1971*** | **1971*** | 1971 | 1964 | 1964 |
| FREF | 1998 | 1998 | 1998 | 2000 | 2000 | 2000 |
| HBEF | **2003** | **1989*** | 1989 | 1971 | 1971 | 1971 |
| HJAEF | 1976 | 1976 | 1976 | 1994 | 1994 | 1994 |
| LUQ | 2000 | 2000 | 2000 | 1989 | 1991 | 1991 |
| MEF | 1965 | 1965 | 1965 | 1999 | 1999 | 1999 |
| NWT | **1995*** | **1995*** | **1995*** | 1999 | 1999 | 1999 |
| NWT | **1997*** | **1995** | **1995*** | 1999 | 1999 | 1999 |
| SEF | 1976 | 1976 | 1976 | 1972 | 1972 | 1972 |

Significant breaking points at p -value < 0 .05 are marked with * and with bold text.

### 2.3.2. Budyko Sensitivity Analysis

Evaporation sensitivities to changes in either P or Ep were positive in all RC indicating that increases in P or Ep would increase E (and vice versa) (Table 2.6). Their magnitude (<1) indicates that changes in P or Ep will have a weakened effect on changes in E under the assumption that catchment properties remain stationary, i.e. the Budyko partitioning parameter $n$ is equal in both periods. For example, in the case of CHL a 10 % change in P would change E by 3.2 %, and a 10% change in Ep would change E by 6.8 %. Catchments with more energy availability (higher DI) were generally less sensitive to changes in Ep and more sensitive to changes in P (Table 2.6). Moreover, E was more sensitive to changes in Ep than to changes in P in all the catchments except for MEF and FREF. Evaporation in this case is more influenced by the incoming energy than by P. Nonetheless, we found important differences in the E sensitivities between catchments. LUQ, an energy limited catchment (Figure 2.3), presented the lowest sensitivity to P and the highest to Ep, meaning that it also had the highest differences between its sensitivities; and similar behavior was present in other energy limited catchments (NWT, CHL and FNEF) (Table 2.6). E sensitivities to changes in Budyko's *n* decreases as catchments had higher *n* values (Table 2.6), and with the exception of the two alpine catchments NWT (1.07) and FREF (1.02) all the RC had sensitivities < 1. The lowest sensitivity to changes in *n* were found in SEF and LUQ, while, NWT, FREF, HBEF and CAS had the highest sensitivities to changes in *n*.

*Table 2.6 Evaporation sensitivity coefficients and observed differences between periods.*

| Reference Catchment | n | Sensitivity coefficients | | | Differences between periods | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | dn/n | dP/P | dEp/Ep | dn | dP (mm) | dEp (mm) | dE (mm) | dE/E (%) |
| CAS | 1.00 | 0.69 | 0.46 | 0.54 | 0.31 | -3 | -33 | 102 | 21 |
| CHL | 1.61 | 0.39 | 0.32 | 0.68 | 0.54 | 0 | 27 | 143 | 16 |
| FNEF | 1.73 | 0.38 | 0.36 | 0.64 | -0.24 | 42 | -3 | -34 | -4 |
| FREF | 0.67 | 1.02 | 0.56 | 0.44 | 0.04 | 2 | 24 | 19 | 8 |
| HBEF | 0.87 | 0.78 | 0.41 | 0.59 | -0.14 | 128 | 24 | -35 | -7 |
| HJAEF | - | - | - | - | - | -1 | -17 | 20 | 2 |
| LUQ | 1.68 | 0.27 | 0.17 | 0.83 | 0.08 | 149 | 211 | 182 | 16 |
| MEF | 2.34 | 0.29 | 0.57 | 0.43 | -0.14 | 25 | 34 | 11 | 2 |
| NWT | 0.63 | 1.07 | 0.40 | 0.60 | -0.47 | -81 | 39 | -214 | -55 |
| SEF | 3.27 | 0.21 | 0.41 | 0.59 | 0.27 | -26 | 11 | 16 | 1 |

## Evaporation under steady state assumptions did not agree to observed changes.

Predicted changes in E for the second period resulted in different outcomes depending on the hydrologic stability assumptions (Figure 2.6). While RC historically are assumed to be stationary, our analysis showed that assumptions of a stationarity resulted in large differences to the observed values of E. On the contrary, assuming that RC are in a non-steady state improves the prediction of E. In this case, the noted capacity of the Budyko framework to estimate E is caused by the inclusion of a calibrated *n* in the calculation of a change in state (dn). In a non-steady state, all the RC are within 2% of the observed values (Figure 2.6). On the other hand, when assumptions of hydrologic stability are made, meaning that catchments characteristics do not change and can be represented by dn = 0, the correspondence between observed difference and predicted difference in E is notably lower (Figure 2.6). Yet, LUQ, MEF and SEF were the three catchments with the lowest differences between observed and predicted E (below 2%). These RC also had sensitivities to changes in *n* lower than 0.30 (Table 2.6), indicating that changes in P and Ep could be more important for partitioning in these catchments than changes in *n*. FNEF and FREF differences to observed records were higher but below 10%, while HBEF, CHL and CAS showed large differences from the observed records (Figure 2.6). The relative difference in NWT was the greatest with a difference of more than 50%, indicating the instability of partitioning in that catchment (Figure 2.6).

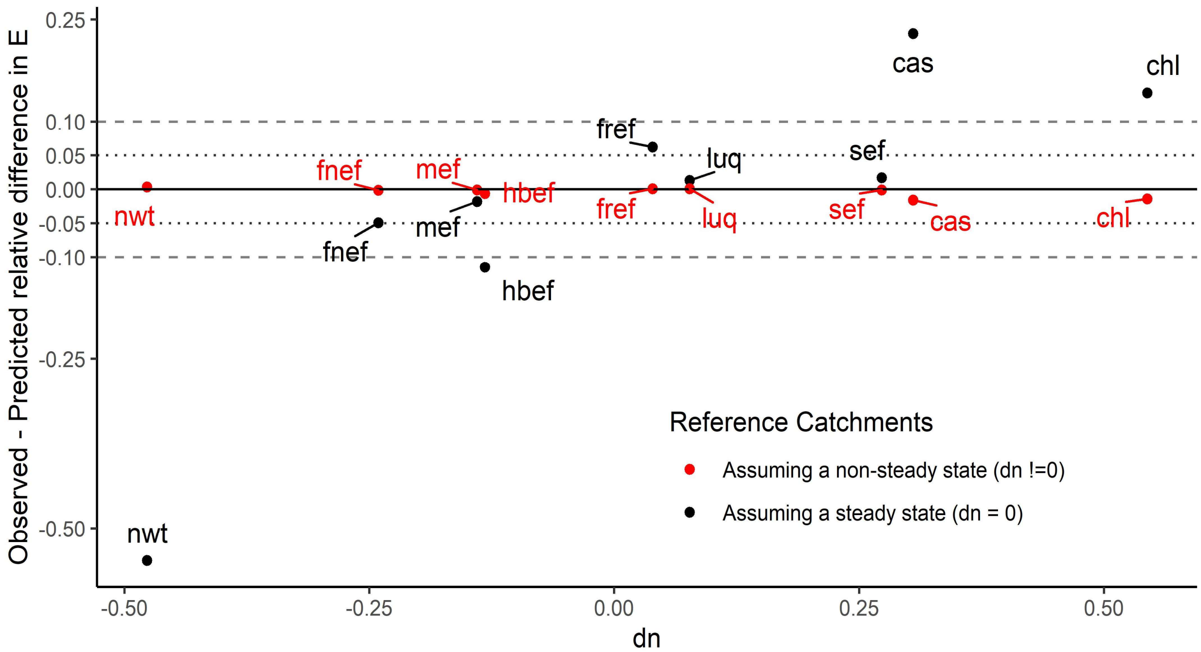


*Figure 2.6 Observed differences in E vs calculated differences in E with a hypothetical steady state: dn = 0 (red points) and a calibrated n (black points). Closeness to zero (0) indicates a higher hydrologic stability.*

The effect of changes in *n* on E followed the pattern of the differences between the observed and predicted E under assumptions of a steady state, indicating that changes in Budyko's *n* were the most influential in modifying E (Figure 2.7). The RC with the largest differences between observed and predicted E had also the strongest effects of *n* (NWT, CAS, CHL), while, catchments that had low difference between observed and predicted E (LUQ, MEF, and SEF) presented the weakest *n* effects on E change (Figure 2.7). Moreover, the overall change in partitioning was not only given by the change in *n* but also by the effects of P and Ep, which augmented or reduced the total change of E. For instance, at NWT the effects of P increased the difference between periods; while for HBEF, the changes between variables masked each other, reducing the overall change in E since the effect were negative for *n* and positive for P and Ep. Differentiating P, Ep and *n* effects demonstrated how some catchments were more affected by P or Ep; as is the case of LUQ which, even as being the most stable RC, presented the highest effect of Ep.

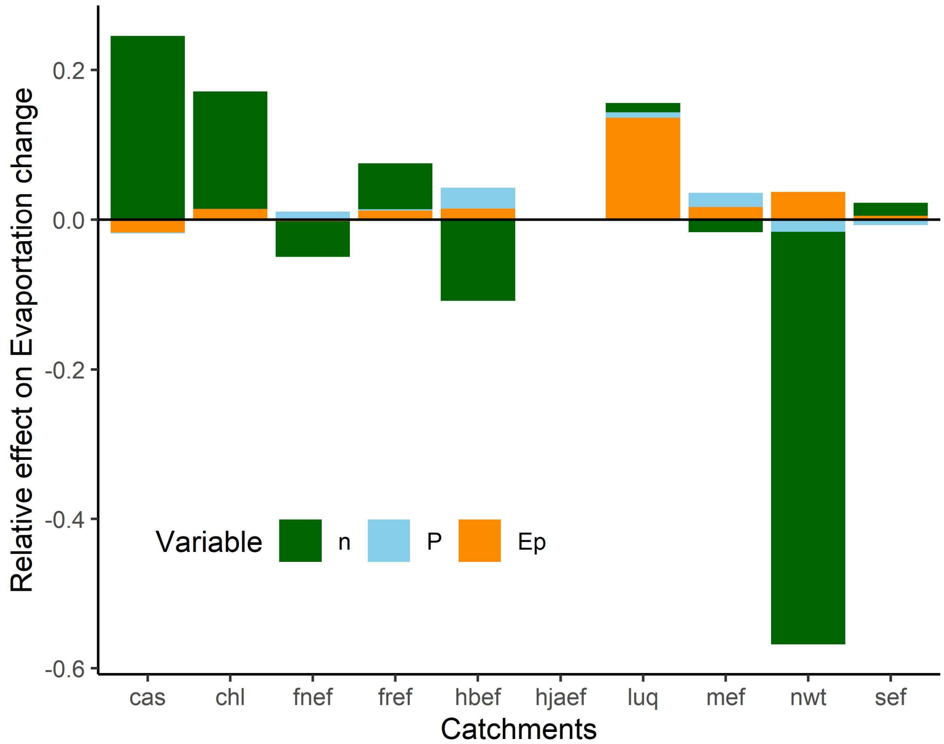


*Figure 2.7 Relative effect of P, Ep and n in the change of E between periods under assumptions of a steady state.*

### 2.3.3. Climate controls' influence over Budyko's *n*.

Changes in climate controls varied across study sites, making it difficult to observe general patterns across all the RC (Table 2.7). Yet, mean annual temperature increased in the second period of most RC, with the exception of CAS and HJAEF which are located closest to the Pacific Ocean. The highest changes in mean annual temperatures took place in NWT and FREF, in the Rocky Mountains, which saw increases > 1°C between periods. Increased temperatures help explain increases in *n* and favor E at several catchments (e.g. CHL, FREF, LUQ). Yet, higher temperature did not always result in more E: in NWT, shifts in the timing of the arrival of spring temperatures could create higher and earlier snow melt and discharge peaks. These sort of complexities and dynamics were found in different forms at several RC, pointing at the heterogeneity of their hydrological processes. Table 2.7 presents a summary of the main changes in climate controls, contextualized with the RC climate type and classified according to how the theoretical effects are in line with the observed changes on Budyko's *n*. In most cases, several controls had unexpected changes based on *dn*: i.e. the change in controls favored Q when *dn* was positive (and vice versa), which points out at damping or masking effects between controls, as well as, the importance of the timing of energy and water inputs to the catchments (Table 2.7). For instance, at an energy limited catchment like HBEF, increased P in the summer and fall favored runoff, while, more water inputs in summer at a water limited catchment like FREF allowed for increases in E (Table 2.7).

*Table 2.7 Effects of climate controls changes on partitioning in reference catchments.*

| Catchments with Increases in Evaporative Index | | | | | |
|---|---|---|---|---|---|
| Climatic type | Catchment | dn | Change in controls that favor E (%) | Controls favoring Q | Seasonality interaction |
| Warm temperature | CHL | +0.54 | FSNOW(-55%) MAT(+7%) SAR (-2%) | ASD(+4%) MAMS (+6%) SSI (+1%) | P and Ep seasonality are less extreme in the dormant season, meaning that more rain can be transpired in the summer. |
| ARID | CAS | +0.31 | ASD(-19 %) P(-2%) MAMS(-6%) SSI(-4%) | SAR(+25%) MAT(-4%) MAMS (+3%) | Lower Ep in the summer decreased the phase shift, yet high atmospheric water demand maintains E. |
| Warm temperature | SEF | +0.27 | P(-2%) ASD(-2%) MAMS(-25%) SSI(-43%) | MAT(+1%) | Phase shift between P and Ep increased slightly. |
| Equatorial | LUQ | +0.08 | MAT(+4%) (ASD -2%) | SAR(+15%) P(+12%) MAMS(+13%) SSI(+15%) | Increases in the Ep seasonality and magnitudes over the spring and summer, with synchronous reductions of P at those periods |
| Snow dominated | FREF | +0.04 | MAT(+1.27°C) FSNOW (-12%) ASD (-1%) P (+4%) | SAR (+8%) SSI(+18%) | Increases in P during warmer periods of the year, together with increase of Ep in water limited catchment could increase E in summer and late summer |
| Arid | HJAEF | n/a | ASD(-2%) MAMS(-2%) | SAR(+4%) MAT(-5%) SSI(2%) | Phase shift between P and Ep decreased. More P summer spring could sustain E for longer periods. |
| Catchments with Decreases in Evaporative Index | | | | | |
| Climatic type | Catchment | dn | Controls favoring Q | Controls favoring E | Seasonality interaction |
| Snow Dominated | NWT | -0.47 | ASD (+1%) FSNOW (+3%) | SAR (-2%) P (-4%) MAT (+0.47°C) MAMS (-7%) SSI (-12%) | Increases in spring temperatures with earlier snowmelt create runoff peaks in the spring, when Ep is not high enough to cause increases in E, which can favor an overall larger partitioning towards runoff. |
| Temperate | FNEF | -0.24 | SAR(+2%) ASD(+2%) MAP (+4%) SSI (+8%) | FSNOW(-20%) SSI(-15%) MAT(+10%) MAMS(-4%) | Summer P increases, making P and Ep to be more in phase. More P during the months with highest Ep would reduce E |
| Snow Dominated | HBEF | -0.14 | SSI(+26%) P(+7%) ASD(+11%) MAMS(6%) SAR(+2%) | FSNOW(-10%) MAT(+10%) SAR (-3%) | Summer and fall P increase, making P and Ep to be more in phase. More P during the months with highest Ep, and also keeping Q high in the fall. |
| Snow | MEF | -0.14 | SAR (+5%) FSNOW(+2%) MAMS(+2%) | ASD(-7%) MAT(+8%) SSI (-5%) | Increases in summer P favor summer Q. |

### 2.4. Discussion

The first critical result of our study is that some RC were hydrologically unstable, shedding light on the general assumption of stationarity of control catchments in pair catchments studies. The most unstable RC were NWT, CAS, CHL and HBEF. Two main lines of evidence to support our results were the trend analysis and the Budyko framework. First, we found that three RC had significant trends in EI and in several water balance components, and although CAS did not present significant EI trends, its E changed significantly. Similarly, the catchments had significant breaking points in EI. Secondly, we found that E could not be accurately predicted using Budyko's framework when steady states were assumed, indicating the presence of changes in catchment characteristics and a lack of stability in P partitioning. This lack of stability can be explained by the qualitative evidence of climate controls, shown in Table 2.7 and that is discussed further below. Yet, apart from changes in climate controls, other causes can also be important to cause instability, primarily vegetation changes. The length of the times scale studied is long (<80 years) reduces the probability of larger changes in topography, geology and pedogenesis. Hence, as changes in the vegetation characteristics are still possible, they should be regarded as critical to changes in partitioning (Bosch and Hewlett 1982; Brown et al. 2005; Donohue, Roderick, and McVicar 2007; Zhang et al. 2004; Zhang, Dawes, and Walker 2001; Xing et al. 2018). Although, RC limit direct human disturbances to vegetation, these areas can still experience incremental modifications, such as, changes in structural characteristics (e.g. basal area, tree height, leaf area index), forest age, and biological diversity. For instance, it has been reported that forest mesophication processes (in which dominance of tree species with ring porous xylem anatomy are substituted by tree species with diffuse porous xylem anatomy which have a larger water use) have caused increases of E at CHL (Ford et al. 2011; Caldwell et al. 2016). Declining E at HBEF, has not been attributed to a particular reason, as its processes are difficult to disentangle, yet, possible causes may lie on decreases in biomass, aging forests or adaptation to enhanced $CO_2$ (Campbell et al. 2011). Besides gradual changes, intense disturbance processes as insect outbreaks, extensive droughts or hurricanes, could also cause changes in vegetation characteristics, that eliminate species or significantly reduce leaf area index, which could have effects on partitioning. Future studies could evaluate specific vegetation controls (NDVI, leaf area index, growing season length patterns) and their relation to hydrologic stability in RC.

Hydrologic stability was found in the remaining catchments. The most stable catchments seen through the lens of partitioning were LUQ, SEF and MEF. A reason for their stability can lie on less variations in EI caused by the lower trends of change found in water inputs (P). RC ability to adapt to changes can be caused by several reasons, e.g. enhanced tree intrinsic water use efficiency due to increased atmospheric $CO_2$ (Mathias and Thomas 2021), ultimately masking climate changes (Young et al. 2019).. Moreover, changes in EI have occurred to a lower degree than those of the DI. The different behavior between indices might be attributed to overall warming in air temperatures in the last decades (IPCC 2014), which is also reflected by higher energy inputs (Ep) and increased mean annual temperature at 8 out of 10 catchments. Our results are similar to previous reports that highlighted the ability of undisturbed environments to mask the effects of climate change on runoff (Jones et al. 2012). Moreover, the elastic qualities of RC to return to partitioning processes after warm or cold periods previously reported by Creed et al. (2014), corroborate the capacities of undisturbed environments to maintain their hydrological states. Finally, given that trends in partitioning could mainly reflect the effect of climate oscillations if the studied time periods are short, we specifically used long-term record (<25 years) at nine out of ten catchments. Hence, SEF shorter record length (12 years) can be prone to reflect the influences of climatic oscillations that can mask the changes in partitioning.

A second key result was that RC that were more sensitive to changes in Budyko's *n* were less stable, and, that the catchments characteristics played a larger role than long-term P and Ep in their instability. First, we saw that E sensitivities to changes in P, Ep, and *n* varied among RC, yet, they also illustrated interesting patterns of how P partitioning is given by either DI or Budyko's *n*. Although, the importance of DI or *n* to partitioning is partly redundant, as they also influence each other, the importance of each element varies at different sites (Padrón et al. 2017). Thus, RC sensitivity to changes in Budyko's *n* was lower at catchments where the position of long-term EI and DI was closer to the limits of energy and water in the Budyko framework, described with a higher Budyko's *n*, meaning that when catchments are closer to the energy and water limits, Ep has a higher influence over E (Patterson, Lutz, and Doyle 2013). For instance, LUQ and SEF where the closest RC to the energy limit and reported the lowest sensitivity to changes in *n* (Figure 2.3 and Table 2.6). In this case, long-term DI is the factor that could create the largest changes to the partitioning processes. The opposite was true for NWT and FREF, which presented the lowest Budyko's *n* and were farthest away from the energy and water limits in the Budyko space. Secondly, the effects of changes in P, Ep and *n* shown in Figure 2.7 exemplify how catchment that are far away from limits, as NWT, are not only less stable, but that such instability is mainly due to changes in the catchment partitioning controls and not to changes in DI. In contrast, the changes at LUQ (less sensitive to *n*) are driven by Ep and not strictly by the partitioning characteristics of the catchments (Figure 2.7). On more concrete terms, this means that the importance of the DI to partitioning is substituted by the particular characteristics of the catchments. In the case of alpine catchments like NWT and FREF, where runoff is dominated by snow melt, partitioning diversions from initial states could be attributed in a lesser degree to changes in DI and more to snowpack dynamics (Clow 2010). Therefore, the catchments positions on the Budyko framework can inform which factors (DI or other controls) could be most influential to the hydrologic stability of RC. Finally, using Roderick and Farquhar's (2011) sensitivity framework proved useful for testing the stability of partitioning in catchments and to understand what factors might have played a larger or smaller role in the changes that occur in catchments through site specific sensitivity coefficients.

Another critical finding was that climate controls could explain the changes in Budyko's *n* as theoretically anticipated (Table 2.3 and Table 2.7). However, in order for climate control to have meaning, they must be contextualized for each site's climate and dominant hydrological processes. For instance, even if catchments experienced high relative changes in temperature related variables such as fraction of snow or mean annual temperature, like CHL, those variables might not be the most influential over runoff in that particular ecosystem (Ford et al. 2011); even if they are important for ecological processes as carbon uptake (Oishi et al. 2018). Another example is presented at catchment with mediterranean climates, like CAS, where variables that would normally be associated with higher Q, such as the storm arrival rate, could cause favor E if rainfall events have smaller magnitudes and occur during the warmer periods of the year. Likewise, seasonality is another key factor of partitioning that could play major roles in changing the stability of RC. The timing of snow melt could change streamflow patterns between spring and early summer, with considerable effects on the predictability of streamflow (Vano 2020). In energy limited sites, like HBEF and FNEF, increases in P during warmer periods of the years might diminish E by increasing cloudiness favoring even more Q despite the reductions of snowpacks and higher temperatures. Seasonal increases in P at HBEF have been linked to increases in streamflow (Campbell et al. 2011). Our results stress the importance of considering Budyko's *n* a broader "partitioning" parameter that includes climate controls (including seasonality) as equally important together with other factors vegetation, as has been previously highlighted (e.g. Padrón et al. 2017; Donohue, Roderick, and McVicar 2012; Fu and Wang 2019; Gerrits et al. 2009; Xing et al. 2018; Roderick and Farquhar 2011).

Our results should be interpreted based on the characteristics of the RC catchments sampled, hence, caution is recommended for inference on undisturbed catchments with different conditions. Specifically, catchments with high energy limitations are lacking from our data set (all RC had in average a DI <1.5) and dry catchments can have important differences in their hydrological processes (Amatya et al. 2016; Jones et al. 2012; Creed et al. 2014). Similarly, more catchments from boreal ecosystems should also be included given the indications of snow as an important factor for stability and as dominant controls (Padrón et al. 2017). Future studies should consider a closer look at these type of catchments at a global representation, as more literature on experimental catchments and their datasets are made more accessible (e.g. Hydrological Processes' Special Issue: "Research and observatory catchments: The Legacy and the Future").

Moreover, the influence of climatic oscillations (e.g. El Niño-Southern Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation) over precipitation partitioning was not specifically controlled in our study. Yet, CHL, FNEF, FREF, HBEF, HJAEF, LUQ and MEF have been found to have significant correlations between streamflow and at least one climatic oscillation during some period of the year (Jones et al. 2012). Moreover, when we carried out time period comparisons the record lengths were reduced, making our result more prone to the effects of climate oscillation signals. As time series increase their length, future studies can continue to disentangle the dynamics between P partitioning and climatic oscillations and a larger number of undisturbed catchments can be analyzed (Jones et al. 2012).

Additionally, we selected the Priestley-Taylor equation as a suitable Ep calculation method, given the daily temperature data availability and to keep the consistency across sites. As expected, Ep values in our study differ from other studies that used other Ep calculation methods (Amatya et al. 2016; Jones et al. 2012; Creed et al. 2014). Notably, Ep at NWT and FREF seem to have been overestimated. On the other hand, Ep at HJAEF could be underestimated as it was lower than E, which limits the application of the Budyko framework analysis since its theoretical principles state that Ep must be higher than E. Low Ep at HJAEW has been previously reported (Amatya et al. 2016; Jones et al. 2012; Creed et al. 2014). Even if inherent method errors are unavoidable on derived variables as Ep, future studies could improve our methods by applying site specific Ep methods.

### 2.5. Conclusions

Reference catchments play a critical role in experimental hydrology by providing a landscape-scale baseline of hydrologic conditions in the absence of disturbance. RC serve as witness of the precipitation partitioning processes that took place when calibrations were established in the paired catchment approach. Therefore, it is important to understand if those relationships have remained. We departed from the assumption that P partitioning is determined by the interplay between water and energy inputs and modified by the local catchment characteristics and processes. Our results on the lack of stability in several catchments call for more research, for (paraphrasing Heraclitus) *no hydrologist ever measures the same river twice, for it is not the same river and she is not the same hydrologist*. Thus, improved knowledge on precipitation partitioning dynamics should pose questions on the validity of decades old calibrations *for it is not the same catchment*; and *nor is the hydrologic community the same community* but one with increased knowledge and tools (Peters-Lidard et al. 2018). Integration of RC precipitation partitioning dynamics with land management experiments in pair catchments studies could be improved in different ways, for example, modeling approaches to estimate how RC would hypothetically behave (Zegre et al. 2010); modification to initial statistical relations by considering elapsed time from calibration as a proxy for change applied to reference catchments (Ford et al. 2011). Other novel techniques and approaches might be conceived as the scientific community takes on this task.

In conclusion, the assumption that RC are hydrological stability is not always a valid one, highlighting the variety of direct and indirect (influence on *n*) climate controls that cause hydrologic instability. While assuming that RC undergo changes is not opposed to the practice of using them as standards for the study of water yield; considering and questioning their stability (or lack of) can improve the quality of the result within paired catchment studies. Finally, our results support the maintenance of catchments undisturbed and fund research in order to create knowledge on the dynamics between land-use management and water yield that otherwise would not be possible.

**Data Availability Statement**

All the data used for this study is publicly available and can be found at the following sources: CAS (Richardson et al. 2021a, 2021b), CHL (Miniat et al. 2015, 2016, 2017), FNEF (P. J. Edwards and Wood 2011b, 2011a, 2011c), FREF (Elder 2005, 2006a, 2006b); HBEF (USDA Forest Service 2020c, 2020a, 2020b), HJAEF (Daly and McKee 2019; Johnson, Wondzell, and Rothacher 2020); LUQ [LTER network EDI data portal: https://portal.edirepository.org]; USGS stream gauging: https://waterdata.usgs.gov/pr/nwis/rt; González (2017)]; MEF (Sebestyen et al. 2020a, 2020b; Verry et al. 2018); NWT (LTER network EDI data portal, https://nwt.lternet.edu/data-catalog; Kittel et al. 2019a, 2019b), SEF (Abatzoglou et al. 2018; Santee Experimental Forest Southern Research Station, n.d.). Summarized time series and R code used in this research is available upon request to the corresponding author.

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# Chapter 3 Controls on the water balance in temperate forest ecosystems

Submitted as Guillen, L.A., Fernandez, R., Gaertner, B., Zegre, N.P. *Climate and landscape controls on the water balance in temperate forest ecosystems: testing large scale controls on undisturbed catchments in the central Appalachian Mountains of the US.* Water Resources Research.

**Abstract**

The long-term water balance of catchments is given by precipitation partitioned into either runoff or evaporation. Understanding precipitation partitioning controls is a critical focus of hydrology and water resources management. Controls can be classified as either related to climate or landscape characteristics. In this paper, we aim to understand the precipitation partitioning controls in the central Appalachian mountains located in the eastern United States. Headwater catchments in this region act as water towers to provide freshwater to metropolitan areas in the eastern and mid-western US (e.g. Pittsburgh, Washington DC). We focused on a set of catchments that are characterized by minimal human disturbance and with large proportions of temperate forests. We used the Budyko framework to study the relative importance of overall climate regimes, then applied partial correlation analysis and multivariate regressions to find the principal partitioning controls. We found that climate controls such as mean annual temperature and fraction of precipitation falling in the form of snow exert a higher influence on partitioning than landscape controls (e.g. forest cover, Normalized Difference Vegetation Index, slope). Thus, the importance of vegetation as a primary driver of partitioning could not be confirmed based on regional or basin wide characteristics. On the other hand, the influence of topography, and in particular, elevation, was highly ranked as important. Our study highlights that partitioning controls are scale dependent and could differ between basins in the same climate region, especially in a complex, mountainous topography setting.

**Keywords**: water balance, evaporation controls, Budyko, climate, vegetation.

## 3.1. Introduction

The water balance of catchments is controlled by the partitioning of the rainfall (P) into either runoff (Q) or evaporation (E) (the bulk flux of water, including transpiration, bare soil, interception loss and vaporization from open water (Miralles et al., 2020)). Determining precipitation partitioning is a core goal of hydrology (Daly et al., 2019; Peters-Lidard et al., 2018), as information about the water balance allows managers to better plan water use in the agricultural, industrial and urban sectors, as well as, water for ecosystem needs. Moreover, it is critical to understand how water fluxes are impacted by environmental change, especially given recent changes in global hydrologic regimes (Sankarasubramanian et al., 2020). A metric used to understand precipitation partitioning is the evaporative index (EI), the ratio between evaporation and precipitation, which is influenced by climate and landscape characteristics (Budyko, 1974) since those are critical to the water and energy balance. In mountainous areas that serve as water towers (Viviroli et al., 2007), such as the central Appalachian Mountains region, understanding what specific catchment characteristics drive the evaporative index is critical since high elevation regions provide water to large populations and vast land areas, making catchment and land management vital for water security in such humid regions (Praskievicz, 2019). Furthermore, aridity in high elevation catchments in the Appalachian region is projected to increase at a disproportionally higher rate compared to the lower lying areas (Fernandez & Zegre, 2019) calling into question the sustainability of contemporary water use management. Here, we investigate the main climatic and landscapes controls on precipitation partitioning for a set of catchments located in the region. This work contributes to a better understanding of the region's hydroclimatology and the importance of land and climatic characteristics for the freshwater provisioning in the region.

The discussion of the most important controls on precipitation partitioning is part of important debates (Berghuijs et al., 2017; Padron et al., 2017; Xing et al., 2018), however, it is not easily resolved since the main controls differ by climatic regimes (Padron et al., 2017) and scale. Climate controls are highly important for partitioning since they influence water supply, in terms of amount, intensity, frequency, type and seasonality of precipitation (Milly, 1994); water demand (magnitude and seasonality of potential evaporation (PE)); and the interaction between water supply and demand, since the synchronization of the seasonal cycles of P and PE is determinant of more or less water surplus or shortage (Fernandez & Zegre, 2019; Stephenson, 1990). Moreover, topographic characteristics are also important for partitioning since, for instance, steeper catchments favor runoff by reducing the time water stays in the catchment (Shao et al., 2012) and larger catchment size can create more conditions for evaporation to occur (Choudhury, 1999). Moreover, soil characteristics, such as texture and depth (Donohue et al., 2012; Milly, 1994) influence a catchment's potential water storage that can be available for plant transpiration, which exert important controls on the water balance in broad-leaf forests of temperate latitudes, such as the Appalachian Region (Brown et al., 2005; Ford et al., 2011; Knighton et al., 2020; Li et al., 2013; Zhang et al., 2001). Given the inherent differences between the aforementioned controls, previous work has utilized the Budyko framework (e.g. Padron et al., 2017), since this framework combines the water supply, atmospheric water demand and the characteristics of catchments to explain precipitation partitioning.

The Budyko framework (Budyko, 1974) is a simple energy-water balance model that explains how precipitation partitioning is determined by a catchment's dryness index (DI) (PE/P), EI, and a catchment's characteristics, here described by Budyko's partitioning parameter $n$. The Budyko framework was initially used to explain large scale and long-term precipitation partitioning; with many studies focusing on the controls of landscape and climate on the water balance in China, Australia and Europe (e.g. Wu et al., 2017; Jaramillo et al., 2018; Roderick & Farquhar, 2011; Shao et al., 2012; Teng et al., 2012; Teuling et al., 2019; Xin et al., 2019). Using the Budyko framework, Padron et al. (2017) carried out a global meta-analysis and a systematic review on the influence of climate controls and landscape controls over the water balance. They found differences in partitioning controls between climate regions and low importance of vegetation controls over partitioning (Padron et al., 2017). Notwithstanding, differences *within* climate regions, as well as inclusion of spatially integrated data, were not carried out given the large scale nature of the study. Another approach to understanding partitioning was recently presented by Younger et al. (2020), who used multivariate regression models to evaluate the effects of climate and landscape controls on catchment evaporation. The Younger et al. (2020) study was regional and in southern Appalachia and found that climatic controls exerted a higher importance than forest for precipitation partitioning.

Here, we adapt the approaches of Padron et al. (2017) and Younger et al. (2020) to examine precipitation partitioning controls *within* a region: the heavily forested central Appalachian Mountains in the eastern USA, which provides freshwater to ~9% of the US population (Gaertner et al., 2019). We incorporate catchment-wise spatially averaged climate and landscape variables to advance methods presented by Padron et al. (2017). Moreover, we aim to contribute to the increasing body of literature focusing on the controls of precipitation partitioning in the United States (Knighton et al., 2020; Vadeboncoeur et al., 2018; Young et al., 2019). The goal of this study therefore is to improve understanding about the controls of precipitation partitioning in the central Appalachian Mountains region, where mainly forested catchments are also influenced by the climate dynamics created by the eastern continental divide (Fernandez & Zegre, 2019; Wiley, 2008). In order to reach that goal, we computed correlations between Budyko's $n$ parameter and various environmental controls known to be important to precipitation partitioning to confirm (or dismiss) the applicability of previous findings. The specific objectives of our study are to (i) quantify the relative importance of the dryness index and Budyko's parameter $n$ for precipitation partitioning for the central Appalachian Mountain region; (ii) identify the most important climatic and landscape controls, and (iii) discuss the importance of controls with respect to future scenarios of climate and landscape for the region. Our study contributes to a better understanding of what environmental factors could be managed to enhance regional water security in an uncertain climate future.

## 3.2. Methods

### 3.2.1. Study site

This study is focused on catchments located in the central Appalachian Mountains region in the eastern US. We included 29 catchments in the states of Maryland, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia and West Virginia, extending from 34 ° - 42° North and 75° - 85° West (Figure 3.1). The selected catchments (Table 3.S1) are part of the Hydro - Climatic Data Network (HCDN) [*https://water.usgs.gov/osw/hcdn-2009/*]. The HCDN network is a subset of USGS stream gauges with relatively low levels of human disturbance and a long-term record that permit for hydroclimatological analysis (Lins, 2012). The 29 catchments used in this study were previously studied by Gaertner et al. (2019) that examined growing season length trends in temperate broad-leaf forest and Gaertner et al. (2020) that examined streamflow sensitivity to climate change. Summary information of the study site are presented in Table 3.1. These catchments drain five basins important to the eastern and mid-western US: the Monongahela, Ohio, Kanawha, Potomac and Tennessee. For the purpose of this study, due to their geographical location and the low number of HCDN catchments included in some basins, catchments were categorized into three groups: the Ohio - Monongahela; Kanawha-Tennessee, and the Potomac. The former two basin groups are located west of the eastern continental divide, with the Potomac located on the east and predominantly leeward side of eastern continental divide (Figure 3.1).

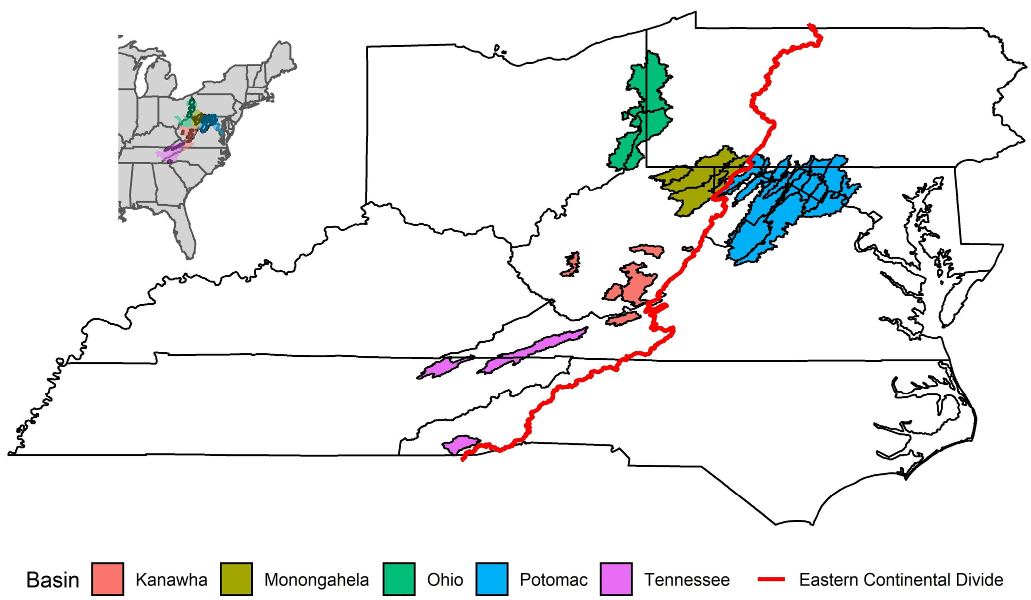


*Figure 3.1 Location map of the selected USGS HCDN catchments studied in the central Appalachian mountain region and the eastern continental divide in the US.*

### 3.2.2. Budyko Framework

Budyko (1974) advanced understanding of the interaction between water demand and water supply, given by the evaporative index and dryness index, respectively, to influence the partition of precipitation into runoff or evaporation. Several equations representing the original Budyko framework were developed in the previous century (e.g. Budyko, 1974; Ol'dekop, 1911; Pike, 1964; Schreiber, 1904), progressively evolving into parametric functions (Choudhury, 1999; Fu, 1981; Zhang et al., 2004). There are two lines of parametric equations, where the Budyko parameter is denoted as either $n$ (Choudhury, 1999) or $w$ (Fu, 1981; Zhang et al., 2004). These parameters however are analogous and explain the same underlying controlling processes (Yang et al., 2008). Budyko's $n$ can be considered an integrative coefficient of the catchment characteristics that aids in the prediction of E based on the long-term hydroclimatology of a basin (Roderick & Farquhar, 2011). Here, we used a Budyko equation form developed by Choudhury (1999) (Equation 1) and obtained Budyko's *n* values for our catchments from Gaertner et al. (2020).

$$E = \frac{P * PE}{[P^n + PE^n]^{\frac{1}{n}}} \qquad \text{Equation 1.}$$

The Budyko framework is graphically shown in Figure 3.2, where catchments are presented as a function of the DI (x axis) and the EI (y axis). The abscissa represents how dry a catchment is on average: catchments with a DI < 1, are considered energy limited/humid since P > PE; and catchments that have a DI > 1 are water limited (PE > P) or drier catchments. Catchments are theoretically bound to fall under the *Energy limit* (which follows the identity line), where E = PE, and the *Water Limit*, where the E = P. The Budyko parameter *n* determines the shape of the curve that describes the catchment. Those catchments with a higher Budyko's *n* are closer to the energy and water limits, meaning that a higher Budyko's *n* is equivalent to a greater capacity of precipitation partitioning at a given dryness index. Hence, understanding what controls are more related to Budyko's *n* constitutes a shorthand to the importance of the respective control to precipitation partitioning.

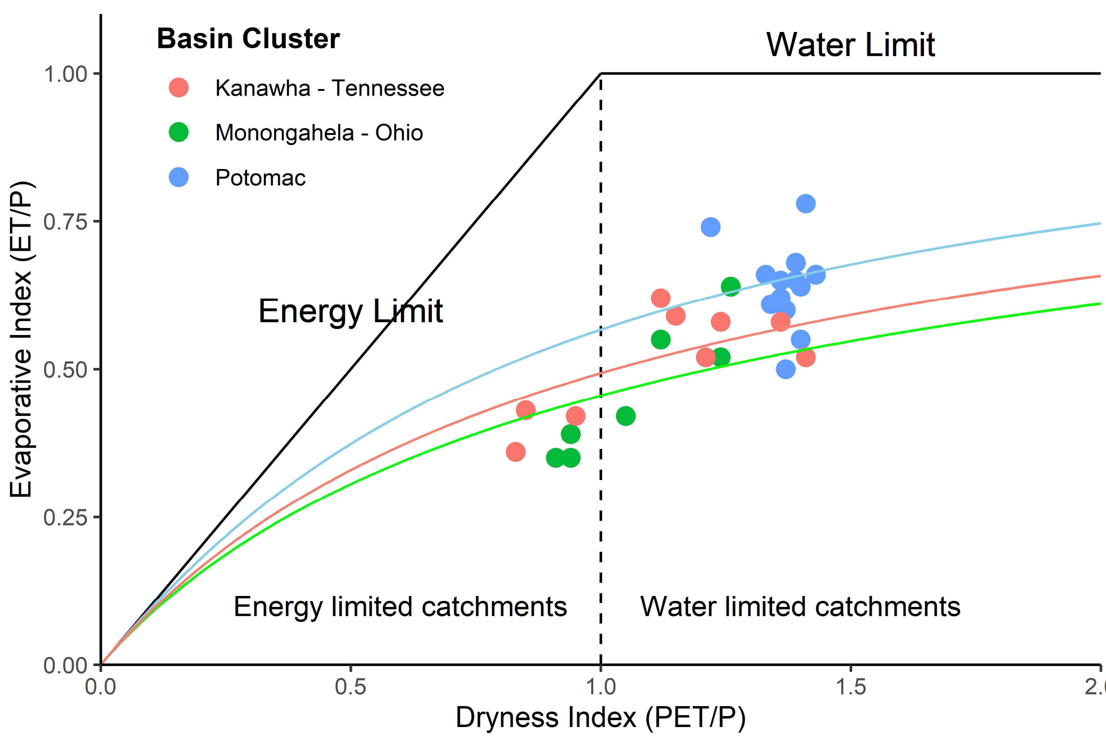


*Figure 3.2 Study catchments of the central Appalachian Mountain region plotted in the Budyko framework. Plotted Budyko curves are based on the average Budyko n value for each basin group.*

*Table 3.1 HCDN catchment characteristics summarized by basin group and region (Data from Gaertner et al. (2020)).*

| Variable | Kanawha-Tennessee | Monongahela-Ohio | Potomac | central Appalachian mountain region |
|---|---|---|---|---|
| Area ($km^2$) | 1285 | 887 | 1413 | 1246 |
| Precipitation (P)[mm] | 1238 | 1183 | 1015 | 1125 |
| Runoff (Q) [mm] | 612 | 649 | 365 | 510 |
| evaporation (E) [mm] | 626 | 534 | 651 | 615 |
| Potential evaporation (PE) [mm] | 1355 | 1247 | 1385 | 1342 |
| Dryness index (DI)[*unitless*] | 1.12 | 1.07 | 1.37 | 1.22 |
| Evaporative index (EI) [*unitless*] | 0.51 | 0.46 | 0.64 | 0.56 |
| Budyko's *n* [*unitless*] | 0.98 | 0.88 | 1.22 | 1.06 |

### 3.2.3. Data

*Climatic controls*

We used climatic controls found to be important to precipitation partitioning as summarized in Padron et al. (2017)'s global meta-analysis. These include annual averages of precipitation, minimum and maximum temperature, potential evaporation and soil moisture which were obtained at monthly scales from TerraClimate (Abatzoglou et al., 2018). Daily precipitation was obtained from gridMET (Abatzoglou, 2013). Gridded data in both gridMET and TerraClimate have a spatial resolution of $1/24^{th}$ °C ~ 4 km. The time frame selected for the analysis was 40 years, spanning from 1979 until 2018, since it was the longest common time frame between the data sets. The climatological controls derived from these datasets represent precipitation, snow and temperature, seasonality and storage controls (Padron et al., 2017). A detailed description of the controls and their theoretical effects on precipitation partitioning are shown in Table 3.2.

*Table 3.2 Description of climate controls and their theoretical effects on precipitation partitioning in the Central Appalachian Mountain region.*

| Variable (Abbreviation)[unit] | Description | Theoretical effect on Precipitation Partitioning |
|---|---|---|
| Mean Annual Temperature (MAT) [°C] | Long-term average annual temperature. | Higher temperatures increase atmospheric water demand and evaporation. |
| Mean Annual Precipitation (MAP) [mm] | Total annual precipitation over long term periods. | Expected to increase runoff in energy limited, and increase E in water limited catchments as more water is available. |
| Average Storm Depth (ASD)[mm] | Reflects the magnitude of an average storm by showing the average rainfall of rainy days. | Larger storms satiate soil storage and increase runoff. |
| Storm Arrival Rate (SAR)[days] | Reflects how often it rains calculated as the amount of rainy days in a year. | For energy limited catchments a continuous supply of water would increase runoff; for water limited catchments, more rainy days decrease radiation and favor runoff. |
| Fraction of Precipitation Falling as Snow (FSNOW) [*unitless*] | Reflects the proportion of total precipitation that occurs in the form of snow; calculated based on months with mean temperature < 2°C. | More snow in both humid and arid catchments should favor runoff as it melts, especially when soils are saturated and if rainfall over snow occurs. Sublimation processes might increase E. |
| Maximum Accumulation Monthly Surplus (MAMS) [mm] | Reflects the maximum water storage of a catchment; calculated by determining the maximum amount of water accumulated in consecutive months from the difference of monthly P - PE (Williams et al., 2012). | Higher water accumulation increases runoff. |
| Seasonal Surplus Index (SSI) [mm] | Reflects the condition if water surplus is more or less seasonal; calculated by subtracting MAMS from the long-term surplus (P - PE). | An increase in runoff should be expected in water limited catchments since it reflects periods when rainfall exceeds PE. The effect should be less important in energy limited catchments since water availability generally exceeds water demand. |
| Soil Moisture (SM) [mm] | Reflects storage or the amount of water present and available for evaporation or runoff. | The influence of more or less water depends on the energy balance of the catchment; in energy limited catchments runoff will be favored and in water limited catchments, it contributes to more evaporation. |
| Relative amplitude of the seasonal cycles of P, SAR and PE (SEAS.P, SEAS.SAR and SEAS.PE) [*unitless*] | Reflects seasonality, i.e. extent of differences between maximums and minimums relative to annual averages. Calculated as the coefficient of the differences of monthly maximum and monthly minimum between the annual mean. | More seasonal precipitation and storm arrival rates would increase runoff for specific periods. |
| Phase shift of the seasonal cycles of precipitation and potential evaporation (PS.P.PE) [*unitless*] | Reflects if water supply and demand are synchronized or not. Calculated as the negative correlation between monthly P and PE. | Highly influential for partitioning if the two variables are in phase larger evaporation is possible. If the two variables are out of phase runoff is likely to increase. |

*Landscape controls*

We selected a set of landscape controls known to be influential to precipitation partitioning (Padron et al., 2017). Controls are based on the topographic characteristics of each catchment (n=29), including elevation, slope, aspect, and compound topographic index. Most variables were derived from the Hydro1K dataset (Earth Resources Observation And Science (EROS) Center, 2017). Two vegetation variables were included in the analysis: mean growing season length from 1981 - 2012 from Gaertner et al. (2019) and average Normalized Difference Vegetation Index (NDVI) (1982-2012) during growing season months (June, July, and August) for the Northern Hemisphere extracted from Advanced Very High Resolution Radiometer (AVHRR) sensors on NOAA satellites (Guay et al., 2015). We also included Land Use and Land Cover spatial data, consisting of a 300 m spatial resolution data from the European Space Agency Climate Change Initiative - Land Cover Project 2017, using the ESA-CCI-LC v.2.0.7 data set [www.esa-landcover-cci.org]. We used the land cover map of 2015, considering that land cover changes were relatively low in HCDN catchments in the region (Gaertner et al., 2019). Since, the ESA-CCI-LC v.2.0.7 has a wide range of specific land cover types, we grouped together similar land cover (e.g. 'Coniferous forest' and 'Broad-leaf forest' into 'Forest') in order to quantify the percent cover in each catchment of forests, grasses, crops, urban/bare and water bodies (Figure 3.5). Finally, we included catchment morphological parameters of catchment area, compactness ratio, elongation ratio and linearity index. A detailed description and their theoretical effects on precipitation partitioning are presented in Table 3.3.

*Table 3.3 Landscape controls descriptions and theoretical effects on precipitation partitioning for the Appalachian region.*

| Variable (Abbreviation)[unit] | Description | Theoretical effect on Precipitation Partitioning |
|---|---|---|
| Aspect [*unitless*] | Reflects the main geographical orientation to where the hillsides face in a catchment. | Aspect influences the amount of solar radiation received by the catchments depending on their latitude; thus, in the Northern Hemisphere, South facing catchments that receive more radiation would favor partitioning towards evaporation. |
| Compound Topographic Index (CTI) [*unitless*] | Reflects the relief of the terrain with respect to the slope and the drainage contributing area. It can be considered a proxy of a steady state soil wetness. | Higher CTI represents more potential for larger soil water accumulation favoring increased evaporation. |
| Elevation [m] | Reflects terrain altitude derived from the digital elevation models. | Higher elevations are associated with colder temperatures, higher cloudiness, more precipitation and a lower potential evaporation; creating conditions that favor runoff. |
| Slope [%] | Reflects the terrain steepness. | Steeper terrain will favor partitioning towards runoff since water residence times in the catchments are reduced. |
| Length of the Growing Season (LOS)[days] | Reflects average length of the vegetative growing season. | A longer growing season indicates higher evaporation as broadleaf forest have more capacity to transpire and interception is higher for longer periods of the year. |

| | | |
|---|---|---|
| Normalized Difference Vegetation Index (NDVI) [*unitless*] | Reflects the amount of vegetation present in the catchments, also considered a measure of greenness. | Larger NDVI would indicate more evaporation capacity due to the increase transpiration by more plants. |
| Percent cover of different Land uses (Forest C, Grass C, Crop C, Bareland C, Waterbodies C) [%] | Reflects the percentage a particular land use cover has over the total area of a catchment. | Generally, land covers that slow the movement of water in the landscape (e.g. forest) should favor evaporation and reduce runoff due to higher interception, transpiration and infiltration. Barelands or urban developments should increase runoff as they decrease storage. |
| Area [$km^2$] | Reflects the surface area of the catchment. | The size of a catchment will mostly influence partitioning at the extent of the variability of the characteristics of the catchment. |
| Compactness ratio (Compact)[*unitless*] | Reflects the complexity of a polygons shape, it is calculated by dividing the area by the perimeter. | More complex catchment shapes can be related to terrain complexity, but the effect on runoff is not clear. |
| Elongation ratio (Elongation)[*unitless*] | Reflects the shape of a catchment. | Catchments that have a more oblong shape will have longer residence times than catchments that have more circular shapes, meaning that E might be favored in oblong catchments. |
| Linearity index (Linearity) [*unitless*] | Reflects how well a polygon can be described by a straight line; calculated based on a regression analysis of the polygon's nodes coordinates. | More linear watersheds can slow down runoff accumulation favoring evaporation. |

### 3.2.4. Analysis

We began our analysis by finding the relative importance of Budyko's *n* and the dryness index for the partitioning of precipitation. Specifically, the squared semi-partial correlation was calculated to find the variance of the EI that is solely explained by the dryness index ($EI_{DI}$, Equation 2) and the variance of the EI that is solely explained by Budyko's *n* ($E_n$, Equation 3). Then, the redundant variance ($Rd$) was calculated, which combines both Budyko's *n* and dryness index variance (Equation 4). The upper limit of the explained variance (EV, Equation 5) is then computed by adding $Rd$ and finally, the relative importance of each Budyko component was calculated using Equations 6 and 7. We carried out this procedure for the whole region, and then to each separate basin group after we used the Kruskal-Wallis test to determine that basin groups influenced the evaporative index and Budyko's *n*.

$$E_{DI} = \rho^2_{EI(DI,n)} = \frac{[\rho_{(EI,DI)} - (\rho_{(EI,n)}) * (\rho_{(DI,n)})]^2}{1 - \rho^2_{(DI,n)}} \qquad \text{Equation 2}$$

$$E_n = \rho^2_{EI(n,DI)} = \frac{[\rho_{(EI,n)} - (\rho_{(EI,DI)}) * (\rho_{(DI,n)})]^2}{1 - \rho^2_{(DI,n)}} \qquad \text{Equation 3}$$

$$Rd = \rho^2_{EI,DI} - \rho^2_{EI(DI,n)} = \rho^2_{EI,n} - \rho^2_{EI(n,DI)} \qquad \text{Equation 4}$$

$EV = E$ (lower limit) & $EV = E + Rd$ (upper limit) Equation 5

$$RI_{DI} = \frac{EV_{DI}}{E_{DI}+E_n+Rd} \quad \text{Equation 6}$$

$$RI_n = \frac{EV_n}{E_n+E_{DI}+R} \quad \text{Equation 7}$$

A second analysis examined the relationship between controls and partitioning using two approaches. First, we looked at the relationship between each individual climate and landscape control variable (Tables 3.2 & 3.3) and Budyko's *n* (sensu Padron et al., 2017) while controlling for location. We computed the partial correlations between each variable and Budyko's *n*, by correlating the residuals from the variable and Budyko's *n* regression's and the geographic locations of the catchments. Land cover controls with very low presence (<1%) in the catchments were not included in the partial correlation analysis. Partial correlation p-values were adjusted (Benjamini & Hochberg, 1995) to avoid overstatement of the significance of the environmental controls. Correlations were considered significant at alpha = 0.05. The second approach consisted of building a set of candidate multivariate models to identify robust predictors of long-term evaporation (sensu Younger et al., 2020). We used the controls with the highest correlations and statistical significance from the first approach in this step and also included the dryness index. Candidate models were selected using the Akaike Information Criteria (AIC) and Mallow's P. This process included a backward and forward stepwise regression.

Code and calculations for the different controls and analysis were carried out using *R* statistical software (R Core Team, 2019) and the following packages: *tidyverse* for data management (Wickham et al., 2019); *rgdal* (Bivand et al., 2019), *raster* (Hijmans, 2020), *sp* (Bivand et al., 2013), and *whitebox* (Wu, 2020) for spatial analysis; *ppcor* (Kim, 2015) for correlation analysis and *MASS* (Venables & Ripley, 2002) for the stepwise regression.

## 3.3. Results

### 3.3.1. Climate and Landscape controls of central Appalachian catchments.

Generally, the basins examined in this study do not present large differences in their climate characteristics, although there are some important exceptions (Table 3.4, Figure 3.3). For instance, precipitation (MAP) was lower in the Potomac basin (12% lower than the Monongahela-Ohio and 20 % lower than the Kanawha-Tennessee). Another important difference was that the seasonal surplus index (SSI), on average 92 mm, was three times larger in the Potomac (Figure 3.3, Table 3.4). Also, maximum accumulation monthly surplus (MAMS) in the Potomac was 40% less than the other two basin groups (Figure 3.3). It rains roughly 60% of the days in a year, as shown by the storm arrival rate (SAR) of 223 days of rain per year, with less rainy days in the Potomac (Figure 3.3). The fraction of precipitation that falls on average as snow (FSNOW) in the region was 0.15. Precipitation is well distributed across the year and more variable in the Potomac (Figure 3.3). Mean annual temperature (MAT) had a regional average of 11°C, with the Potomac as the warmest basin with 11.4°C, followed by Kanawha-Tennessee with

11.29°C and Monongahela-Ohio with 9.9°C, as the coldest basin. Seasonality of potential evaporation was higher than the seasonality of precipitation variables since there is more energy available during the summer months. Finally, the phase shift of the seasonal cycles of precipitation and potential evaporation (PS.P.PE) was on average -0.21, meaning that precipitation and potential evaporation occur slightly in phase.

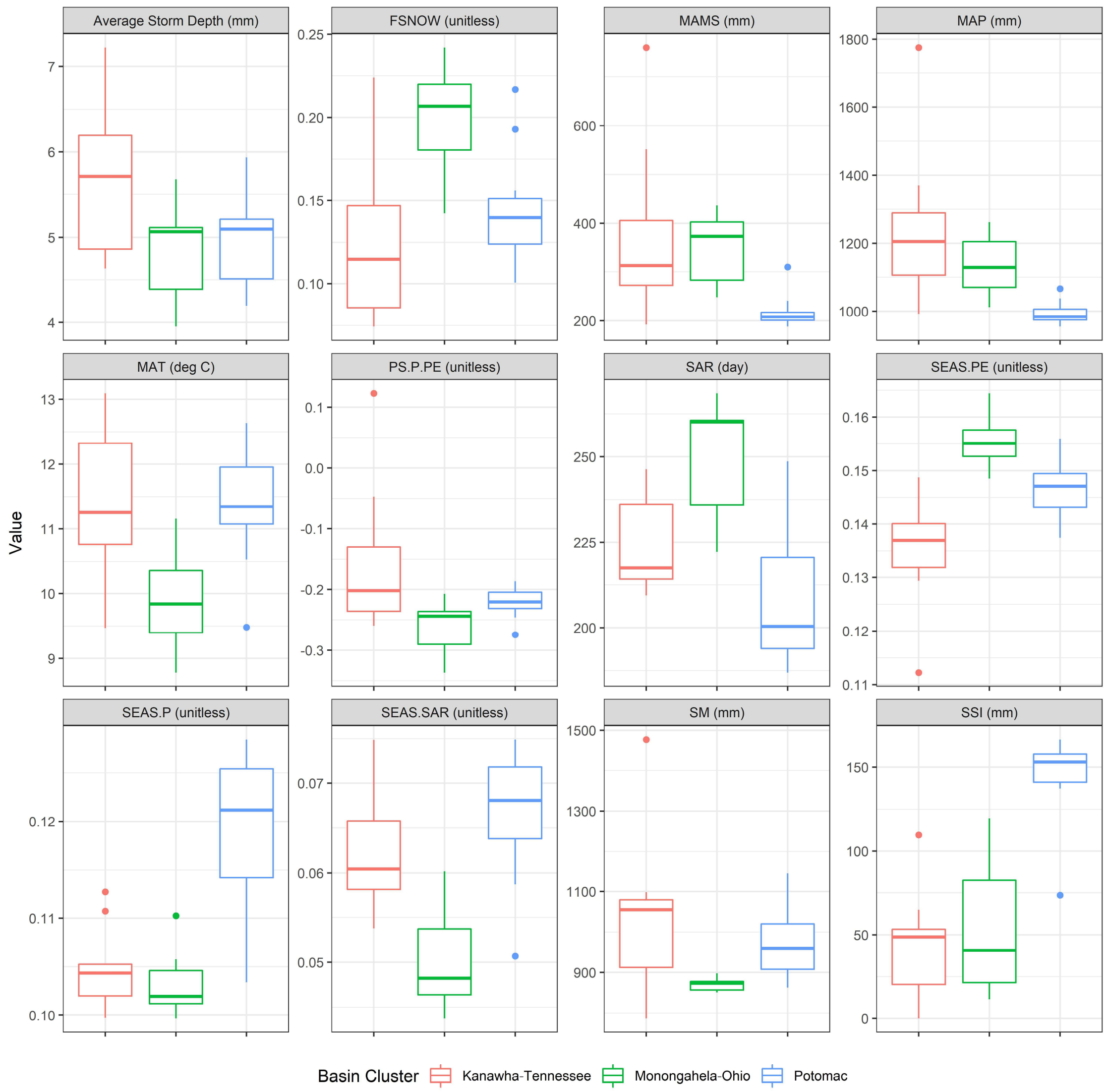


*Figure 3.3 Boxplot of climate controls for central Appalachian HCDN catchments.*

Mean catchment elevation ranged between 157 – 915 m with the Potomac presenting the lowest elevations (Figure 3.4). Average slopes were 10.73 %, ranging from 4-22 %, with Kanawha-Tennessee being the steepest basin group (Figure 3.4). Aspects were similar between most of the catchments except the ones in the Potomac. The main land use and land cover was represented by forest (76.34 %) and grasses (21.58 %), however, several catchments in the Potomac had low forest cover (<30%) (Figures 3.4 & 3.5 and Table 3.4 & 3.S1). Grass cover was smaller in the Kanawha-Tennessee basin and similar in the Potomac and Monongahela-Ohio basin groups (Figure 3.4). The remaining land cover types included cropland, urban/bare lands and water bodies, which together represented less than 3 % of the total area (Table 3.4), yet, it is worth mentioning that a catchment in the Potomac had 1.46 % cropland, high in comparison to the rest of the catchments (Table 3.S1). The regional average of the length of the growing season (LOS) was 179 days and was similar between basin groups (Figure 3.4). NDVI was on average 0.89 and lowest and more variable in the Potomac (Figure 3.4).

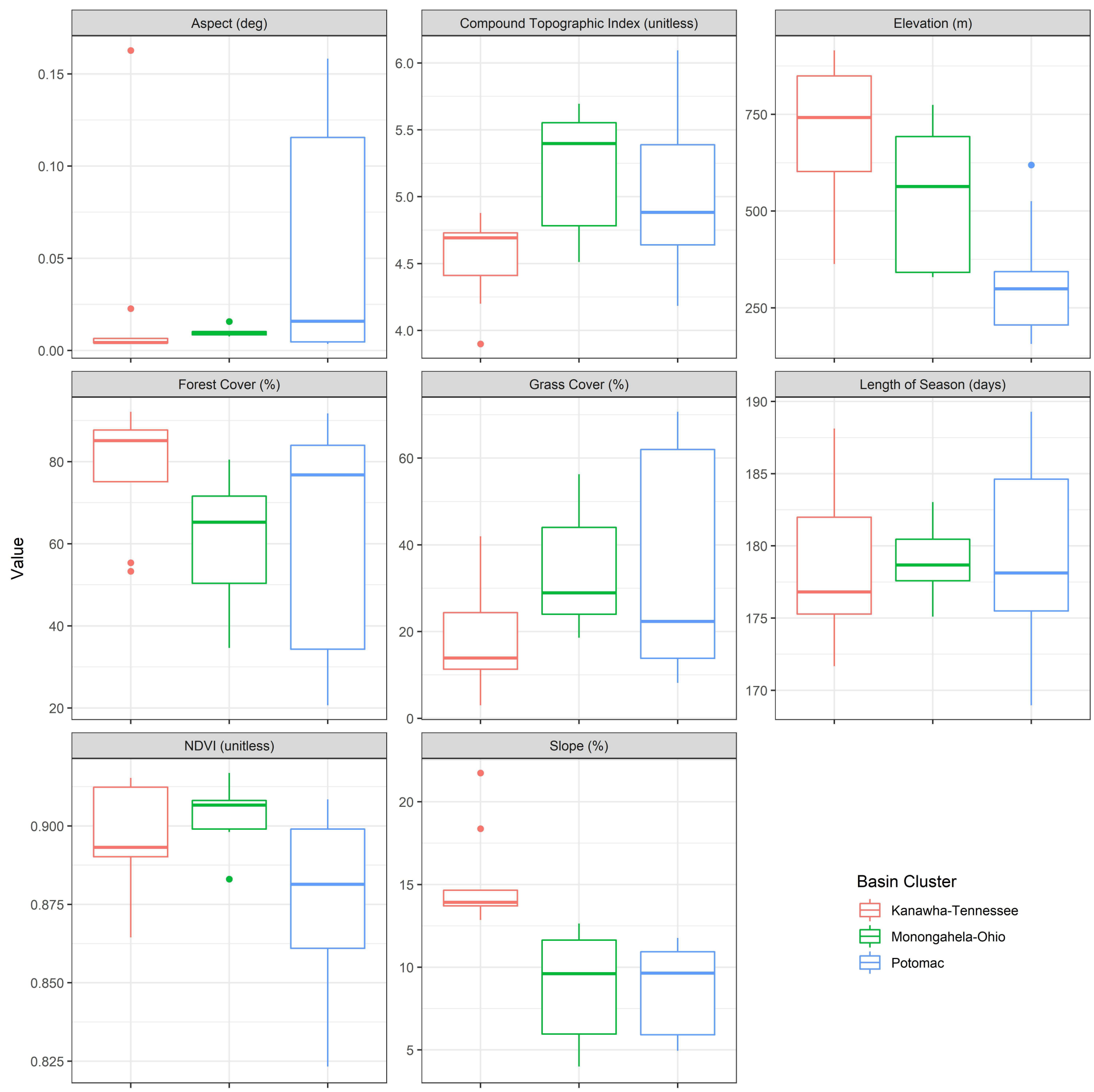


*Figure 3.4 Boxplot of landscape controls for central Appalachian HCDN catchments.*

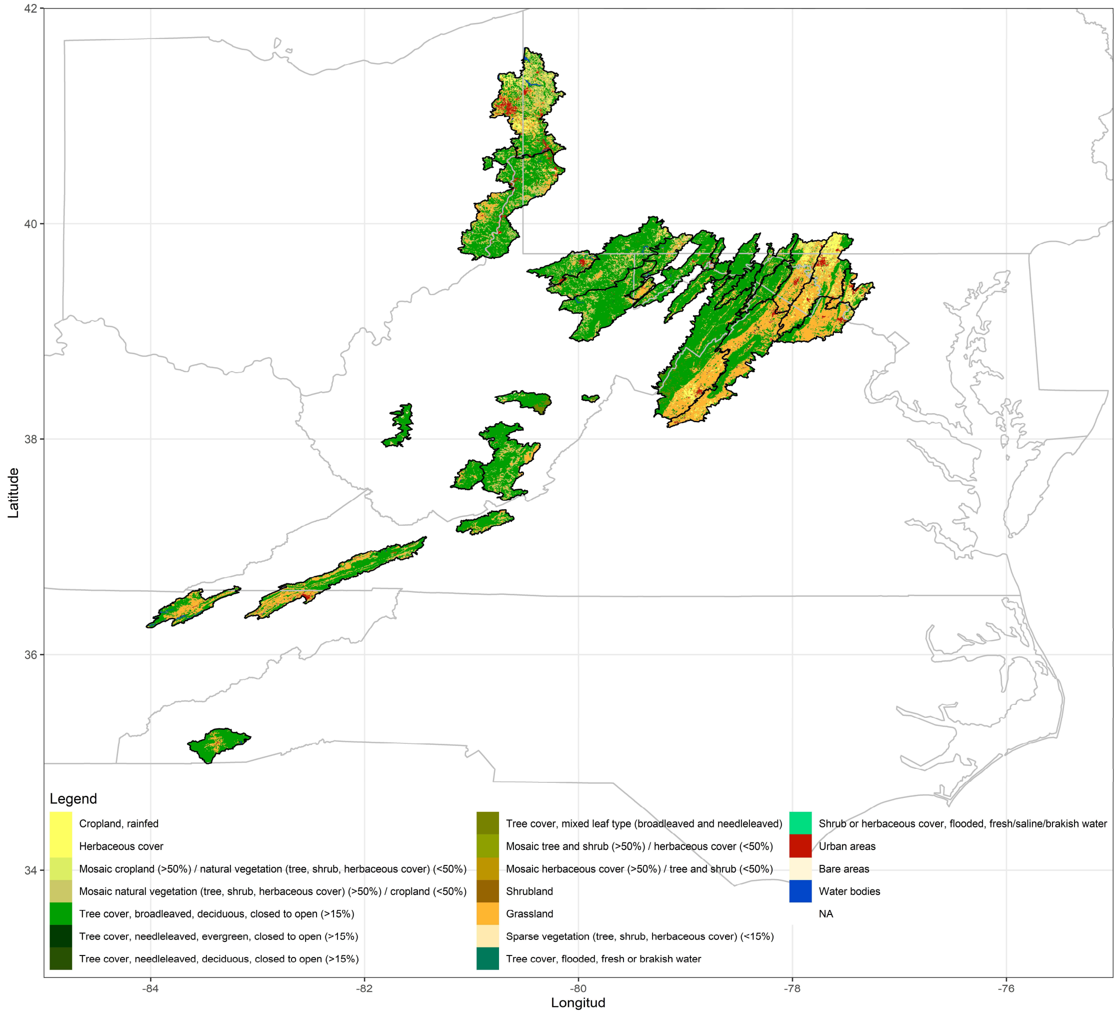


*Figure 3.5 Land cover and land use of central Appalachian HCDN catchments. Source: European Space Agency Climate Change Initiative – Land Cover Project 2017 (www.esa-landcover-cci.org).*

### 3.3.2. Budyko's *n* parameter exceeds dryness index in relative importance for precipitation partitioning.

Based on the semi partial correlation analysis, Budyko's $n$ was more influential than the dryness index on precipitation partitioning across the region and basin groups (Figure 3.6). The relative importance of Budyko's $n$ was nearly ten times greater (55.3%) than the dryness index (4.8%). Moreover, there are important interactions between both variables, as is shown by the importance of the redundant variance (39.9%), being almost as high as the importance of the Budyko $n$ parameter, which can be understood as the influence that the dryness index has over processes that will change the Budyko $n$ parameter. For instance, a higher dryness index will influence a catchment's vegetation characteristics which will in turn alter the catchments Budyko parameter.

*Table 3.4 Basin group summaries of climatic controls in central Appalachian HCDN catchments.*

| Variable | Kanawha-Tennessee | Monongahela-Ohio | Potomac | central Appalachian mountain region |
|---|---|---|---|---|
| MAP (mm) | 1243 | 1136 | 994 | 1105 |
| ASD (mm) | 5.62 | 4.82 | 5.00 | 5.15 |
| SAR (days) | 224 | 249 | 209 | 223 |
| MAT (°C) | 11.3 | 9.9 | 11.4 | 11.0 |
| FSNOW (*unitless*) | 0.13 | 0.20 | 0.14 | 0.15 |
| SEAS.P (*unitless*) | 0.10 | 0.10 | 0.12 | 0.11 |
| SEAS.SAR (*unitless*) | 0.06 | 0.05 | 0.07 | 0.06 |
| SEAS.PE (*unitless*) | 0.14 | 0.16 | 0.15 | 0.15 |
| PS.P.PE (*unitless*) | -0.15 | -0.26 | -0.22 | -0.21 |
| MAMS (mm) | 380 | 347 | 217 | 299 |
| SSI (mm) | 42 | 54 | 146 | 92 |
| Soil moisture (mm) | 1022 | 870 | 968 | 961 |
| Aspect (*unitless*) | 0.02 | 0.01 | 0.06 | 0.04 |
| Elevation (m) | 696 | 534 | 318 | 487 |
| Forest cover (%) | 78 | 61 | 62 | 67 |
| Grass cover (%) | 20 | 34 | 34 | 30 |
| Cropland cover (%) | 0 | 0 | 0 | 0 |
| Urban/bare land cover (%) | 1 | 3 | 2 | 2 |
| Water bodies cover (%) | 1 | 1 | 0 | 1 |
| LOS (days) | 179 | 179 | 179 | 179 |
| NDVI (*unitless*) | 0.89 | 0.90 | 0.88 | 0.89 |
| Slope (%) | 15.16 | 8.78 | 8.70 | 10.72 |
| CTI (*unitless*) | 4.54 | 5.18 | 5.04 | 4.92 |
| Elongation ratio(*unitless*) | 0.56 | 0.56 | 0.62 | 0.59 |
| Compactness ratio (*unitless*) | 0.03 | 0.04 | 0.03 | 0.03 |
| Linearity index (*unitless*) | 0.25 | 0.36 | 0.55 | 0.41 |

We analyzed the relative importance of the dryness index and Budyko's *n* for each of the basin groups (Figure 3.6) after confirming through a Kruskal-Wallis test that basin groups were influential on the evaporative index (chi-squared=16.64, p-value < 0.05) and Budyko's *n* (chi-squared=12.84, p-value < 0.05). Results showed that the Kanawha-Tennessee basin group had the highest dryness index importance, although still low (3.2%) and the second highest relative importance explained by Budyko's *n* (75.4%), with only 21.4% redundant explained variance by both factors. The Monongahela-Ohio had the highest redundant explained variance (89.1%), extremely low importance of dryness index (0.1%), and low importance of Budyko's *n* parameter (10.8%). Finally, in the Potomac redundant variance was negative (-0.8%) since dryness index and Budyko's *n* were negatively correlated. The importance of the Budyko's *n* in the Potomac was the highest (99.7%), while dryness index was minimal (1%).

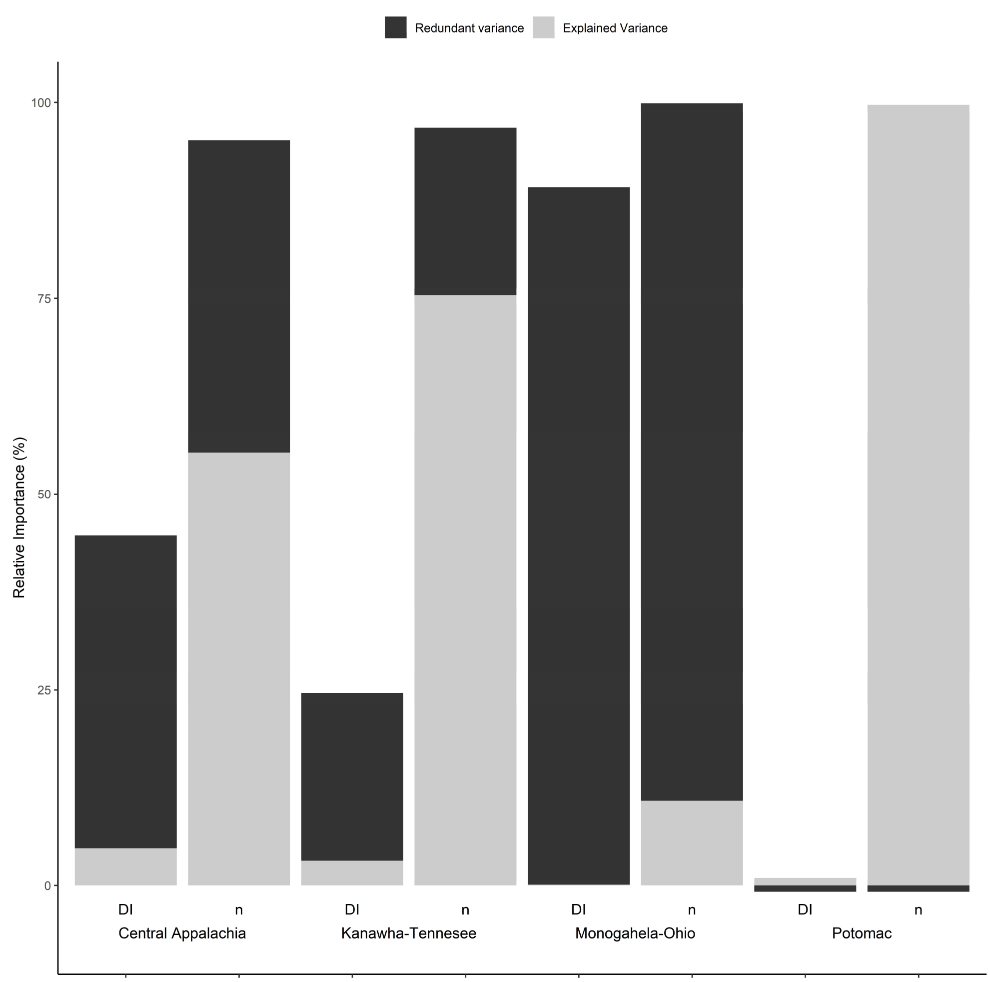


*Figure 3.6 Relative importance Budyko's n and Dryness index for precipitation partitioning for central Appalachian HCDN catchments, Kanawha-Tennessee, Monongahela-Ohio and Potomac basin groups.*

*Climate controls correlations with Budyko's* n.

Of the climate controls analyzed in this study, temperature related variables were the most important climate controls for precipitation partitioning (Figure 3.7 and Table 3.S2). Mean annual temperature (MAT) (0.52, p value < 0.05) and the fraction of precipitation falling as snow (FSNOW)(-0.52, p-value < 0.05) were the only two climate controls that were statistically significant. Other controls, such as seasonal surplus index (SSI), soil moisture (SM) , maximum accumulation monthly surplus (MAMS) were also strongly correlated, but not significant (Figure 3.7, Table 3.S2). Correlation analysis for the Kanawha-Tennessee, the southernmost basin group, showed several strong correlations that favored runoff: maximum accumulation monthly surplus (MAMS) (-0.82, p-value = 0.25), precipitation (-0.79, p-value = 0.25) and average storm depth (ASD) (-0.77, p-value = 0.25), but none were statistically significant. In the Kanawha-Tennessee basin group the variables that favored evaporation were only temperature, soil moisture and seasonal surplus index. The Monongahela-Ohio basin group had two variables that were statistically significant: mean annual precipitation (-0.99, p-value < 0.01) and seasonal surplus index (0.99, p-value < 0.05). In contrast to the other two basin groups, the Potomac had the most variables favoring evaporation, from which the most important was the storm arrival rate (0.61, p-value = 0.24) followed by mean annual precipitation, maximum accumulation monthly surplus and fraction of precipitation falling as snow; the strongest climate controls favoring runoff were the seasonality of storm arrival rate and the seasonal surplus index. Partial correlations between the climate controls and Budyko's *n* are shown in Figure 3.7 and Table 3.S2.

In addition to the partial correlation analysis, we found through examination of scatter plots of the climate controls that there were differences between the Potomac and the other two basin groups (Figure 3.S1). Two examples were maximum accumulation monthly surplus (MAMS) and precipitation: in the Monongahela-Ohio and Kanawha-Tennessee basin groups the two controls have a negative slope, i.e. higher maximum accumulation monthly surplus and precipitation are related to lower Budyko's *n* and more runoff. On the other hand, the Potomac shows that increasing maximum accumulation monthly surplus and precipitation is related to higher Budyko's *n* values allowing for more evaporation to take place.

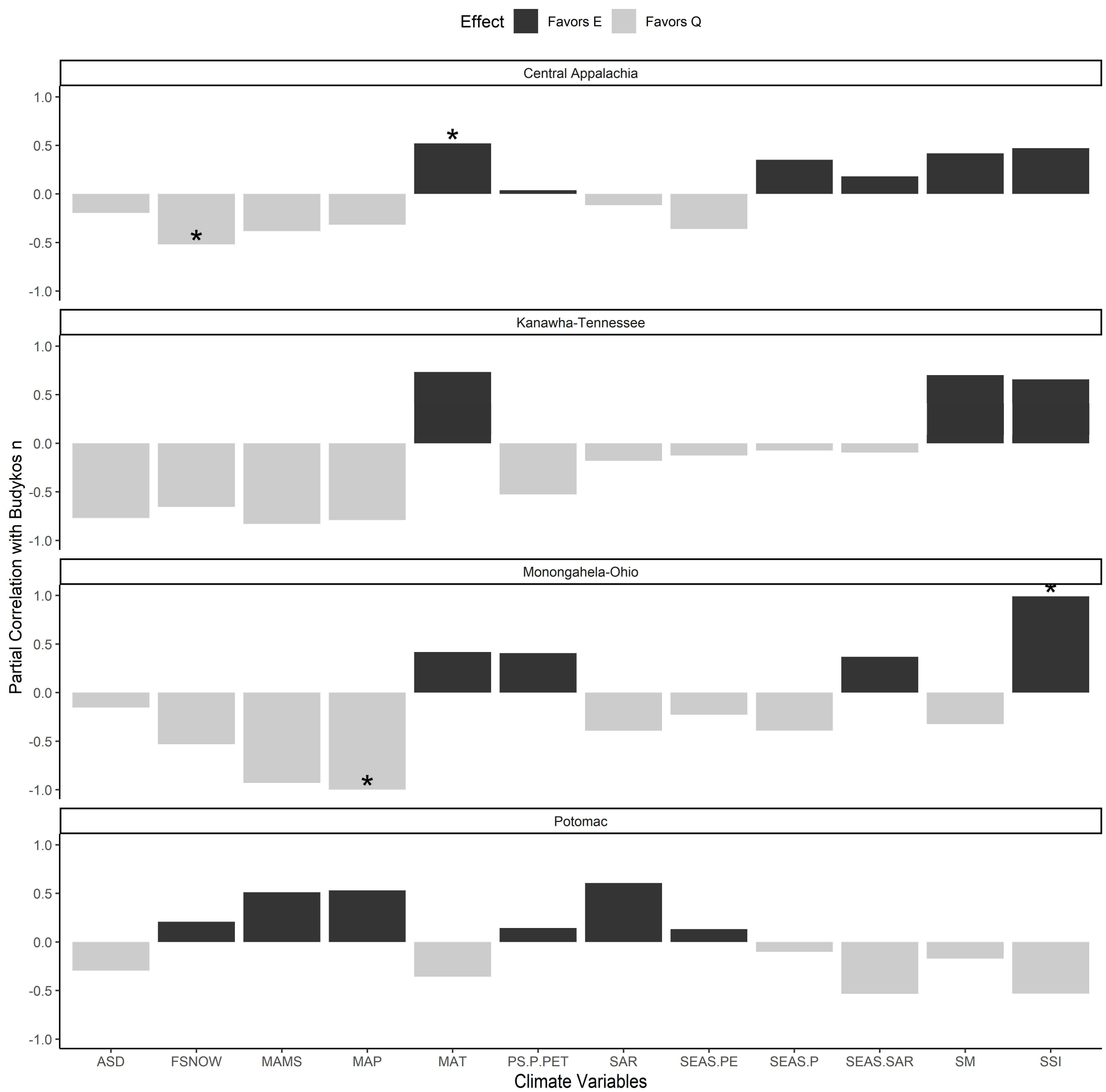


*Figure 3.7 Partial correlations between climate controls and Budyko's n. Statistically significant (p-value <0.05) controls are denoted by * according to the adjusted p-value.*

### 3.3.3. Landscape controls exert low influence on partitioning.

Of the landscape controls analyzed in this study, only elevation was significant (-0.54, p-value < 0.05)(Figure 3.8) while slope had the lowest correlations favoring runoff in the central Appalachian mountain region. There were no statistically significant variables in the basin based analysis. In the Kanawha-Tennessee basin group, the highest negative correlations were elevation, forest cover and urban/bare cover. In the Monongahela-Ohio basin group, aspect had the strongest negative correlation and length of season had the most important positive correlations. In the Potomac basin, grass cover favored evaporation the most. Three variables favored runoff: forest cover, slope and NDVI (Figure 3.7). The morphological controls (area, compactness index, elongation ratio and linearity index) did not show high or significant correlations for the central Appalachian mountain region; but the elongation correlation was > 0.4 in the Monongahela-Ohio and the compactness ratio was > 0.4 in the Potomac (Figure 3.S2).

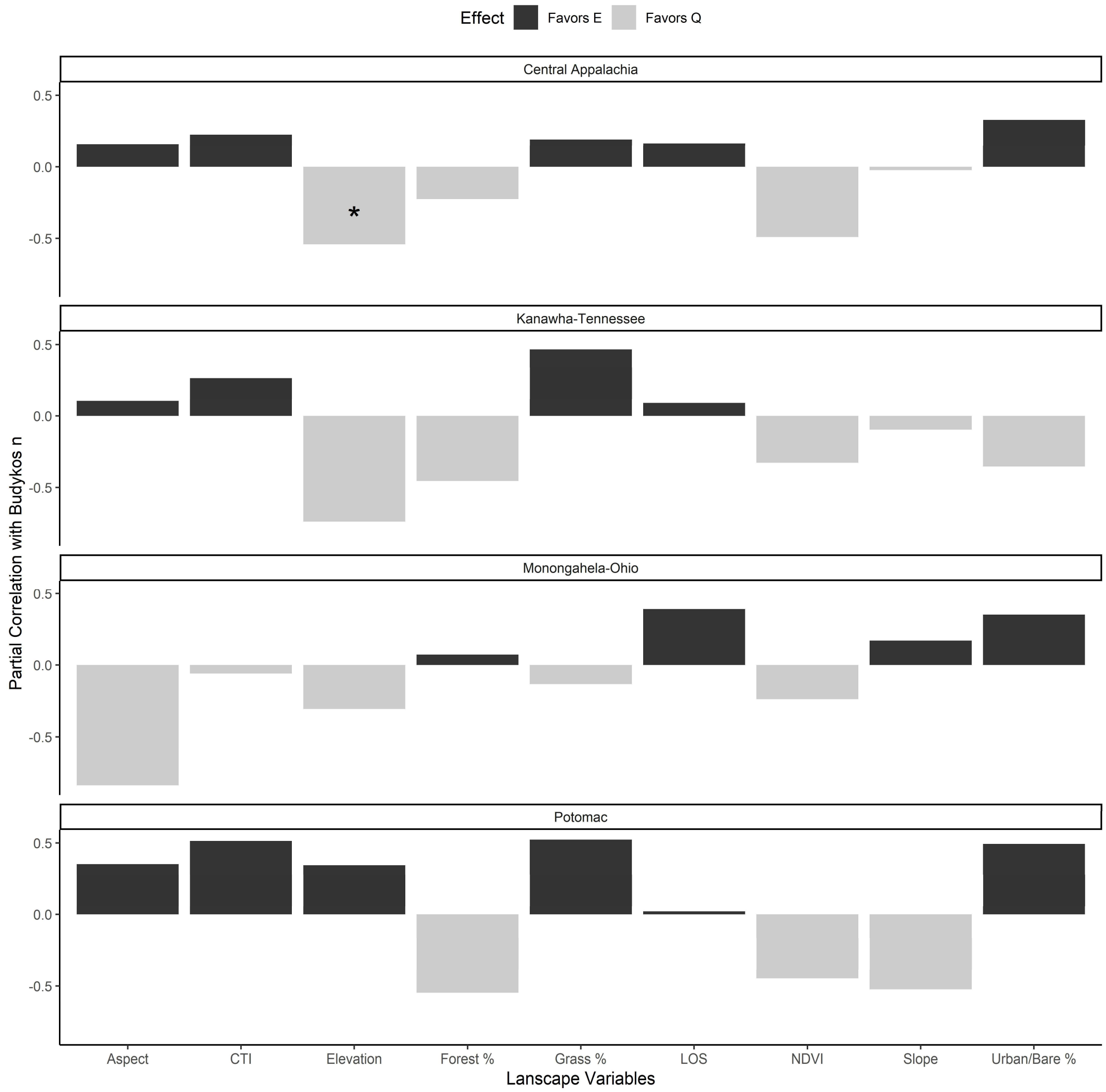


*Figure 3.8 Partial correlations between landscape controls and Budyko's n. Statistically significant controls are denoted by * according to the adjusted p-value < 0.05.*

Contrary to the climatic controls, where the Potomac basin had a different behavior in several of the controls, scatter plots and regressions of the landscape controls and Budyko's *n* did not exhibit stark differences in most trend directions between the three basin groups (Figure 3.S3). In terms of the landscape controls, the main differences are present only with slope and elevation. The Potomac is the only basin that has increasing Budyko's *n* values at higher elevations and steeper slopes. In the other two basin groups the Budyko's *n* decreases, meaning that higher elevation and steeper terrain favor runoff.

Finally, the stepwise multivariate linear regression analysis showed that mean annual temperature (MAT) and the fraction of precipitation falling as snow (FSNOW) were the most important variables that explain the variability in evaporation throughout the central Appalachian mountain region (Table 3.5). Models with a larger set of variables did not improve the model fit, but instead reduced the model's adjusted $R^2$, p-values and AIC (Table 3.5 and Table 3.S3).

*Table 3.5 Regressions results for the best six models that explain evaporation and important partitioning controls.*

| Model # | Variable | Estimate | Std. Error | t value | Pr(>\|t\|) | | model p-value | Adjusted $R^2$ | AIC |
|---|---|---|---|---|---|---|---|---|---|
| 1 | (Intercept) | -35.2 | 133.1 | -0.264 | 0.793 | | | | |
| | MAT | 59.09 | 12.03 | 4.91 | 3.88E-05 | *** | 0 | 0.4522 | 335.552 |
| 2 | (Intercept) | 822.45 | 46.92 | 17.53 | 2.80E-16 | *** | | | |
| | FSNOW | -1357.62 | 292.83 | -4.636 | 8.10E-05 | *** | 0 | 0.4226 | 337.076 |
| 3 | (Intercept) | 524.16 | 882.67 | 0.594 | 5.58E-01 | | | | |
| | MAT | 51.03 | 17.49 | 2.918 | 7.17E-03 | ** | 0 | | |
| | NDVI | -530.1 | 826.72 | -0.641 | 5.27E-01 | | 0.0002 | 0.44 | 337.097 |
| 4 | (Intercept) | -74.419 | 176.834 | -0.421 | 6.77E-01 | | | | |
| | MAT | 59.691 | 12.359 | 4.829 | 5.27E-05 | *** | 0.0002 | 0.4337 | 337.420 |
| | MAP | 0.028 | 0.0840 | 0.345 | 7.33E-01 | | | | |
| 5 | (Intercept) | -41.396 | 140.483 | -0.295 | 7.71E-01 | | | | |
| | MAT | 60.021 | 13.458 | 4.46 | 1.40E-04 | *** | 0.0002 | 0.4317 | 337.520 |
| | SSI | -0.044 | 0.265 | -0.168 | 8.68E-01 | | | | |
| 6 | (Intercept) | -17.219 | 184.275 | -0.093 | 0.9262 | | | | |
| | MAT | 57.915 | 14.711 | 3.937 | 0.0005 | *** | 0.0002 | 0.4316 | 337.529 |
| | Elevation | -0.010 | 0.0724 | -0.144 | 0.8865 | | | | |

### 3.4. Discussion

The first key result from our study is that precipitation partitioning was different depending on the scale and that it varied within the region due to the complexity created by the eastern continental divide. We found that the relative importance of the dryness index and Budyko's *n* in determining precipitation partitioning in the central Appalachian Mountains had a similar behavior to catchments denoted as "snow" in Padron et al. (2017): in our study, the relative importance of the dryness index was 4.8% and Budyko's *n* was 55.3%, similarly, snow catchments in Padron et al. (2017) showed lower relative importance of dryness index (17.4%) than that of Budyko's *n* (36.1%). These results corroborate the influence that regional climatologies have on precipitation partitioning found by Padron et al. (2017). However, we discovered that for the central Appalachian Mountains, classifying catchments based on regional climate obfuscates important complexities about the controls of precipitation partitioning when intra-regional analyses are made. In other words, we noticed that the controlling factors of partitioning are scale dependent, meaning that results could change dependent on the analytical unit chosen (e.g. region or sub-region). We found large divergence between basins that where geographically located either east or west of the eastern continental divide. The relative importance of dryness index and Budyko's *n* to partitioning in each of the basins was dissimilar and, if studied separately, the basins could no longer be considered solely as "snow" catchments. This was particularly true in the case of the Potomac basin, located leeward of the eastern continental divide and showed water-limited characteristics, in which the relative importance of dryness index and Budyko's *n* were negatively correlated, similar to the characteristic of "arid" catchments in Padron et al. (2017). The same less humid nature of the Potomac basin in comparison to the Kanawha-Tennessee and Ohio-Monongahela basin groups has been previously reported by Gaertner et al. (2020) and Fernandez & Zegre (2019), which are consistent with the known effects that the eastern continental divide has on the central Appalachian climate and meteorology (Wiley, 2008). Therefore, taking an intra-regional approach can complement water research's understanding on the influence of regional climates on partitioning, by showing that not all the basin groups might fit a general partitioning classification based on the large scale climatic regime, this consideration is more relevant when topographical climatic divides are found in the area.

Considering the intra-regional complexities provides insight into how specific variables control precipitation partitioning. For instance, energy limited catchments west of the eastern continental divide would partition higher amounts of summer precipitation towards higher runoff, but could mean larger partition towards evaporation and low contributions to runoff in the water limited catchments east of the eastern continental divide. Consequently, the less humid nature of the Potomac helps explain the contrasts in partial correlations between climate controls and Budyko's *n*. Controls that relate to increased water availability, such as, fraction of precipitation in the form of snow, maximum accumulation monthly surplus, precipitation, and storm arrival rate effectively favored evaporation in the Potomac instead of favoring runoff, as occurred in the other two basin groups, and as would be expected for the region considering large scale climate drivers (Fernandez & Zegre, 2019). The characteristics of the Potomac basin (e.g. located leeward of the continental divide; lower elevations; lower precipitation) result in a higher dryness index, permitting larger amount of water inputs to be partitioned towards evaporation than in the other two basin groups. In the Potomac, the seasonal surplus index was similar to previous reports of arid basins (Padron et al., 2017; Williams et al., 2012). We also found negative correlation between temperature and the seasonality of potential evaporation with Budyko's $n$ in the Potomac basin. These can be explained by warmer temperatures in winter months that create fast snow melts increasing winter runoff, or by higher temperatures are associated with precipitation events of larger magnitude, such as, summer convective precipitation events. Monongahela-Ohio and the Kanawha-Tennessee basin groups, on the other hand, behaved as expected for their 'snow' climate type where the precipitation related variables were highly important to favor runoff.

Another critical finding of our study is that climatic controls were more important than landscape controls. Mean annual temperature and fraction of precipitation falling in the form of snow were the most related variables to the Budyko partitioning parameter $n$, contributing the most to the precipitation partition process as has been previously reported for 'snow' type climates (Padron et al., 2017). Moreover, our results indicate that few landscape controls exert importance on partitioning. For example, elevation was found as an influential landscape control contributing to precipitation partitioning, which we deem to be related to the higher precipitation magnitudes that occur at higher altitudes, however, slope was not found as an important factor (cf. Padron et al., 2017). Unexpectedly, our results also showed, similarly to Padron et al. (2017) large scale study, that vegetation variables were not important to the partitioning process, which is contrary to previous studies that have highlighted the importance of vegetation to the partitioning process (Donohue et al., 2012; Mercado-Bettín et al., 2019; Ning et al., 2020; Tran et al., 2019; Zhang et al., 2001). Similarly, we found that NDVI and forest cover favored runoff, when we should have expected the opposite, given the general understanding of vegetation's effects on partitioning is to increase evaporation (e.g. Brown et al., 2005; Ford et al., 2011; Knighton et al., 2020; Li et al., 2013; Zhang et al., 2001). One explanation could stem from the contribution of orographic precipitations prevalent in the headwater catchments of the region, which could mask the role of vegetation partitioning. Thus, the location of forest at higher elevations and near the continental divide could explain why vegetation is correlated to higher runoff. Yet, other studies have shown that NDVI can be negatively correlated to Budyko's partitioning parameter (Bai et al., 2020), particularly in the southern Appalachian mountains, Younger et al. (2020) found that only needle evergreen forest favored evaporation while deciduous forest favored runoff and total forest cover had no significant relationship to evaporation. There, elevation, temperature and available soil water storage were better related to evaporation than the vegetation cover (Younger et al., 2020). Interpretation of such results can take several avenues, such as a hydrologic paradox (Teuling, 2018); a matter of scale (Zhang et al., 2017) or even to novel considerations of how vast forested areas affect the water balance (Ellison et al., 2012; Sheil, 2018).

It is important to denote some caveats of our study. Our statistical analysis showed that only few controls were significantly correlated with the Budyko's *n*, a result that contradicted previous findings (Padron et al., 2017). Yet, creating multivariate regression models to describe evaporation helped to confirm that only a few variables could describe most of its variance. Although we consider this information valuable, our results could mask the importance of other processes that occur in the catchments, especially if the studies are carried out at smaller scales where vegetation might excerpt a higher influence on partitioning (Zhang et al., 2017). The role of different forest types was not included in our study since all forest types were lumped into one category; future studies could make a differentiation between types, as it has been shown that needle evergreen forests and broadleaf forests have different effects on precipitation partitioning at the regional scale (Younger et al., 2020). Increasing the sample size could also result in better statistical models of evaporation that include a larger number of variables; or a correlation analysis that demonstrates that Budyko's *n* is strongly correlated to a larger number of environmental controls. Moreover, another caveat in the study are the strong correlations that exist between some variables, e.g. between fraction of precipitation falling as snow and mean annual temperature, or elevation and precipitation (see correlogram in Figure 3.S4). It is also important to reiterate that we limited the study to catchments with low human disturbance (e.g. low amount of urban areas, crops, impoundments) meaning that anthropogenic activities that affect the water balance (e.g. use of water for irrigation or industrial processes) were not represented and, consequently, assessing the influence of human driven activities on the partition of precipitation is beyond the scope of this study.

Although, we indicate that vegetation does not exert a high influence over precipitation partitioning, we consider that the importance of vegetation might change in the future due to three main factors. First, expected regional climatic changes will affect energy and water balance seasonalities and their interaction (Fernandez & Zegre, 2019). Dryness index is projected to increase in central Appalachia according to future downscaled projections of climate change (Fernandez & Zegre, 2019) which could mean that more energy is available for forest transpiration in humid catchments. Secondly, potential changes in forest species composition can mean a different use of water resources. Climate change is predicted to create shifts in the suitable habitat for multiple tree species (Iverson et al., 2019). Moreover, evidence shows that major changes have already occurred due to multiple interacting factors (McEwan et al., 2011), such as climate mesophication (Kutta & Hubbart, 2018; McEwan et al., 2011), fire management and suppression (Nowacki & Abrams, 2008, 2015), pathogens that have eliminated important species (Paillet, 2002) and air pollution that reduce the growth of different tree species (Horn et al., 2018; Mathias & Thomas, 2018). Understanding how diversity in forest types might change could be important to assess the future water balance in Appalachia (Younger et al., 2020). Third, cascading effects of climate change also influence forest ecosystem processes related to evaporation. One example is longer growing seasons in the region, that allow for longer periods of transpiration (Gaertner et al., 2019); also tree specific transpiration rates could be affected by higher magnitudes of vapor pressure deficit in a warmer climate (Guillén et al. , submitted); and reduced transpiration could occur due increased water use efficiency as an effect of higher concentrations of ambient $CO_2$ (Warren et al., 2011). We deem, therefore, that the study of climate and landscape controls to be even more important in the future.

Our findings reaffirm the importance of devoting research to understanding the implication of the climatic variables for precipitation partitioning and confirm results from large scale studies (Padron et al., 2017) and regional studies (Younger et al., 2020). The projected changes in the regional dryness index and the fact that those will be spatially heterogeneous (Fernandez & Zegre, 2019), are another reason for increased regional studies on partitioning. Moreover, besides advancing water resources research, noticing the importance of climatic controls in partitioning could also contribute to improving regional water security. In this regard, enhanced attention should be given to climate drivers when designing policies for watershed management. For instance, the effects of maintaining/increasing forest cover should be contextualized and integrated to climate change mitigation and adaptation strategies, since there are examples where climatic related controls can be more important to partitioning than vegetation (Soulsby et al., 2017). Looking at climate drivers should not lessen the continued focus on secondary controls that can be directly influenced by land use management and policies. Finally, there are inherent mismatches between the scales in which research and management activities take place and bridging those differences should be considered when designing future water resources research.

### 3.5. Conclusions

Our study shows that the partitioning of precipitation in the central Appalachian Mountain region is primarily driven by the Budyko parameter *n*, and secondarily driven by the dryness index. Partitioning in the region is heterogeneous and influenced largely by the eastern continental divide that influences climate and weather. Additionally, climate controls were more important than landscape controls on precipitation partitioning in general and within basin groups. Mean annual temperature and fraction of precipitation falling as snow were the most important controls of partitioning and explain, each on its own, the highest variance in evaporation according to multivariate regressions. Elevation was the most important landscape control for precipitation partitioning and was positively correlated to runoff.

To maintain sustainability in water resources and enhance regional water security we need to understand that catchments will behave differently depending on their specific characteristics. Here, we showed that methodologies used for a global review can be adapted to a regional approach by using spatially averaged data. We also highlighted that catchments pertaining to the same regional climates (e.g. snow dominated), can have distinct hydrological characteristics and precipitation partitioning controls, especially if they are influenced by the effect of mountain ranges. Similar cases to the central Appalachian mountains might exist in other regions of the world, where medium elevation mountain ranges do not affect large scale climate regimes but are still capable of influencing basin precipitation controls. Finally, we encourage scientists to continue the conversation about important controls for precipitation partitioning as a fundamental research question for the hydrologic community and as a tool for improved adaptation to climate change.

**Data availability statement**

All the data used for this study is publicly available and can be found in the referenced sources found in the data section of our methods.

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## 3.7. Supplementary information

*Table 3.S1: Precipitation controls for central Appalachian catchments.*

| USGS | Name | ID | LINEARITY | asd | sar |
|---|---|---|---|---|---|
| 1595000 | North Branch Potomac River at Steyer, MD | 9P | 0.8395 | 4.46 | 220.6 |
| 1601500 | Wills Creek near Cumberland, MD | 1P | 0.344 | 5.211 | 193.2 |
| 1604500 | Patterson Creek near Headsville, WV | 4P | 0.6916 | 4.482 | 248.7 |
| 1608500 | South Branch Potoamc River near Springfield, WV | 6P | 0.7744 | 5.098 | 193.9 |
| 1610000 | Pototmac River near at Paw, WV | 2P | 0.6108 | 4.905 | 200.4 |
| 1611500 | Cacapon River near Great Cacapon, WV | 3P | 0.6949 | 5.192 | 198.8 |
| 1614500 | Conococheague Creek and Fairview, MD | 7P | 0.706 | 5.262 | 195.7 |
| 1617800 | Marsh Run at Grimes, MD | 8P | 0.3897 | 5.132 | 205.1 |
| 1632000 | North Fork Shenandoah River at Cootes Store, VA | 12P | 0.5056 | 4.197 | 239.2 |
| 1634500 | Bennett Creek at Park Mills, MD | 5P | 0.6655 | 4.511 | 227.7 |
| 1637500 | Catoctin Creek near Middletown, MD | 10P | 0.592 | 4.95 | 217.7 |
| 1643500 | Cedar Creek near Winchester, VA | 13P | 0.1061 | 5.936 | 186.9 |
| 1644000 | Goose Creek near Leesburg, VA | 11P | 0.2623 | 5.689 | 193.2 |
| 3061000 | West Fork River at Enterprise, WV | 2M | 0.2895 | 5.069 | 233 |
| 3069500 | Cheat River near Parsons, WV | 5M | 0.434 | 5.158 | 260.2 |
| 3075500 | Youghiogheny River near Oakland, MD | 3M | 0.5284 | 5.681 | 222.2 |
| 3078000 | Casselman River at Grantsville, MD | 1M | 0.459 | 5.067 | 238.9 |
| 3080000 | Laurel Hill Creek at Ursina, PA | 4M | 0.609 | 4.707 | 268.5 |
| 3102500 | Little Shenango River at Greenville, PA | 1O | 3e-05 | 3.953 | 260.7 |
| 3109500 | Little Beaver Creek near East Liverpool, OH | 2O | 0.2293 | 4.073 | 260.5 |
| 3175500 | Wolf Creek near Narrows, VA | 1K | 0.2809 | 4.862 | 214.2 |
| 3179000 | Bluestone River at Pipestem, WV | 5K | 0.1696 | 5.103 | 217.6 |
| 3180500 | Greenbrier River at Durbin, WV | 2K | 0.00211 | 5.715 | 209.4 |
| 3183500 | Greenbrier River at Alderson, WV | 6K | 0.00124 | 4.632 | 242.2 |
| 3186500 | Williams River at Dyer, WV | 3K | 0.09078 | 6.255 | 236.2 |
| 3198500 | Big Coal River at Ashford, WV | 4K | 0.1198 | 5.769 | 211.6 |
| 3488000 | North Fork Holston River near Saltsville, VA | 1T | 0.8655 | 4.835 | 246.3 |
| 3500000 | Little Tennessee River near Prentiss, NC | 3T | 0.1574 | 7.224 | 221.1 |
| 3528000 | Clinch River above Tazewell, TN | 2T | 0.5893 | 6.192 | 214.2 |

*Table continues below*

| mat | fsnow | seas.ppt | seas.sar | seas.pet | ps.p.pet | mams | ssi |
|---|---|---|---|---|---|---|---|
| 11.08 | 0.1488 | 0.1089 | 0.05926 | 0.149 | -0.2744 | 207.3 | 153.4 |
| 10.53 | 0.1928 | 0.1077 | 0.06781 | 0.1539 | -0.2204 | 240.7 | 148.5 |
| 9.482 | 0.2167 | 0.1034 | 0.05067 | 0.156 | -0.2289 | 309.8 | 73.58 |
| 11.13 | 0.1511 | 0.1181 | 0.0718 | 0.1492 | -0.2382 | 208.4 | 158.1 |
| 11.08 | 0.1559 | 0.1142 | 0.0681 | 0.1511 | -0.2314 | 213.3 | 166.7 |
| 11.35 | 0.1499 | 0.1212 | 0.07155 | 0.1494 | -0.2121 | 217.1 | 157.8 |
| 11.53 | 0.1398 | 0.1234 | 0.07282 | 0.1471 | -0.221 | 210.2 | 153.1 |
| 11.96 | 0.1251 | 0.1254 | 0.06972 | 0.1454 | -0.2046 | 208.2 | 160 |
| 10.97 | 0.1316 | 0.1192 | 0.05874 | 0.1431 | -0.2458 | 201.1 | 137.4 |
| 11.92 | 0.1111 | 0.1249 | 0.0638 | 0.1389 | -0.2149 | 191.3 | 146.5 |
| 12.01 | 0.124 | 0.1271 | 0.06443 | 0.1439 | -0.188 | 219.1 | 141.1 |
| 12.51 | 0.1088 | 0.1272 | 0.0749 | 0.14 | -0.1891 | 188.2 | 161.4 |
| 12.63 | 0.1007 | 0.1285 | 0.07287 | 0.1375 | -0.1866 | 200.2 | 139.5 |
| 11.16 | 0.1424 | 0.1005 | 0.05429 | 0.1485 | -0.2844 | 285.2 | 71.91 |
| 9.841 | 0.2102 | 0.102 | 0.04823 | 0.1513 | -0.2373 | 436.3 | 11.54 |
| 8.998 | 0.2296 | 0.1034 | 0.06018 | 0.1557 | -0.2352 | 428.2 | 15.29 |
| 8.781 | 0.242 | 0.1019 | 0.05315 | 0.1594 | -0.2074 | 373.6 | 40.74 |
| 9.908 | 0.2068 | 0.09966 | 0.04618 | 0.1539 | -0.2437 | 377.2 | 27.52 |
| 9.793 | 0.1981 | 0.1103 | 0.04372 | 0.1644 | -0.3367 | 280.8 | 93.44 |
| 10.8 | 0.1627 | 0.1058 | 0.04655 | 0.1551 | -0.2964 | 248.4 | 119.7 |
| 11.25 | 0.1147 | 0.1107 | 0.06581 | 0.1335 | -0.2324 | 192.3 | 109.6 |
| 10.76 | 0.1469 | 0.1048 | 0.06044 | 0.1397 | -0.236 | 263.6 | 49.48 |
| 9.547 | 0.2238 | 0.1031 | 0.06243 | 0.1487 | -0.1299 | 405.4 | 33.29 |
| 10.77 | 0.1451 | 0.1052 | 0.05378 | 0.1401 | -0.2387 | 275.1 | 48.75 |
| 9.469 | 0.2176 | 0.102 | 0.05558 | 0.1484 | -0.2019 | 551.4 | 1.487 |
| 12.32 | 0.09927 | 0.1043 | 0.05812 | 0.1369 | -0.2597 | 313.1 | 20.34 |
| 12.39 | 0.08561 | 0.09971 | 0.05866 | 0.1294 | -0.1605 | 272.5 | 64.9 |
| 12.01 | 0.07808 | 0.1127 | 0.07485 | 0.1122 | 0.1228 | 760.1 | 0 |
| 13.09 | 0.07431 | 0.102 | 0.06817 | 0.1319 | -0.04712 | 382.3 | 53.27 |

*Table continues below*

| sm | aspect | elevation | forest_c | grass_c | cropland_c | urban_bare_c |
|---|---|---|---|---|---|---|
| 907.9 | 0.003577 | 340.4 | 84.05 | 15.58 | 0.06524 | 0.2144 |
| 862.4 | 0.006314 | 395.4 | 83.99 | 13.84 | 0.05165 | 1.291 |
| 885.9 | 0.004575 | 619.4 | 83.04 | 12.82 | 0.2195 | 3.546 |
| 1020 | 0.004666 | 336.9 | 87.53 | 12.44 | 0.03252 | 0 |
| 950.2 | 0.004127 | 299.3 | 91.75 | 8.161 | 0 | 0.06689 |
| 960.1 | 0.01593 | 267.4 | 76.79 | 22.36 | 0.2593 | 0.3772 |
| 964.7 | 0.00566 | 275.5 | 82.75 | 16.75 | 0.07908 | 0 |
| 924.3 | 0.1114 | 182.9 | 23.3 | 66.44 | 1.463 | 3.461 |
| 1046 | 0.1066 | 525.6 | 69.23 | 29.67 | 0.2773 | 0.7357 |
| 1146 | 0.1155 | 343.6 | 46.44 | 50.43 | 0.9169 | 1.698 |
| 967.2 | 0.1583 | 205.4 | 20.66 | 70.69 | 0.6422 | 3.917 |
| 888.3 | 0.1507 | 156.7 | 28.45 | 62.13 | 0.5604 | 6.88 |
| 1066 | 0.1272 | 180.3 | 34.33 | 61.97 | 0.3296 | 2.48 |
| 877 | 0.008416 | 353.7 | 66.24 | 26.54 | 0.194 | 5.332 |
| 860.8 | 0.01574 | 633.7 | 80.49 | 18.58 | 0.08054 | 0.3189 |
| 878.1 | 0.008603 | 774.4 | 39.07 | 56.3 | 0.4152 | 1.938 |
| 850.6 | 0.007593 | 751.9 | 61.67 | 33.71 | 0.0658 | 2.303 |
| 852.2 | 0.009771 | 563.6 | 77.01 | 21.41 | 0.08605 | 0.6428 |
| 897.8 | 0.0107 | 329.6 | 34.6 | 54.36 | 0.6804 | 6.75 |
| 873.5 | 0.009384 | 329.7 | 65.26 | 28.93 | 0.346 | 3.605 |
| 1055 | 0.004373 | 742 | 75.13 | 24.37 | 0.1293 | 0.3361 |
| 1064 | 0.006522 | 776.3 | 85.14 | 13.65 | 0.06263 | 0.06263 |
| 785.8 | 0.1627 | 849.3 | 86.09 | 13.91 | 0 | 0 |
| 930.7 | 0.004367 | 721.1 | 76.11 | 23.19 | 0.02877 | 0.374 |
| 790.5 | 0.003826 | 874 | 91.25 | 6.297 | 0 | 2.317 |
| 1098 | 0.004164 | 363 | 92.16 | 3.023 | 0.01679 | 4.685 |
| 1080 | 0.005744 | 602.2 | 55.38 | 41.98 | 0.2297 | 1.797 |
| 912.5 | 0.00368 | 915.3 | 87.7 | 11.32 | 0.1347 | 0.4124 |
| 1477 | 0.02268 | 421 | 53.3 | 41.76 | 0.2872 | 0.4308 |

*Table continues below*

| water_c | LOS | ndvi | slope | cti | ELONGATION | COMPACT | LINEARITY.1 |
|---|---|---|---|---|---|---|---|
| 0.01864 | 186 | 0.8954 | 11.34 | 4.64 | 0.792 | 0.02186 | 0.8395 |
| 0.8264 | 169 | 0.9024 | 10.93 | 4.183 | 0.6179 | 0.013 | 0.344 |
| 0.3265 | 175.5 | 0.9085 | 10.26 | 4.24 | 0.6683 | 0.02872 | 0.6916 |
| 0 | 179.8 | 0.9006 | 10.29 | 4.987 | 0.6962 | 0.01628 | 0.7744 |
| 0.0223 | 181.1 | 0.899 | 11.12 | 4.8 | 0.6591 | 0.01674 | 0.6108 |
| 0.1886 | 178.1 | 0.8947 | 9.646 | 4.883 | 0.6231 | 0.01467 | 0.6949 |
| 0.4053 | 175.5 | 0.8814 | 8.105 | 4.857 | 0.7106 | 0.02073 | 0.706 |
| 0.7027 | 173.3 | 0.8233 | 5.137 | 6.094 | 0.6164 | 0.03524 | 0.3897 |
| 0.03425 | 189.3 | 0.8791 | 11.77 | 4.471 | 0.657 | 0.04295 | 0.5056 |
| 0.09816 | 184.6 | 0.8614 | 7.95 | 5.199 | 0.6937 | 0.03726 | 0.6655 |
| 0.7454 | 177.1 | 0.8368 | 4.949 | 5.92 | 0.6501 | 0.04182 | 0.592 |
| 0.3338 | 174.5 | 0.844 | 5.634 | 5.893 | 0.2599 | 0.01943 | 0.1061 |
| 0.7639 | 187.1 | 0.861 | 5.917 | 5.389 | 0.4662 | 0.03794 | 0.2623 |
| 1.544 | 180.2 | 0.8999 | 12.18 | 5.504 | 0.6339 | 0.02917 | 0.2895 |
| 0.393 | 175.1 | 0.9168 | 12.64 | 4.735 | 0.5763 | 0.04323 | 0.434 |
| 1.453 | 183 | 0.9066 | 5.282 | 5.695 | 0.647 | 0.01707 | 0.5284 |
| 1.14 | 177.3 | 0.9084 | 6.646 | 4.512 | 0.6211 | 0.02462 | 0.459 |
| 0.4226 | 178.7 | 0.9078 | 9.614 | 4.83 | 0.6841 | 0.04745 | 0.609 |
| 1.91 | 177.8 | 0.883 | 3.997 | 5.602 | 0.3076 | 0.04639 | 3e-05 |
| 1.648 | 180.7 | 0.8981 | 11.09 | 5.398 | 0.4429 | 0.05217 | 0.2293 |
| 0.03878 | 174.2 | 0.8913 | 13.71 | 4.411 | 0.6859 | 0.02326 | 0.2809 |
| 0.9551 | 178.9 | 0.9153 | 14.18 | 4.201 | 0.4077 | 0.02832 | 0.1696 |
| 0 | 175.3 | 0.9135 | 13.93 | 4.73 | 0.5631 | 0.01138 | 0.00211 |
| 0.3056 | 176.8 | 0.8982 | 13.27 | 4.716 | 0.212 | 0.03563 | 0.00124 |
| 0.06815 | 176.8 | 0.9123 | 13.74 | 4.559 | 0.6113 | 0.02528 | 0.09078 |
| 0.1175 | 171.7 | 0.8932 | 21.74 | 4.781 | 0.4247 | 0.01377 | 0.1198 |
| 0.4027 | 185.9 | 0.8645 | 14.66 | 4.692 | 0.8683 | 0.03257 | 0.8655 |
| 0.4292 | 182 | 0.8902 | 18.37 | 3.9 | 0.5192 | 0.03605 | 0.1574 |
| 4.208 | 188.1 | 0.8661 | 12.86 | 4.879 | 0.7558 | 0.02453 | 0.5893 |

*Table 3.S2: Partial correlation results for the Study region.*

| | *Central Appalachia* | | *Kanawha - Tennessee* | | *Monongahela - Ohio* | | *Potomac* | |
|---|---|---|---|---|---|---|---|---|
| *Variable* | Estimate | P.adj | Estimate | P.adj | Estimate | P.adj | Estimate | P.adj |
| *AREA* | 0.052 | 0.881 | 0.370 | 0.839 | -0.078 | 0.962 | -0.274 | 0.623 |
| *ASD* | -0.195 | 0.510 | -0.768 | 0.270 | -0.153 | 0.962 | -0.294 | 0.604 |
| *ASPECT* | 0.159 | 0.550 | 0.105 | 0.907 | -0.840 | 0.406 | 0.353 | 0.505 |
| *COMPACT* | 0.111 | 0.681 | -0.036 | 0.938 | -0.339 | 0.962 | 0.501 | 0.277 |
| *COMPLEXITY* | 0.344 | 0.193 | 0.097 | 0.907 | 0.112 | 0.962 | 0.102 | 0.829 |
| *CTI* | 0.225 | 0.468 | 0.263 | 0.902 | -0.058 | 0.962 | 0.514 | 0.277 |
| *ELEVATION* | -0.542 | 0.049 | -0.737 | 0.270 | -0.305 | 0.962 | 0.345 | 0.505 |
| *ELONGATION* | 0.040 | 0.881 | -0.151 | 0.907 | 0.432 | 0.962 | -0.130 | 0.824 |
| *FOREST_C* | -0.225 | 0.468 | -0.454 | 0.688 | 0.073 | 0.962 | -0.547 | 0.277 |
| *FSNOW* | -0.520 | 0.049 | -0.655 | 0.332 | -0.532 | 0.962 | 0.209 | 0.764 |
| *GRASS_C* | 0.191 | 0.510 | 0.466 | 0.688 | -0.132 | 0.962 | 0.522 | 0.277 |
| *LINEARITY* | 0.200 | 0.510 | 0.293 | 0.883 | 0.016 | 0.979 | -0.053 | 0.912 |
| *LOS* | 0.164 | 0.550 | 0.090 | 0.907 | 0.391 | 0.962 | 0.020 | 0.953 |
| *MAMS* | -0.383 | 0.187 | -0.830 | 0.270 | -0.929 | 0.169 | 0.512 | 0.277 |
| *MAP_M* | -0.317 | 0.222 | -0.789 | 0.270 | -0.997 | 0.005 | 0.530 | 0.277 |
| *MAT* | 0.521 | 0.049 | 0.735 | 0.270 | 0.419 | 0.962 | -0.358 | 0.505 |
| *NDVI* | -0.491 | 0.063 | -0.329 | 0.848 | -0.236 | 0.962 | -0.447 | 0.350 |
| *PS.P.PET* | 0.038 | 0.881 | -0.526 | 0.609 | 0.407 | 0.962 | 0.143 | 0.824 |
| *SAR* | -0.115 | 0.681 | -0.180 | 0.907 | -0.393 | 0.962 | 0.607 | 0.277 |
| *SEAS.PET* | -0.359 | 0.193 | -0.125 | 0.907 | -0.226 | 0.962 | 0.133 | 0.824 |
| *SEAS.PPT* | 0.352 | 0.193 | -0.075 | 0.907 | -0.390 | 0.962 | -0.101 | 0.829 |
| *SEAS.SAR* | 0.181 | 0.520 | -0.095 | 0.907 | 0.369 | 0.962 | -0.534 | 0.277 |
| *SLOPE* | -0.024 | 0.904 | -0.095 | 0.907 | 0.174 | 0.962 | -0.523 | 0.277 |
| *SM* | 0.419 | 0.133 | 0.701 | 0.305 | -0.324 | 0.962 | -0.172 | 0.824 |
| *SSI* | 0.471 | 0.071 | 0.659 | 0.332 | 0.991 | 0.014 | -0.533 | 0.277 |
| *URBAN_BARE_C* | 0.326 | 0.218 | -0.355 | 0.839 | 0.353 | 0.962 | 0.494 | 0.277 |

*Table 3.S3: Summary information for the best 13 models to predict evaporation in Central Appalachia. Sample size 29 watersheds.*

| n | predictors | adjr | predrsq | cp | aic |
|---|---|---|---|---|---|
| 1 | mat | 0.4521666 | 0.3806287 | -1.5546287 | 335.5523 |
| 1 | fsnow | 0.4226119 | 0.3469622 | -0.2897892 | 337.0761 |
| 2 | mat ndvi | 0.4399524 | 0.3315887 | 0.0803903 | 337.0973 |
| 2 | mat P | 0.4336813 | 0.3439043 | 0.3388316 | 337.4202 |
| 2 | mat ssi | 0.4317132 | 0.3537354 | 0.4199387 | 337.5208 |
| 2 | elevation mat | 0.4315501 | 0.3418005 | 0.4266603 | 337.5292 |
| 2 | fsnow mat | 0.4314807 | 0.3331475 | 0.4295197 | 337.5327 |
| 2 | mat DI | 0.4314528 | 0.3371697 | 0.4306701 | 337.5341 |
| 2 | fsnow ndvi | 0.4306819 | 0.3230117 | 0.4624417 | 337.5734 |
| 2 | elevation fsnow | 0.4268203 | 0.3303035 | 0.6215847 | 337.7695 |
| 3 | mat ndvi P | 0.4230925 | 0.2971032 | 1.8607787 | 338.8200 |
| 3 | elevation fsnow P | 0.4229577 | 0.3152527 | 1.8661229 | 338.8268 |
| 3 | mat P DI | 0.4226902 | 0.3256276 | 1.8767214 | 338.8403 |

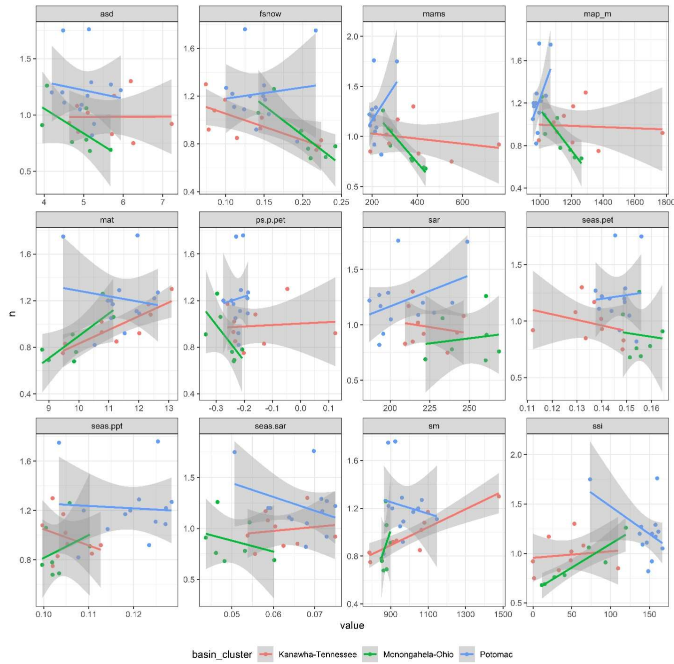


*Figure 3.S1: Scatter plot of Budyko's n against climate controls.*

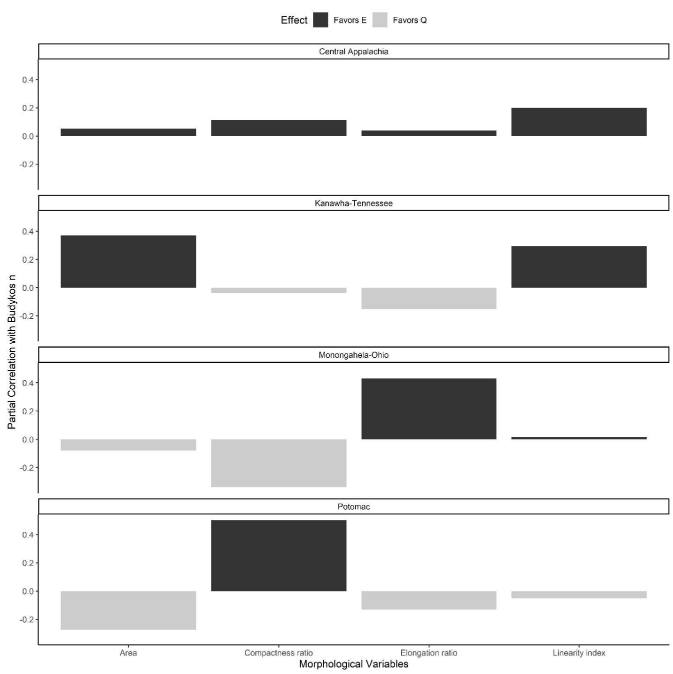


*Figure 3.S2: Partial correlations of the morphological controls against Budyko's n. None of the controls was statistically significant according to the adjusted p-value < 0.05.*

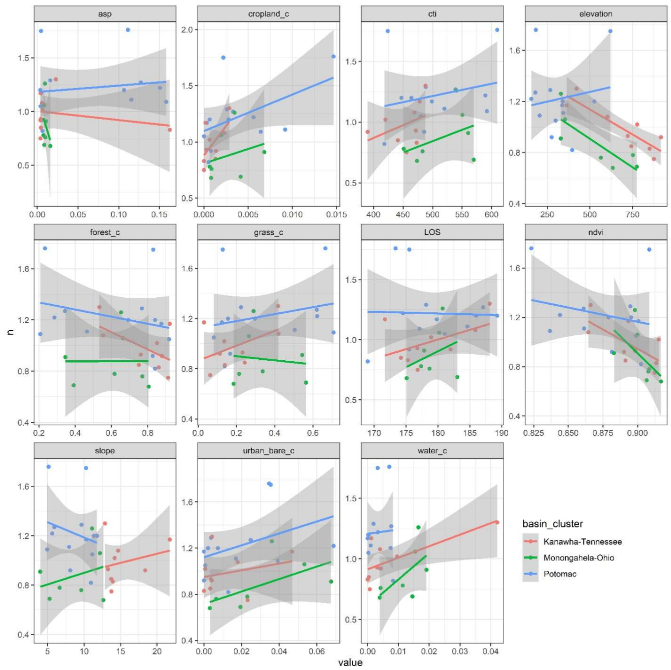


*Figure 3.S3: Scatter plot of Budyko's n against landscape controls.*

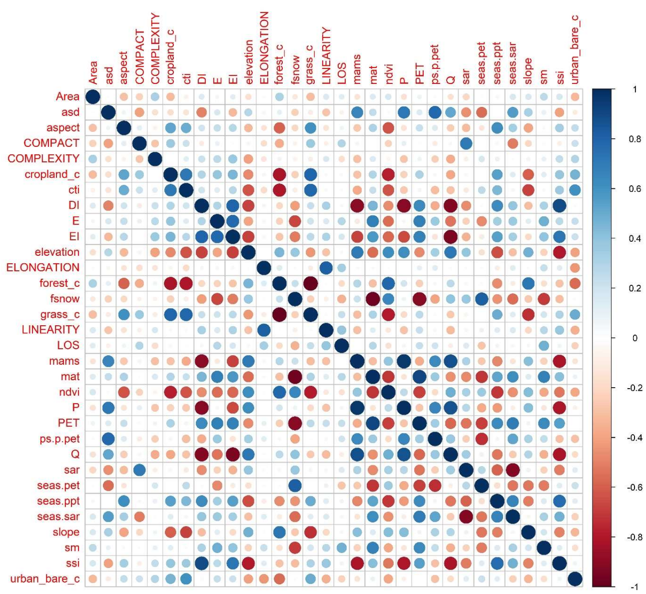


*Figure 3.S4: Correlogram of precipitation partitioning controls.*

# Chapter 4 Environmental controls of sap velocity and implications of future forest evaporation.

Submitted as Guillén, L.A., Brzostek, E., McNeil, B., Raczka, N., Casey, B., Turner, B., Zegre, N. P. *Differences in sap velocities of Acer saccharum and Quercus velutina in West Virginia during a drought experiment: environmental controls and implications for future forest evapotranspiration*. Ecohydrology.

**Abstract**

Forest species composition can mediate evapotranspiration and the amount of water available to human-use downstream. In the last century, the heavily forested Appalachian region has been undergoing forest mesophication which is the progressive replacement of more xeric species (e.g. *Quercus velutina*) by more mesic species (e.g. *Acer saccharum*). Given differences between xeric and mesic species in water use efficiency and interception, investigating the consequences of these species shifts on coupled carbon-water cycles is critical to improving predictions of ecosystem responses to climate change. To meet this need, we quantified the degree to which the sap velocities of two dominant broadleaved species (*Acer saccharum* L. (sugar maple) and *Quercus velutina* Lam. (black oak)) in West Virginia, responded to ambient and experimentally altered soil moisture conditions using a throughfall displacement experiment. We then used these data to explore how predictions of future climate under two emissions scenarios could affect forest evapotranspiration rates. Overall, we found that the maples had higher sap velocity rates than the oaks. Sap velocity in maples showed a more plastic response to vapor pressure deficit (VPD), particularly at high levels of VPD, than sap velocity in oaks. Experimentally induced reductions in shallow soil moisture did not have a significant impact on sap velocity. In response to future climate scenarios of increased vapor pressure deficits in the Central Appalachian Mountains, our results highlight the different degrees to which two important tree species will increase transpiration, and potentially reduce the water available to the heavily populated areas downstream.

**Keywords**: Sap velocity, transpiration, climate change, Acer saccharum, Quercus velutina, Appalachia, mountain water resources.

### 4.1. Introduction

Differences between hydraulic traits in tree species play a fundamental role in determining evapotranspiration fluxes in temperate forest ecosystems (Ford, Hubbard, and Vose 2011). Temperate forests partition the precipitation they receive into evapotranspiration that delivers water back to the atmosphere and runoff that recharges aquifers and forms creeks and rivers that can fuel human-use and maintain ecosystem functions. This partitioning by temperate forests is highly sensitive to both abiotic and biotic factors. Biotically, tree species composition can impact transpiration due to species' differences in multiple traits, including, rooting depth (Canadell et al. 1996), water use-efficiency (Yi et al. 2019), hydraulic safety margins (Allen et al. 2010), and interception rates (Brown et al. 2005). Abiotically, both the supply of water in soils and the demand for water by the atmosphere are important drivers of transpiration rates (Bovard et al. 2005; Oren and Pataki 2001; Wullschleger, Meinzer, and Vertessy 1998). Given that temperate forests are facing ongoing shifts in tree species composition (McEwan, Dyer and Pederson 2011) coupled with predicted shifts in water regimes, there is a critical need to investigate how these shifts will impact the ability of forests to maintain water resources for downstream communities.

The temperate forests of West Virginia (WV) provide a valuable case study to determine the role differences in hydraulic traits between tree species as well as climate shifts impact water resources. WV forests are an important "water tower" (Viviroli et al. 2007), as this relatively small state (62038 $Km^2$) provides precipitation driven streamflow to  circa 9 million people  in the Mississippi/Gulf of Mexico and Potomac/Chesapeake Bay basins (Young et al., 2019). Moreover, WV forests are facing shifts in climate and species composition that are predicted to occur across most temperate forest regions (Iverson et al 2019). These forests are predicted to have an increase in potential evapotranspiration rates that will be greater than the increase in precipitation, likely leading to more frequent and intense droughts (Fernandez and Zegre 2019).  This shift in the water cycle is coupled with an ongoing shift in tree species composition owing to pests, management decisions, and environmental change (McEwan et al., 2011). Importantly, this species shift has resulted in the mesophication of these forests (Nowacki and Abrams, 2008), with the replacement of xeric species by mesic species that have greater water demand and lower water use efficiency (i.e. carbon fixation per unit of water use). This shift is important because it may result in increases in forest transpiration rates and in decreases in streamflow during the growing season (Caldwell et al. 2016; Ford et al. 2011).

These shifts in trees species impact water use but may also impact the ability of temperate forests to respond to extreme events such as drought. Previous research has shown that the strategies used to minimize the negative impacts of drought differ between dominant tree species in the Appalachian Mountains region (Ford, Hubbard, and Vose 2011; Wullschleger, Hanson, and Todd 2001). Tree species can be classified based on the isohydric-anisohydric spectrum (McDowell et al. 2008). Isohydric species reduce stomatal conductance to avoid cavitation of xylem cells, which reduces photosynthesis and tree growth (McDowell et al. 2008); on the other hand, anisohydric species maintain high rates of transpiration and photosynthesis under water stress at the risk of suffering hydraulic failure due to the cavitation of xylem cells (McDowell et al. 2008). However, the hydrisity classification should not be considered absolute, as species can have different degrees of hydrisity (e.g. Franks, Drake and Froend 2007, Martínez-Vilalta et al. 2014); for instance, sugar maples have shown both isohydric (Roman et al. 2015, Yi et al. 2017) and anisohydric strategies (Loewenstein and Pallardy, 1998). Similarly, the relationship between hydrisity and drought resiliency are not always generalizable (McDowell et al. 2008, Coble et al. 2017). Nevertheless, anisohydric tree species in temperate forest, among them several oak species (Yi et al. 2017), tend to inhabit more xeric sites and can be more resistant to long-term droughts than mesic and isohydric species (Brzostek et al. 2014). Thus, the ongoing mesophication of temperate forests and the hydraulic strategies of the trees that will compose future forest, could play an important role in future drought resiliency (Nowacki and Abrams, 2008; Coble et al. 2017).

Here, we use the temperate forests of WV as a case study to investigate the degree to which shifts in tree species and climate will impact forest functioning and the ability of forests to provide water resources to downstream communities. Our objective was to empirically determine the degree to which the sap velocity of two dominant tree species, *Acer saccharum* L. (sugar maple) and *Quercus velutina* Lam. (black oak), differ in their response to shifts in the supply of water in soils and the demand of water by the atmosphere. To do this, we measured sap velocities of sugar maple and black oak in plots that received ambient climate conditions as well as in plots where we experimentally reduced soil moisture using throughfall displacement. This measurement design allowed us to determine which climatic variables (i.e., soil moisture, vapor pressure deficit) have a greater impact on sap velocity rates for each species. We then used these empirical relationships to explore the impacts of climate change and species shifts on transpiration and water resources for the region.

### 4.2. Material and Methods

#### 4.2.1. Site Description and Experimental Design

Our research was performed at Tom's Run Natural Area, a 34 ha forest operated by the West Virginia Land Trust, located in Monongahela County, West Virginia, approximately 10 km south of Morgantown, WV (39.55°N 80.00°W) (see Figure 4.1). Tom's Run Natural Area is a secondary forest that is highly representative of the Appalachian region, established during the first quarter or the beginning of 1900's (Kutta and Hubbart 2019). Prior agricultural/grazing land-use is evidenced at the upper end of the hill by stone walls and stone piles. Elevation of the study site ranges from 336 m to 438 m, and slopes range from 3 -25% (Soil Survey Staff 2020). Hillslopes are primarily drained by one intermittent stream, but several ephemeral streams occur during the winter or after heavy precipitation events during the growing season. Soils are classified as Alfisols order and Ultic Hapludalfs family (Soil Survey Staff 2020). The specific soil series present are the Culleoka-Westmoreland, Dormont and Guernsey series, with silt loam and silt clay – loam textures, originated from weathered limestone, sandstone and shale. The slightly acidic (pH 4.5 – 6. 0) soil series have a depth to lithic bedrock that ranges from 50 – 168 cm and the average water storage in the profile is low to moderate from 12.95 – 22.86 cm. (Soil Survey Staff 2020). Mean annual temperature (1980-2010) is 11.61 °C, ranging from -0.39 °C (January) to 22.89 °C (July). Precipitation is uniformly distributed throughout the year, with a mean annual precipitation of 1063 mm, with summer (June, July, and August) precipitation averaging 312 mm and winter averaging 211 mm measured nearby (12km) at the Morgantown Hart Field Airport (NOAA station # USW00013736). Vegetation is mixed temperate broadleaved deciduous forests, consisting of *Acer saccharum* Marshall (sugar maple), *Acer rubrum* L. (red maple), *Quercus velutina* Lam. (black oak), *Quercus rubra* L. (red oak), *Quercus alba* L. (white oak), *Liriodendron tulipifera* L. (tulip poplar), *Carya sp*. (hickory), *Fagus grandifolia* Ehrh. (american beech), *Cornus florida* L. (flowering dogwood), *Platanus occidentalis* L. (sycamore).

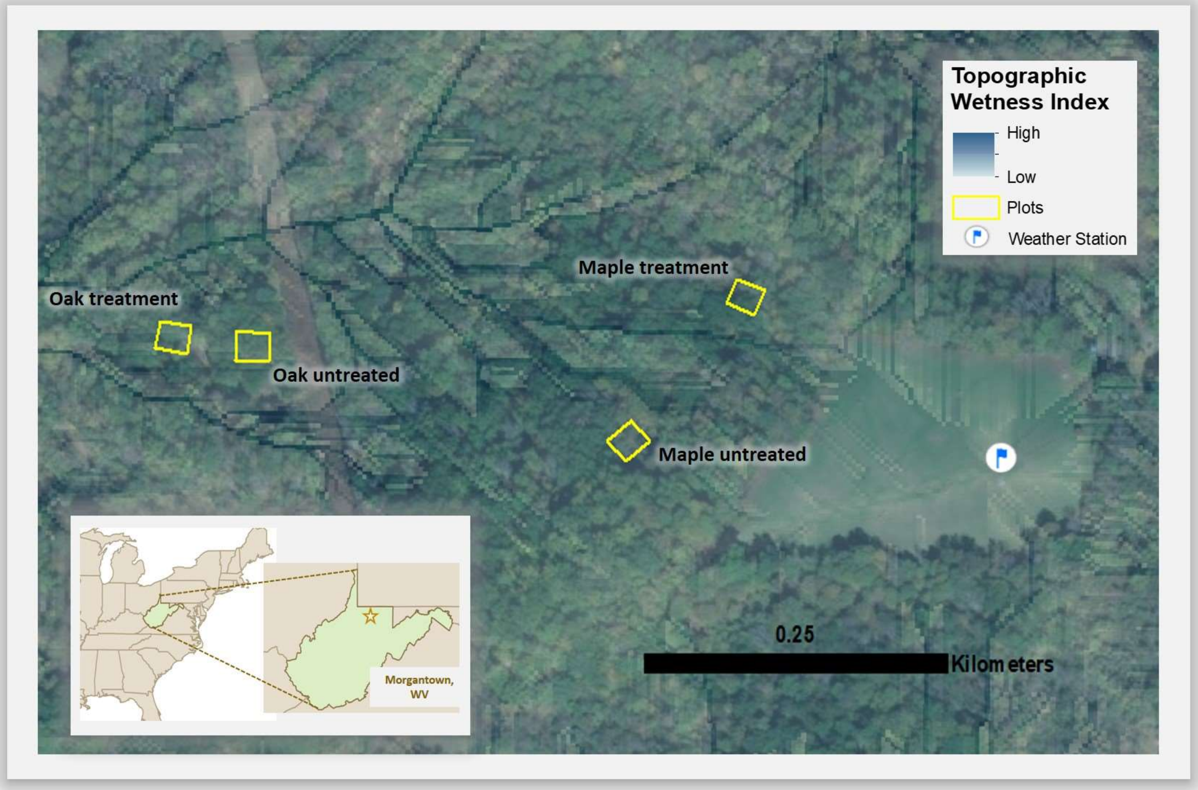


*Figure 4.1 Tom's Run Natural area location, as well as, the experimental plot and weather station location. Background is composed by an overlay of an air photo with the site-based Topographic Wetness Index (Beven and Kirkby, 1979), which is used to explain the spatial variation of soil moisture based on slope and upstream contributing area. The darker areas represent higher potential for groundwater saturation.*

**Throughfall exclusion experiment**

In order to study the effects of chronic water stress on a temperate forest ecosystem, a throughfall exclusion experiment was established in 2017. Using the natural species distribution of Tom's Run Natural Area, experimental plots were established in mature forest stands of *Quercus velutina* or *Acer saccharum* (see Table 4.S4 for basal areas of species at each plot). Beside the abundance and dominance of the two species in the area, they were selected based on differences in hydrisity, associated mycorrhiza, and crown architecture (aspects relevant for other studies part of a larger ecological project), and their relative importance in WV forest. For each species, one 20m x 20m untreated plot and one 20m x 20m treatment plot where throughfall was experimentally reduced were co-located within a 100m of each other on similar aspects and slopes (2 species x 2 treatments = 4 plots total). Project expenses and logistics limited further plot replication; hence trees were considered as our experimental level of replication. However, we note that many large-scale ecosystem experiments where replication is limited due to logistical constraints use a similar design where plots are sub-divided into replicated sub-plots on which statistical inferences are made (Melillo et al. 2011; Frey et al. 2014). In addition, plots were selected with as similar basal areas and leaf area indices as possible (Supplementary Tables 4.S4 and 4.S5) and at least 6 dominant overstory canopy trees. We measured the sap velocities in trees that were farthest away from the edges of the plot. In the treatment plots, throughfall was excluded using a wood structure to support plastic panels at 1.2m-2.5m that converged into gutters to transport water downslope of the plot area (Figure 4.S1a). The untreated plots did not have any wooden structures except a small frame that contained the datalogger box. The plastic panels were removed outside of the growing season to limit snowfall damage, allow natural litterfall, and to only exclude throughfall and manipulate soil moisture during the time of peak forest water demand (Figure 4.S1b). Dormant season precipitation was sufficient to refill soil water content and reach soil field capacity prior to the start of the growing season, an important feature of eastern forest (Hanson and Weltzin, 2000). Throughfall exclusion during 2018 had three configurations: a) 0% throughfall exclusion from day-of-year (DOY) 1-69 b) 50% throughfall exclusion from DOY 70 – 151 and DOY 200-312; and c) 90% throughfall exclusion from DOY 152-199. Overall, in 2018, the 50% exclusion totaled 195 days and the 90% exclusion totaled 48 days.

### 4.2.2. Data

**Sap velocity**

Sap velocity measurements in this study were made using the heat pulse method which was theoretically developed by Marshall (1958) and improved by Swanson and Whitfield (1981) by accounting for the variability due to wounding effects on the xylem (Green 1998). The rate of water flowing through the xylem of a tree stem is estimated based on the thermal dissipation of a heat pulse applied to its sapwood (McJannet and Fitch 2004). Three probes were used in the configuration, one as heater and the other two as thermocouples, that are parallel to each other with vertical orientation. The probes were inserted into the tree at breast height (130 cm) with a fixed spacing: the thermocouple upstream is separated by 5mm from the heat probe and 10 mm from the downstream thermocouple (for a detailed methodology see McJannet and Fitch (2004)). Heat pulse velocity Vc (cm $h^{-1}$) was calculated using the distance D (cm) from the heating probe to the center of the thermocouples, divided by the time T (h) from the application of the heat pulse until the two thermocouples reach the same temperature (McJannet and Fitch 2004) (equation 1).

$Hv = \frac{D}{T}$ (Equation 1)

Heat pulse velocity was corrected with coefficients from Swanson and Whitfield (1981) to account for the wounding effects of the installation of the probes in the trees (McJannet and Fitch 2004). The corrected heat pulse velocity (Hv (cm $h^{-1}$)) was then transformed into sap velocity (Sv (cm $h^{-1}$)) (equation 2) by considering the specific properties of the woody matrix (Becker and Edwards, 1999):

$Sv = Hv(0.441 * Fwood + Fwater)$ (Equation 2),

where, 0.441 (unitless) is the coefficient to convert heat pulse velocity to sap velocity, given by the wood's heat capacity at 20 ° C (Becker and Edwards, 1999), Fwood ($m^3m^{-3}$) is the volume fraction of wood, and Fwater ($m^3m^{-3}$) is the volume fraction of water Fwater ($m^3m^{-3}$) (see supplementary information). Stand level transpiration (T [mm $h^{-1}$]) was calculated by multiplying the average sap velocity of the plot (cm/h) by the plot's sapwood area ($cm^2$/ha). The conservation objectives at Tom's Run Natural Area limited the ability of coring the trees for the estimation of the sapwood area, hence, equations developed from similar Appalachian Forests by Wullschleger, Hanson, and Todd (2001) were used (equation 3):

$Swa = B_0 DBH^{B_1}$ (Equation 3)

where, Swa ($cm^2$) is the sapwood area at diameter at breast height (DBH) in cm, and $B_0$ and $B_1$ are species specific parameters from Wullschleger, Hanson, and Todd (2001).

Sap velocity can be sampled by inserting several probes around the tree's trunk diameter and with probes that measure heat pulses at several depths into the sapwood to improve quantification when upscaling sap velocity to transpiration. We only measured sap velocity at one depth and with one probe set per tree since our focus was to understand plant - soil- atmosphere interactions and more relative than absolute comparisons. Moreover, given that sapwood areas and volume fractions of water and wood were calculated using allometric equations from different sites, we arbitrarily assumed a relative error of 20% and performed a Gaussian error propagation analysis on our calculations following Bevignton and Robinson (1992) (see supplementary information). Transpiration rates obtained from heat pulse methods are practical, but have inherent uncertainty (Foster, 2017). Thus, we focused the analysis on sap velocities and our transpiration results serve as indicative values and aid in the contextualization of our results, and not as an accurate quantification of whole tree water use. We sampled six trees that reached the canopy in all four plots in 2018 (see Table 4.S1 for information on DBH and sapwood basal areas). The measurement period started on DOY 152 (June) and ended on DOY 277 (October). The thermocouple probes and heat-pulse probes were connected to a CR1000 Datalogger that was located in each plot (Campbell Scientific, Logan UT, USA). The heat pulse was fired every 30 minutes for 2 seconds and the dissipation of this heat pulse was recorded by the thermocouple probes for 5 minutes following. R (R Core Team 2019) was used to for the calculations of sap velocity from the measured temperatures. Time series of daily sap velocity and other meteorological variables were constructed using the R package hydroTSM (Zambrano-Bigiarini, 2017). Sap velocity was calculated for the mean day length since nighttime transpiration is expected to be minimal and cannot be measured by the type heat pulse velocity system used.

**Meteorological and soil moisture data**

A weather station was established in an open field adjacent to the study site on DOY 152 in 2018. Precipitation was measured using a tipping-bucket rain gauge (TR525, Texas Electronics, Dallas TX, USA) and supplemented with data from Hartfield Airport National Weather Service (NWS) station (12 Km away) during eight days of instrument malfunction (linear regression between the stations: $R^2$=0.67, p<0.01, n=110 days). Air temperature and relative humidity were measured with a HMP60 probe (Campbell Scientific, Logan UT, USA). We also measured photosynthetic active radiation (LI190R, LI-COR, Lincoln, NE, USA), net solar radiation (CMP6, Campbell Scientific, Logan UT, USA), wind speed and wind direction (M05013, Young, Traverse City MI, USA). Data were logged every 60 minutes (except precipitation which was logged every 10 minutes) using with a CR6 Datalogger (Campbell Scientific, Logan UT, USA). Within each plot, volumetric soil water content (VWC) ($m^3m^{-3}$) of the top 30 cm was measured using four soil time domain reflectometry probes set at random locations (CR616, Campbell Scientific Logan UT, USA), with a time resolution of 30 minutes, during the duration of the experiment. Soil sampling was conducted next to the soil moisture probes (4 samples per plot) and then two samples at random locations per plot. We sampled weekly from May until September and biweekly from October until April. We used standard gravimetric methods to obtain actual water content, which was compared to the soil moisture probes to assure the probes reflected the changes in the soil moisture. Finally, air temperature and relative humidity (HMP60, Campbell Scientific, Logan UT, USA) were measured at a 30 min resolution in three plots: the maple treatment, oak untreated and oak treatment. VPD was calculated for the three plots following the equation by Monteith and Unsworth (2007) (equation 4):

$$VPD = (1 - \frac{RH}{100}) \times 610.7 \times 10^{\frac{7.5Ta}{(237.3+Ta)}} \text{ (Equation 4)}$$

where VPD (Pa) is vapor pressure deficit, RH (%) is relative humidity and Ta (C°) is air temperature.

### 4.2.3. Future climate and sap velocity projections

We used the MACAv2-METDATA dataset (Abatzoglou 2013) to assess the sensitivity of sap velocity to future climate projections. The MACAv2-METDATA dataset consists of downscaled biased corrected outputs from 19 different General Circulation Models (GCMs) for the continental US. The MACAv2-METDATA looks at two carbon emission scenarios: a low emissions scenario (RCP 4.5) and a high emissions scenario (RCP 8.5). The MACAv2-METDATA includes the atmospheric variables important in the control of sap velocity (VPD and incoming solar radiation at the daily scale). Since MACAv2-METDATA lacks hydrologic information such as soil moisture, we modeled it using the Variable Infiltration Capacity (VIC) model (Hamman et al. 2018; Liang et al. 1994). VIC model is a semi-distributed hydrologic model widely used in climate change studies (Hamman et al. 2018). We used a daily time series for the atmospheric variables from the MACAv2-METDATA to run the VIC model for the watershed containing Tom's Run Natural Area, for a time-frame of 94 years (2006 – 2099). The raw VIC model output was soil moisture in mm, between 0-0.1 m and 0.1 – 1 m depth from soil surface. The corresponding fractions and the proportion of water height were used to calculate volumetric water content in the first 30 cm of soil. Summer values from the data ensemble was extracted to only focus on the growing season. Yearly averages of the summer months (June, July, August and September [JJAS]) conditions of VPD, radiation and soil moisture were calculated to have a time series of 94 years (2006 – 2099). Future climatic variables were tested for significant trends using the ranked, non-parametric Mann Kendal tests with the 'trend' R package (Pohlert 2018).

Using data from July through September of 2018, a stepwise linear regression was carried out to find the most parsimonious model based on the Akaike Information Criteria (AIC), utilizing R package MASS (Venables and Ripley 2002). The model selection included interactions between the variables as well as their logarithmic transformation, based on initial model fitting that found increased correlations after logarithmic transformations. Future sap velocity was projected using the models shown in Table 4.S2.

#### 4.2.4. Statistical analysis

We used a two-way ANOVA with species (maple, oak) and treatments (untreated, treatment) as factors to test for differences of growing season mean daily values of soil moisture and sap velocity between the plots. Given that we could not have replications of the treatment or the controls plots and instead focused on replicate trees within each plot, we are cautious to claim statistical inference about the effect of treatments from the test results. However, these analyses can still provide important information to make ecological interpretations. Post hoc comparison were carried out using the Tukey-HSD test. Tree-to-tree variability caused by several factors, among them, the differences in probe insertion, probe depth with respect to conducting tissue, xylem anatomy, tree specific rooting depth and soil moisture, might have added random noise to the signal of how environmental conditions influence sap velocity. To enhance this signal, sap velocity was mean centered and scaled within each individual, and then the resulting tree level z-scores were averaged by species, treatment and day. The new data set of z-scores reduced the large variability between the treatments and allowed to make better comparisons to the sensitivity of sap velocity to the controlling variables. Then, a second analysis, consisted on building a linear mixed effects models using the 'nlme' (Pinheiro et al. 2019) and 'MuMin' (Barton 2019) R packages. The purpose of the linear mixed effect model was to examine the influence of the environmental controls and their interactions on sap velocity during the study period. From 113 candidate models, the most parsimonious model was selected using Akaike Information Criteria (AIC), a common approach for LME (Zuur 2009). The best model differed by more than 4 AICc to the second-best model, information that permitted identification of the nature of the relationship between the best explanatory variables and sap velocity (Mathias and Thomas 2018). The four measured explanatory variables (VPD, radiation, soil moisture, precipitation) and all their interactions were initially included as fixed effects to the models, while species, treatment and tree were included as random effects. Furthermore, an autocorrelation structure AR(1,0), implying a 1-day lag in the covariance structure was added to the model to account for temporal autocorrelation (Mathias and Thomas 2018). Nonlinear relationships between the variables was accounted for by logarithmic transformation of the variables to improve the linear fit. The Two-Way ANOVA and the linear mixed effect model had both a total sample size of 2775 data points, obtained from 23 individual trees and 126 daily values (123 data points had to be omitted due to missing or erroneous values at individual trees across the growing season). All statistical analysis was carried with a significance level of $\alpha$=0.05.

*Table 4.1 Summary of variables used, units and range.*

| Variable | Symbol | Mean (SD) | Range | Unit |
|---|---|---|---|---|
| Precipitation | P | 4.13 (8.16) | 0, 63 | mm $d^{-1}$ |
| Radiation | Rad | 209.13 (83.55) | 36, 372 | W $m^2d^{-1}$ |
| Soil Volumetric Water Content | VWC | 0.21 (0.06) | 0.12, 0.37 | $m^3m^{-3}$ |
| Vapor Pressure Deficit | VPD | 0.55 (0.31) | 0.05, 1.32 | kPa |
| Sap velocity | Sv | | | cm $d^{-1}$ |
| *Acer saccharum* | | 136.27 (55.37) | 12.33, 263.24 | |
| *Quercus velutina* | | 65.63 (21.04) | 6.27, 107.25 | |
| Transpiration | T | | | mm $d^{-1}$ |
| *Acer saccharum* | | 2.44(1.28) | 0.16, 5.78 | |
| *Quercus velutina* | | 0.43(0.15) | 0.04, 0.78 | |

## 4.3. Results

### 4.3.1. Differences in sap velocity

**Sugar maple had higher sap velocity rates than black oak**

Sap velocities during the study period were almost twice as high in the sugar maple trees than with the black oak trees (Figure 4.2b and Table 4.1). The sap velocity was not only significantly different among the species but also between treatments and between the species and treatment interaction (Table 4.2). Due to the lack of treatment replication and potential issues due to pseudoreplication, we cautiously interpret these results as an indication of differences between the plots and not as treatment effects. During the 126 days of the mean daily sap velocity was highest at the maple treatment with 147 ± 22 cm $d^{-1}$ (SD=58), followed by the maple untreated with 126 ± 19 cm $d^{-1}$ (SD=50). The oak treatment had a mean daily sap velocity of 67.80 ± 10 cm $d^{-1}$ (SD=22) and the lowest was the oak untreated with 64 ± 9 cm $d^{-1}$ (SD=19). Sap velocity was dissimilar between species during most days of the season, except for rainy days when both species experienced the lowest sap velocities (Figure 4.2c).

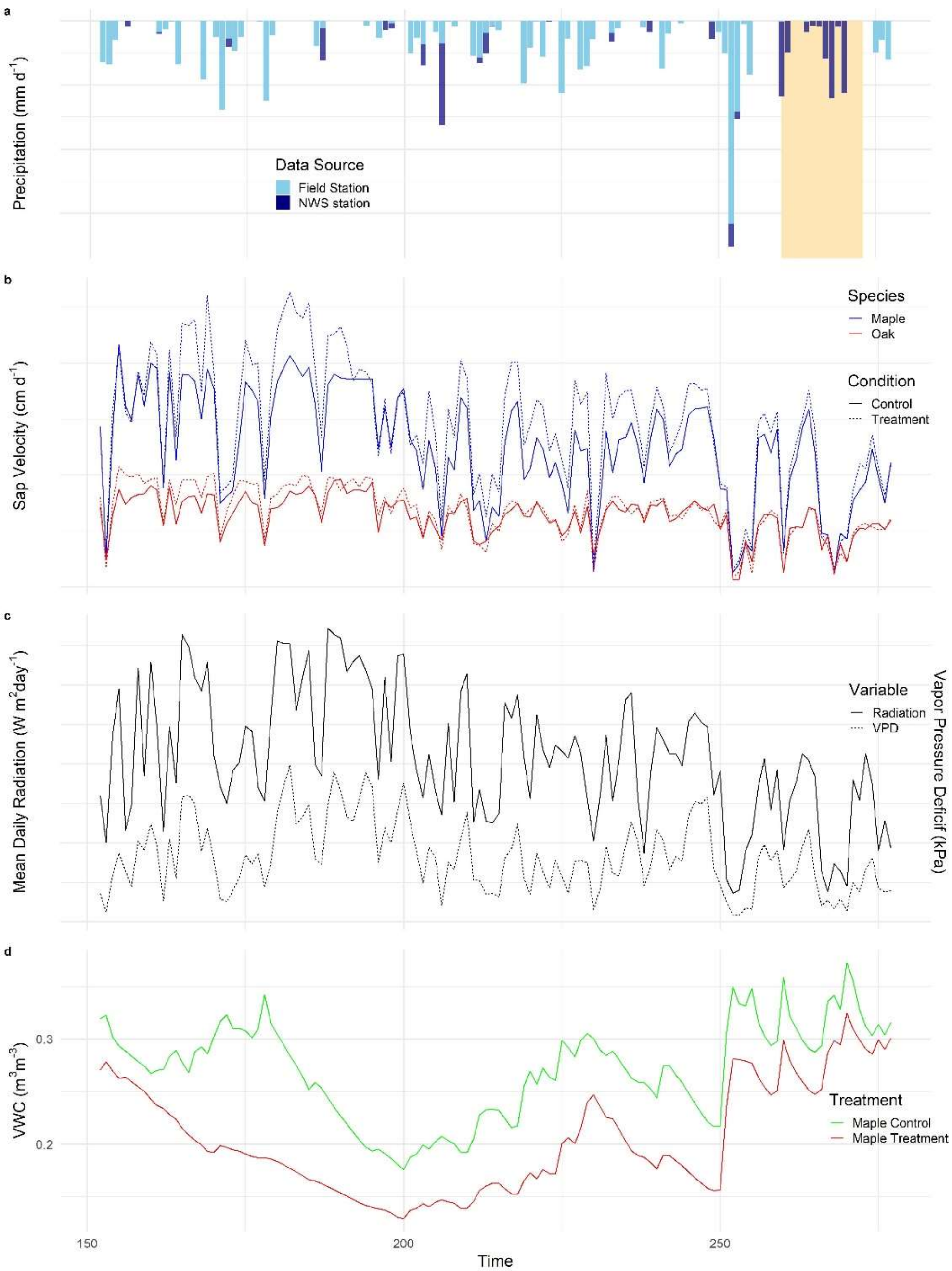


*Figure 4.2 Daily Time Series for a) Precipitation from field station and Hartfield Airport National Weather Service (NWS) station; b) Sap velocity; c) VPD and radiation and d) 0 – 30 cm soil moisture expressed as volumetric water content ($m^3m^{-3}$) from 2018-06-01 until 2018-10-04. Note that precipitation events have important influences on the other variables and was used to identify missing data due to rain gauge malfunction at the field station during the third week of September (shaded area in yellow). When data from the NWS is used to fill in the gap the rain events match the increasing precipitation and the lower sap velocity, VPD and radiation magnitudes.*

Summer transpiration was approximately five times higher for the maple species than the oaks. The maple treatment plot had an average daily transpiration of 3.22 ± 0.6 mm (SD= 1.29), while the maple untreated had 1.67 ± 0.3 mm (SD= 0.66), and the oaks were much lower with daily means at oak treatment of 0.49 ± 0.1 mm (SD=0.17) at and 0.38 ± 0.06 mm (SD=0.11 ) at the oak untreated. The total transpiration over the four-month growing period was 308 ± 54 mm for maples and 55 ± 12 mm for the oaks. Precipitation during that same period was high and totaled 574 mm. Overall, transpiration was highly uneven between species, which is caused by the large differences in sapwood areas between plots, in which maples had more than twice as large sapwood areas than oaks (Table 4.S1).

*Table 4.2 Analysis of Variance results. Response variable was sap velocity and the listed explanatory variables were the categorical factors.*

| | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
|---|---|---|---|---|---|
| Species | 1 | 3748743.11 | 3748743.11 | 1083.55 | 0.000 |
| Treatment | 1 | 219640.10 | 219640.10 | 63.49 | 0.000 |
| Species:Treatment | 1 | 33809.82 | 33809.82 | 9.77 | 0.002 |
| Residuals | 2771 | 9586831.03 | 3459.70 | NA | NA |

**Tree size influence on sap velocity and its sensitivity to VPD.**

Sap velocity variability was high between trees within each plot (Figure 4.3a). Maple treatment had data from only five trees due to the malfunction of one sensor during most of the study period. Maple treatment had three trees with median values near 200 ± 30 cm $d^{-1}$ and the remaining with medians of approximately 60 cm $d^{-1}$. Maple untreated had one tree with median above 200 ± 30 cm $d^{-1}$, two trees between 100 ± 15 and 150 ± 22 cm $d^{-1}$ and the remaining below 100 ± 15 cm $d^{-1}$. All the oak trees had median and mean values lower than 100 ± 14 cm $d^{-1}$. Oak treatment had two trees with very low medians of 25 ± 4 cm $d^{-1}$ and 35 ± 5 cm $d^{-1}$, while the remaining trees had a median around 60 ± 9 cm $d^{-1}$. Oak untreated had the lowest variability in sap velocity with most trees having medians of between 40 ± 6 and 60 ± 9 cm $d^{-1}$. Sap velocity was well correlated within plots despite large variations.

Variation in tree-to-tree sap velocity was likely driven by small differences unique to each tree in probe insertion depth and the inherent characteristics of the xylem around each sapflow probe. Tree size influence on sap velocity was not clearly recognizable due to the large variance between trees, as both large and small trees presented a wide range of sap velocities for all the species and treatments (Figure 4.3a). On the other hand, after we checked the relationship between the slope of the linear regression of sap velocity vs VPD and the size of each tree we found that sap velocity sensitivity to VPD was not influenced by differences in DBH (Figure 4.3b).

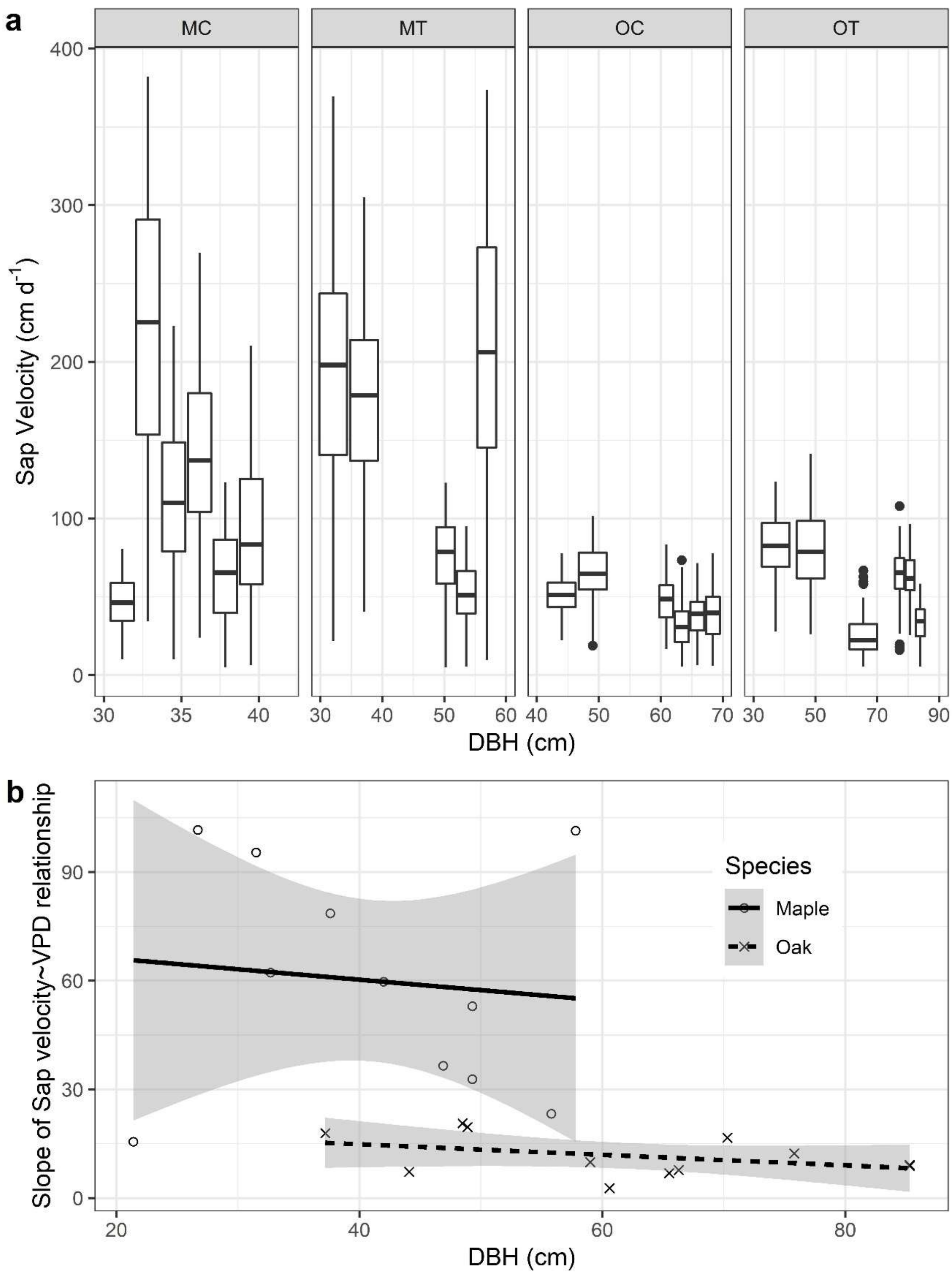


*Figure 4.3 Panel a) Boxplots of sap velocity against tree DBH. b) Scatterplot of the slope of the regression between sap velocity and log(VPD) against DBH for maples ($R^2$=0.012, p-value=0.64, n=11) and oaks ($R^2$=0.16, p-value=0.75, n=12).(DBH: Diameter at Breast Height, VPD: Vapor Pressure Deficit)*

### 4.3.2. Environmental controls on sap velocity

**VPD, radiation and their interactions are the most important controls on sap velocity**

Precipitation, VPD, radiation, soil moisture and four interactions (precipitation:radiation, precipitation:VPD, radiation:VPD and soil moisture:VPD) were significant predictors of sap velocity after controlling for the effects of species, treatments, and individual trees (Table 3). VPD was the most important control according to the linear mixed effects model, followed by radiation, the interaction between precipitation and VPD, the interaction of soil moisture and VPD, which was more important than soil moisture. The interactions between precipitation and radiation, as well as, radiation and VPD were the only ones that had a negative effect on sap velocity (Table 4.3). The selected linear mixed effect model was obtained from 113 models based on the combinations from 16 variables.

*Table 4.3 Estimate results (standard error) for Linear Mixed Effects Models*

| Scaled Dependent variable | Estimate |
|---|---|
| Precipitation | 0.113*** (0.029) |
| Radiation | 0.274*** (0.031) |
| Soil moisture | 0.081*** (0.024) |
| VPD | 0.460*** (0.035) |
| Precipitation:Radiation | -0.138*** (0.031) |
| Precipitation:VPD | 0.265*** (0.048) |
| Radiation:VPD | -0.059*** (0.017) |
| Soil moisture:VPD | 0.133*** (0.018) |
| Constant | 0.158*** (0.032) |
| **Model information:** | |
| Observations | 2775 |
| Log Likelihood | -2987.494 |
| Akaike Inf. Crit. | 6002.988 |
| Bayesian Inf. Crit. | 6085.941 |

Significance levels: * p<0.05; ** p<0.01; ***p<0.001

**Maple exhibited higher plasticity to changes in VPD**

The response of sap velocity to changes in VPD decreased as the VPD reached higher magnitudes (Figure 4.4). Effects of VPD on sap velocity were similar between the untreated and treatment plots of each species but were different between the two species (Figure 4.4). In particular, sugar maple had a more sensitive response to both high and low VPD values (Figure 4.4).

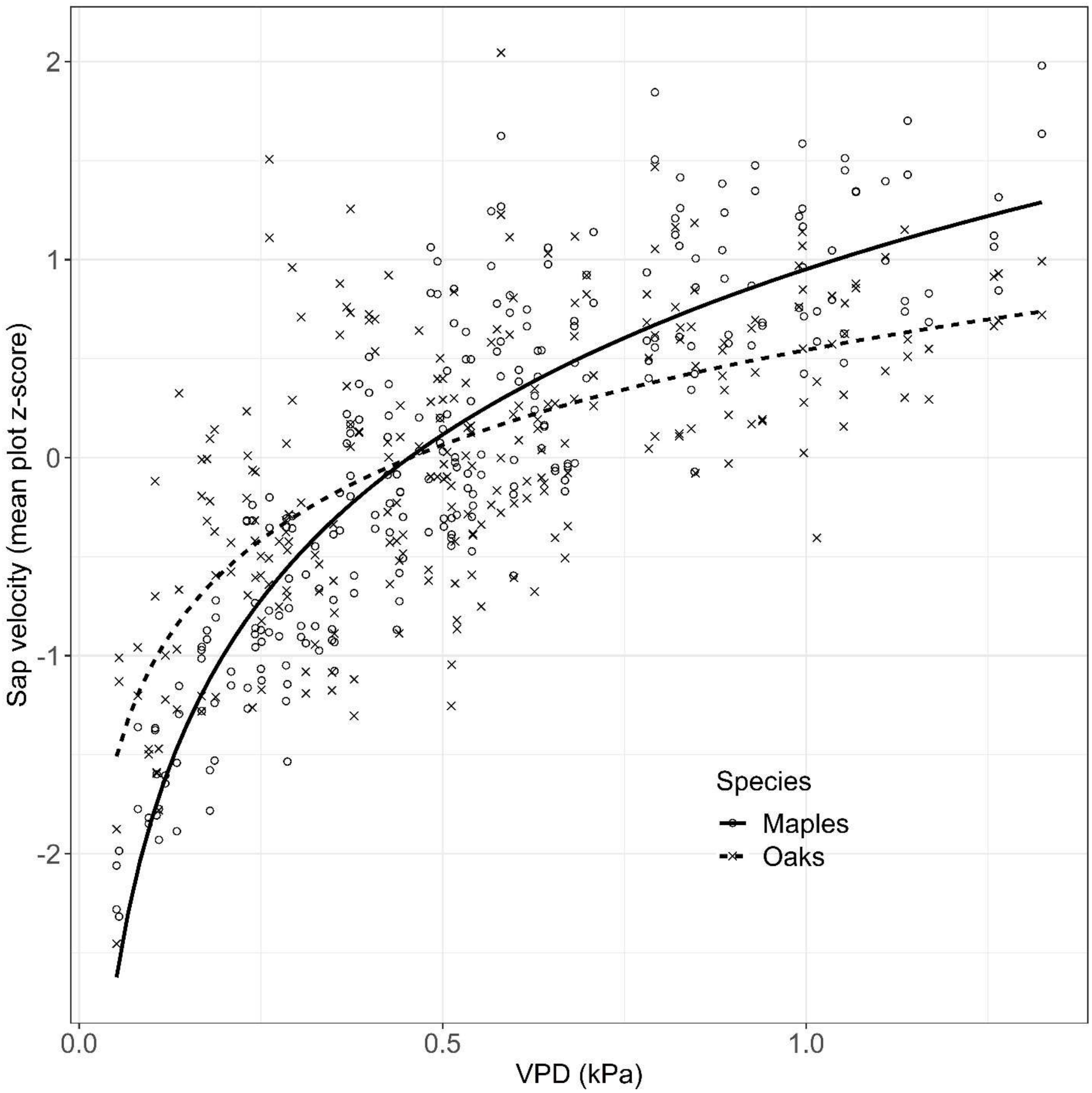


*Figure 4.4 Daily sap velocity Z-scores vs VPD for maples and oaks during the 2018 growing season.*

**Shallow soil moisture needs to be very low to affect the tree sap velocity**

Significant differences in soil moisture between the sugar maple and black oak plots were found (ANOVA, $F=665.1$, $p<0.0001$). Generally, shallow soil moisture was higher in the sugar maple plots than in the black oak plots, and particularly higher in the maple untreated in comparison to the rest of the plots (Figure 4.5a). The maple untreated had a daily mean VWC of $0.27 m^3m^{-3}$ (SD=0.05) whereas the maple treatment had daily mean VWC $0.2\ m^3m^{-3}$ (SD = 0.05). Oaks were lower with the untreated plot daily mean VWC of $0.2\ m^3m^{-3}$, (SD= 0.03), and the oak treatment VWC of $0.18\ m^3m^{-3}$ (SD = 0.04). Dry conditions of shallow soil moisture below a VWC of $0.15\ m^3m^{-3}$ lowered sap velocity for the same VPD magnitudes (Figure 4.5b).

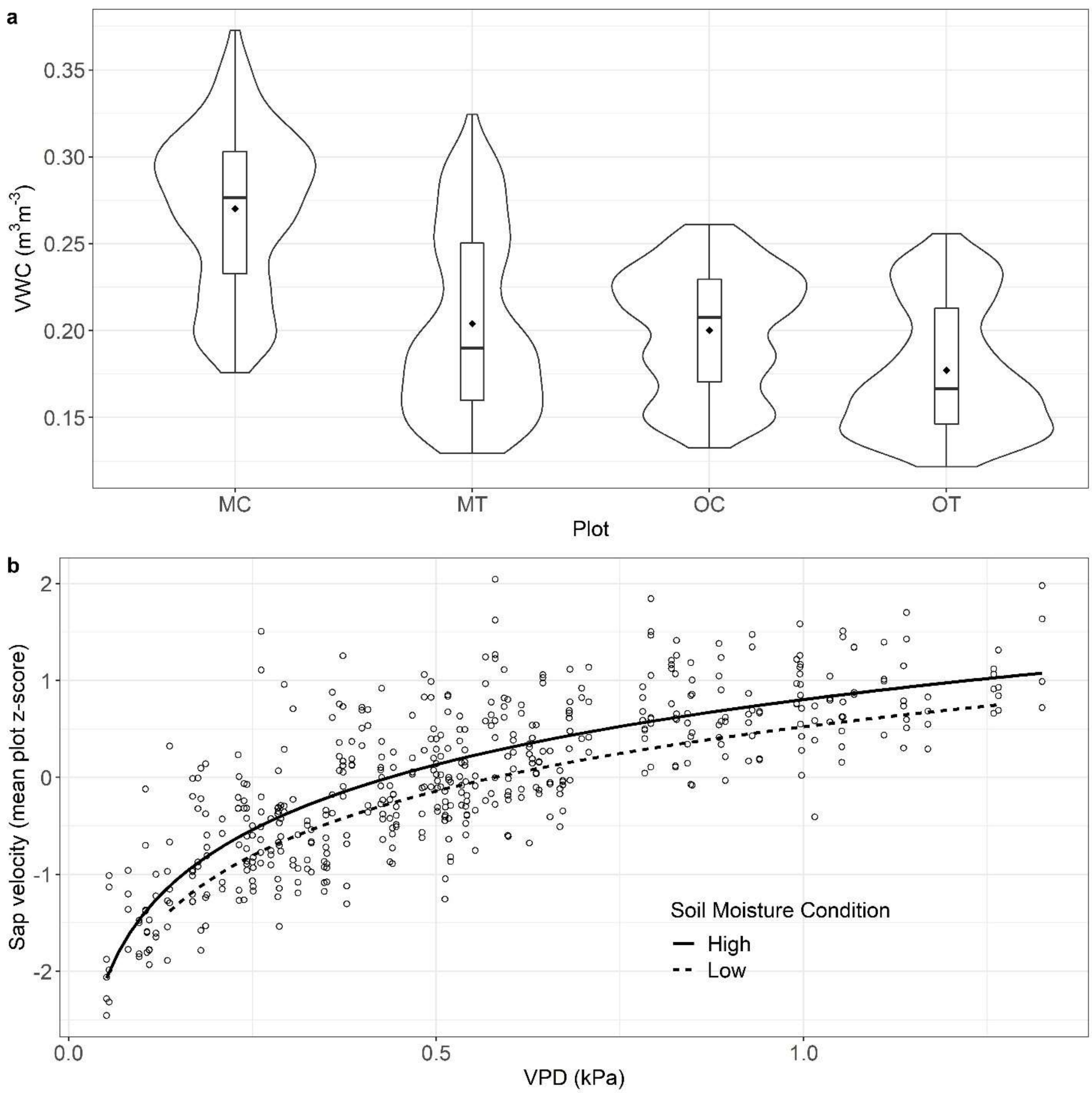


*Figure 4.5 a) Violin plot of Volumetric Water Content (VWC) for four different plots during the study period. b) Scatterplot of Z scores of sap velocity vs Vapor Pressure Deficit, with regression lines for low and high soil moisture.*

### 4.3.3 Future VPD, soil moisture and sap velocities.

Summer averages of VPD and radiation are projected to significantly increase (Figure 4.6) (Mann-Kendal $p < 0.001$). In contrast, shallow soil moisture is projected to significantly decrease. The higher emission scenarios RCP 8.5 is the most extreme scenario creating the largest increases in VPD, as well as, the largest decreases in shallow soil moisture. VPD was the variable that had the highest difference between both scenarios. For the RCP 8.5 summer VPD increased by 0.078 kPa/decade while on the RCP 4.5 it increases by 0.0305 kPa/decade, a difference of 39% (Figure 4.6b). Radiation increased 0.797 $Wm^2day^{-1}$/decade for the RCP 4.5 and 0.996 $Wm^2day^{-1}$/decade (Figure 4.6c). Soil moisture showed decreasing trends over the next century, with lowest magnitudes in the RCP 8.5, VWC decreased by 0.002 $m^3m^{-3}$ /decade on the RCP 4.5 and by -0.004 $m^3m^{-3}$/decade on the RCP 8.5 (Figure 4.6d). Despite the decrease in future projections of average summer soil moisture, it was higher than VWC 0.20 $m^3m^{-3}$ for both climate scenarios.

Future summer VPD for the last quarter of the century had an average of 0.92 (SD=0.13) for RCP 4.5 and 1.27 kPa (SD=0.19), results that are much higher than the mean value for the first 25 years of model output (2006-2030), RCP4.5: 0.70 (SD=0.09) and RCP8.5: 0.74 (SD=0.1) or the measured valued for 2018 VPD (mean = 0.55 kPa, SD = 0.3). Figure 4.6a shows how the future VPD would be in relation to 2018 values. Average future VPD correspond to VPD values that are currently seldom (RCP 4.5) or extreme (RCP 8.5); and that created the appropriate conditions for the highest magnitudes of sap velocity, especially for maple species (Figure 4.6a). Summer transpiration predictions for 2075-2099 based on the two climate change scenarios showed important increases. If trees in our study site would experience the climate conditions of the future stand transpiration in the maples would increase by 32±5% (RCP 4.5) and by 39±6 % (RCP8.5). Similarly, the black oak stand would increase transpiration by +21±9 % (RCP4.5) and +29±10% (RCP 8.5) (see table 4.S3).

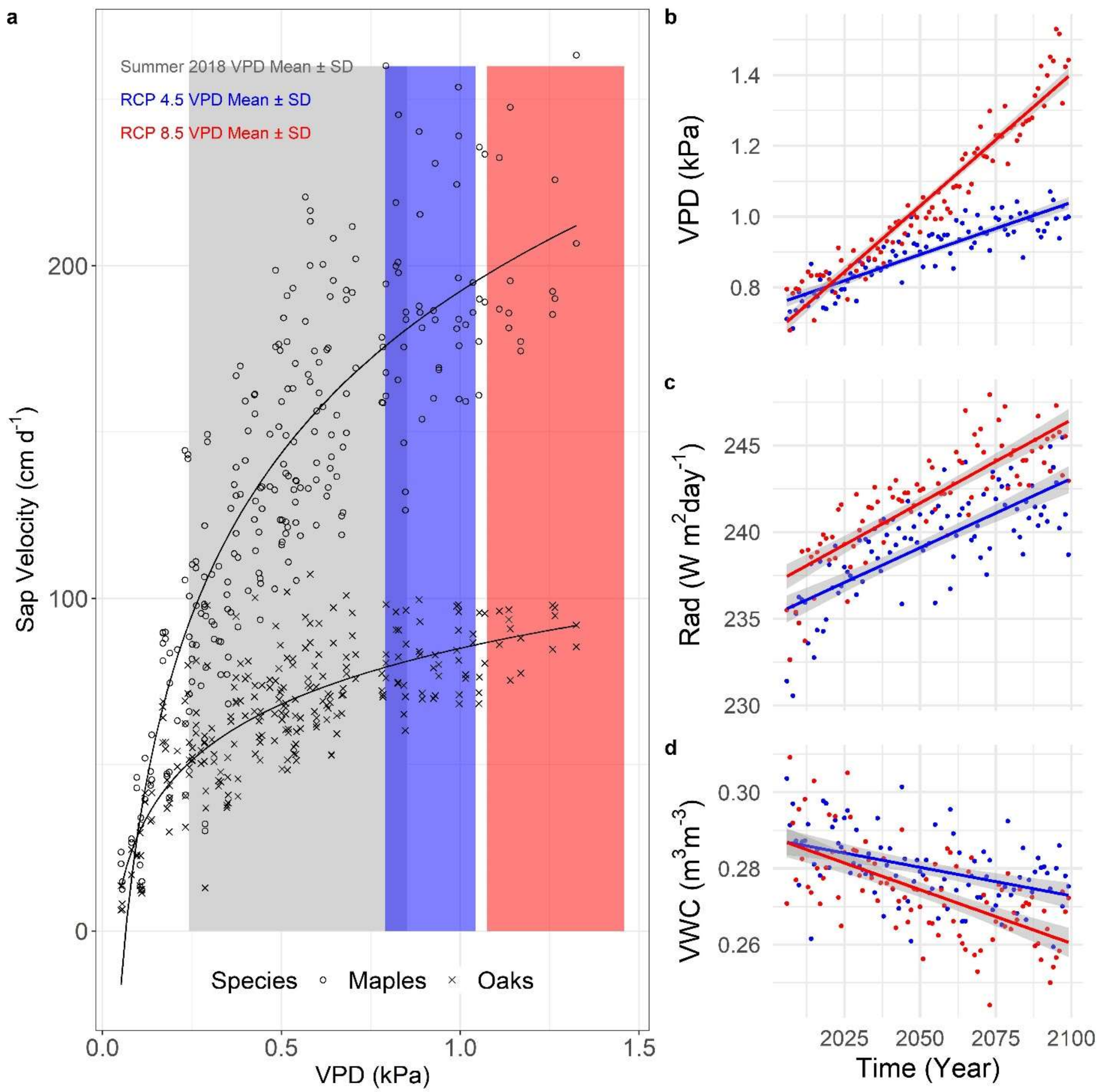


*Figure 4.6 a) Sap velocity as a function of Vapor Pressure Deficit (VPD) for maples and oaks (background colors represent the average VPD +- one standard deviation for the summers of 2018 and between 2075-2099); and future projections of summer (June, July, August and September [JJAS]) averages based on 19 MACAv Model Ensemble and emission scenario RCP 4.5 (blue) and RCP 8.5 (red) for b) VPD; c) Radiation; and d) Soil moisture as volumetric water content (VWC).*

### 4.4. Discussion

The higher water use by maple species compared to oak species has been reported by several studies in the midwestern and the eastern USA (Yi et al. 2017; Bovard et al. 2005; Wullschleger, Hanson, and Todd 2001; Ford, Hubbard, and Vose 2011). Interestingly, we found that maple plots had about five times larger sap velocity than oaks plots, and although, quantitative comparisons with other regions should be avoided given the differences in site (e.g. elevation, topography, latitude) and forest (e.g. types, ages, sizes and species) characteristics. In support of our results, however, Yi et al. (2017) reported six-fold differences in sap flux mid-day rates (maples species had 15.4 $cm^3cm^{-2}h^{-1}$ while two oak species had 2.5 $cm^3cm^{-2}h^{-1}$) during certain periods of the growing season and Wullschleger, Hanson, and Todd (2001) reported maples species using 2-3 times more water than oak species. However, we know that differences in water use between species is highly influenced by the stark difference in sapwood areas and water conducting capacities between diffuse porous (sugar maple) and ring porous (black oak) species (Ford, Hubbard, and Vose 2011; Gebauer, Horna, and Leuschner 2008; Oren and Pataki 2001). Diffuse porous species transport more water as their conducting tissues has a higher pore density across the whole width of the tree ring. In contrast, ring porous species have less pore density, concentrated near the start of the ring and tend to reduce the number of pores as the growing season ends (Pallardy and Kozlowski 2008). Thus, the results of higher sap velocity of sugar maple in comparison to black oak in our study is representative of species specific anatomical characteristics such as: sapwood area, non-uniformity of the sapwood depth around the trees stem (Benson, Koeser, and Morgenroth 2018; Cermak, Kucera, and Nadezhdina 2004), and xylem anatomy (Ford, Hubbard, and Vose 2011; Gebaurer, Horna, and Leuschner 2008; Wullschleger, Meinzer, and Vertessy 1998).

Higher values of sap velocity in the throughfall reduction plots were unexpected since the goal of the treatments was to reduce sap velocities in relation to the untreated plots. One potential explanation to this result is the higher sapwood areas of the treatment plots (Table 4.S2). Soils were probably not the cause in sap velocity differences since they were hydrologically similar (Soil survey staff 2020). The greater sap velocity in the treatments could be also caused by unaccounted differences in depth and location during insertion of the probes, or inherent physiologic differences between the trees at the different plots. In addition, throughfall reductions at the treatment plots, might have only influenced soil moisture in the upper layers of the soil horizon, and trees could have access water in deeper soil horizons by deep roots. Likewise, the high precipitation magnitudes received during 2018 might have reduced the effectiveness of the treatment. Further studies with increased replication could aid in disentangling these results.

Different sap velocity rates between the species is likely attributable to their distinct sensitivity to environmental controls (Yi et al. 2017; Dragoni, Caylor, and Schmid 2009; Oren and Pataki 2001). In that respect, the observed strong influence of VPD helps confirm its role as a first-order control on transpiration, as has been highlighted in recent literature (Grossiord et al. 2020; Novick et al. 2016; Sulman et al. 2016) and more classical studies on transpiration (Bovard et al. 2005; Oren et al. 1999; Tang et al. 2006). Our results show relationships between sap velocity and VPD (Figure 4.4 and 4.6a) that are similar to reported findings in broadleaf deciduous forests in eastern North America (Bovard et al. 2005; Oren and Pataki 2001). We found that the rate of change (slope) of sap velocity was higher (stepper) at low VPD, and then decreased when VPD became higher, yet, the slope did not flatten completely, meaning that sap velocity continued to increase (although at a lower rate) at the highest values of VPD. We expected that sugar maple would show a stronger response to changes in VPD, and stopped increasing sap velocity during high VPD, presenting high sensitivity to high water atmospheric demand. Hence, our results suggest a deviation from the isohydric behavior reported by Roman et al. (2015) and Yi et al. (2017); and is closer to the anisohydric classification in Loewenstein and Pallardy (1998). Since, drought severity can influence the evaluation of isohydric-anisohydric behavior (Coble et al. 2017), we presume that the sugar maple could have had enough access to soil water which allowed them to keep increasing sap velocity even at periods of high VPD.

Sapflow can be insensitive to changes in soil moisture when soil water is not a limiting factor. Low soil moisture thresholds have been identified as lower than a VWC of 0.10 $m^3m^{-3}$ (Bovard et al. 2005), a soil moisture depletion of at least 10mm (Oren and Pataki 2001) or a water potential ($\Psi_s$) ≤ −0.5 MPa (Yi et al. 2017). In such circumstances, soil moisture limitations modify the prevalent control of VPD and radiation over sapflow in isohydric species (Bovard et al. 2005; Oren and Pataki 2001). In our study site, the micro topography and soil characteristics contributed to greater water accumulation in the maple stands (notice the higher topographic wetness index in the maple plots in Figure 4.1 and the higher VWC in Figure 4.5a). Soil moisture averaged a VWC of 0.21 $m^3m^{-3}$ and had a minimum VWC of 0.12 $m^3m^{-3}$ despite the throughfall displacement. Such high soil moisture prevented the ability to measure a strong effect of soil water on sap velocity on sugar maple, explaining a deviation from a normal isohydric behavior during high VPD. On the other hand, we do not rule out the relevance that soil moisture could have as a control. Particularly, if we consider low soil moisture periods showed a slight decrease in sap flow (Figure 4.5b). Hence, continuation of field studies and drought forcing during years that have lower precipitation frequency and magnitude are needed in order to better understand how soil moisture mediates the control of VPD and radiation over the sap velocity of the two species. Moreover, in case trees access deep soil water, subsurface water movement could be avoided by trenching (Asbjornsen et al. 2018). Logistic and financial constrains were two other factors that limited the plot size and replication efforts. These, limitations highlight the importance of site selection for investigating specific sap flow and soil moisture relations (Kyongho and Tague 2019), as well as, continuing field studies of drought forcing experiments during years that have lower precipitation frequency and magnitude, in order to better understand how soil moisture mediates the control of VPD and radiation over the sap velocity of the two species.

To explore the implications of future climate and future forest on transpiration, we performed a modeling experiment using simple linear regression models fitted with regional predictions of future VPD, radiation and soil moisture derived from an ensemble of global circulation models. Model predictions of future climate indicated increases in VPD and modest reductions in available soil moisture (Figure 4.6). In other words, climate change in this region is likely to create conditions in which trees can transpire more as the atmosphere has a higher water demand and the water sources are still sufficient. More interestingly, when we combined the modeled future climate with a shift in forest composition towards larger maple dominance, as a result of the mesophication of eastern forests (Nowacki and Abrams, 2008; Nowacki and Abrams, 2015), the resulting transpiration was even higher as the inherent difference between species' transpiration greatly magnifies the change created solely by climate change. For instance, a forest composed of 60% maples and 40% oaks, without composition changes, would increase transpiration by +31±5 % (RCP 4.5) and +38±6 % (RCP8.5), while a forest that shifts to a 70% maple 30% oak could increase transpiration by +47±6 % (RCP 4.5) and +56±7 % (RCP 8.5) (see Table 4.4). Hernandez-Santana et al. 2015 found that future scenarios of 100% sugar maple dominance could lead to substantial increases (+74%) in transpiration compared to forest with a mix of ring and diffuse porous species. However, forest composition changes entail that as species migrate into new habitats that might not be as suitable as their present ones, creating a mismatch between species traits and site conditions, or in other words, mesic species occupying xeric sites. In that case, microsite conditions can have important effects on transpiration. This phenomenon is well exemplified in our study site, where maples occupy sites with higher topographic wetness index and soil moisture than the sites occupied by the oaks. We explored this mismatch by reducing future soil moisture by 50% to mimic more xeric site conditions (Table 4.4). Including microsite conditions in our analysis resulted in a less extreme picture of future transpiration, even if it was still significantly high. Maples in xeric sites presented lower transpiration than those in mesic sites by approximately 20% in each of the climate and forest composition scenarios. Although, our experiment is speculative, it sheds light on the complexity of predicting future transpiration rates and highlights the importance of coupling the information on future climate and potential shifts in tree species composition while considering specific site conditions.

*Table 4.4 Future transpiration (T) and percentage difference (% Δ) for two representative concentration pathways, different forest composition scenarios and mesic and xeric soil moisture conditions.*

| 2018 T (mm) 60% maple: 40% oak | Scenario | Soil moisture site conditions | Future T (mm) 60% maple 40% oak | % Δ | Future T (mm) 70% maple 30% oak | % Δ |
|---|---|---|---|---|---|---|
| 206.4 mm | RCP 4.5 | Mesic | 270±11 | +31±5 | 304±12 | +47±6 |
| | | Xeric | 236±14 | +14±7 | 265±16 | +28±8 |
| | RCP 8.5 | Mesic | 286±12 | +38±6 | 322±14 | +56±7 |
| | | Xeric | 253±16 | +23±8 | 283±18 | 37±9 |

These climate model predictions are consistent with other projections for the 21$^{st}$ climate in the Appalachian region, in which atmospheric water demand is expected to increase throughout the century (Fernandez and Zegre 2019). Moreover, such scenarios indicate that the complexity of the future climates must be considered in conjunction with how forest composition shifts can influence evapotranspiration. Over the last century, the central Appalachian Mountains experienced large expansions in the amount of land covered by forests, making forest the most abundant land cover (Morin et al. 2016). Forest cover alters the energy balance through evapotranspiration (Budyko 1974), reducing sensible heat leading to wetter and more temperate regional climate (Kutta and Hubbart 2019). More mesic conditions favor species such as *Acer saccharum*, *Liriodendron tulipifera*; and limit more drought tolerant species (e.g. *Quercus sp, Carya sp*). Given that reductions in long-term streamflow have been attributed to increased evapotranspiration due to vegetation changes in the Appalachian the mountains, the northeastern USA and in other continents (Caldwell et al. 2016, Hornbeck et al., 1993, Brown et al. 2005), it is plausible that greater water use by mesic species in a warmer future can change the regional water balance and ultimately decrease streamflow to the downstream urban areas that rely on water originating at headwater catchments (Caldwell et al. 2016). These assumptions, however, should be contextualized within the complexity and uncertainty around future dynamics between forest and the water cycle (Sheil, 2018). Other factors such as scale, forest type and climatic regimes can determine forest cover effects on streamflow (Zhang et al. 2017) and should be also considered to inform land use policies and their impacts on water supply (Ellison, Futter and Bishop 2012). These results, although specific to the central Appalachian mountains, serve to reflect on how other forested mountain regions in the world that also serve as "water towers" will be affected by climate change (Viviroli et al., 2011). It is therefore crucial to continue improving our understanding of how forest species transpiration rates will be affected by its environmental controls such as VPD, as well as an altered future forest composition.

In conclusion, our research shows that sap velocity rates are strongly affected by VPD but differ between two species of varying hydrisity. Additionally, using GCM downscaled information to model future VPD and soil moisture allowed to inquiry into the possible interplay between future climate, the transpiration rates of forest species, and microsite conditions. This effort seeks to initiate the discussion of coupling forest transpiration and climate change in order to understand the effects of climate change on the regional water balance. We hypothesize that increases in transpiration by mesic species would result in streamflow deficits during summer months, yet it is unknown if forest water use efficiency adaptations could dampen the effects of higher atmospheric demands on transpiration. Further investigation could look into these questions, given the importance of transpiration in the water cycle, and the role that forested regions around the world such as the Appalachian Mountains have as water towers to downstream populations.

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**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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### 4.6. Supplementary Information:

*Uncertainties in the calculations of sapwood area and Fraction of Volumes of Wood and Water:* Sapwood areas and fractions of the volume of wood and water are normally obtained from tree core samples. Given the coring limitation in the study site due to nature conservation rules of Tom’s Run Nature Preserve, we used as proxy for these measurements the allometric equations and information obtained from Wullschleger, Hanson, and Todd (2001)  and Yi et al. (2017). In order to account for the inherent uncertainty of using information from other sites, we used a Gaussian error propagation analysis (Bevington and Robinson, 1992) with an arbitrarily and cautious relative uncertainty of 20% for the proxied variables. Then, we applied addition (for the plot level sapwood areas) and multiplication (calculation of sap velocities and transpiration) error propagation equations (Bevington and Robinson, 1992). The resulting relative uncertainty of sap velocity was 14.87% in the maples and 14.18% in the oaks; for transpiration the relative uncertainties for maples were 17.43% for the untreated and 16.5% for the treatment, while, the oak had 16.5% for the untreated and 21.87% for the treatment.

*Measurement of Sapwood areas:* sapwood areas are measured from tree cores at DBH and determined by adding ink to the fresh sample to create a better visual contrast between the conducting and non-conducting xylem.

*Measurement of Fractions of Wood and Water:* Samples are weighted when they are fresh, and then are dried in an oven weighted again. The difference in weight corresponds to the amount of water present in the samples which is then divided by water's density to obtain its volume. The volume of the tree core sample is calculated using the volume of a cylinder. Ultimately, the fraction of volume water fraction is the share of volume water with respect to the whole sample. The volume wood fraction volume is the remaining fraction volume.

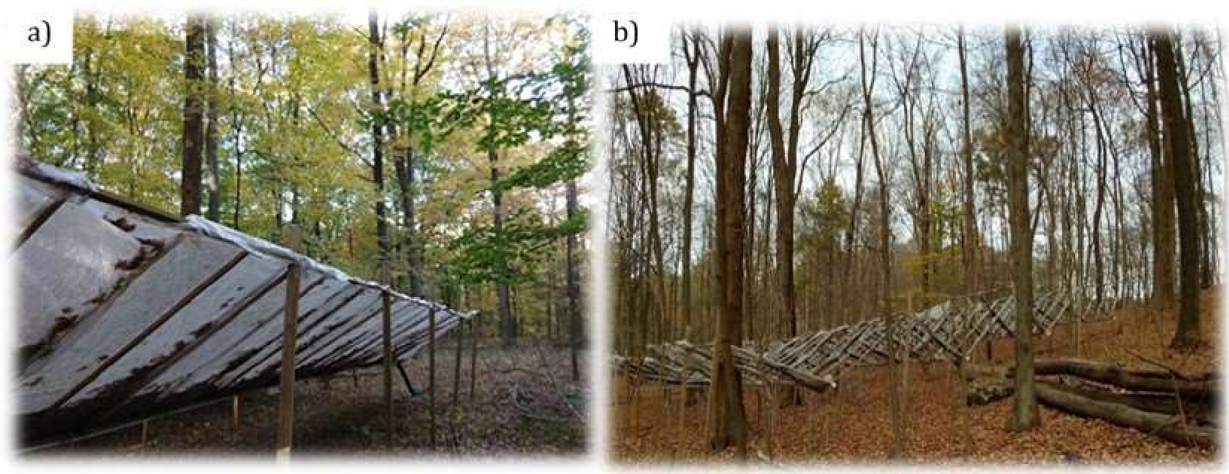


Figure 4.S1: a) Through fall experiment in early fall. b) through fall experiment off season.

Table 4.S1. DBH for the instrumented trees in the different plots.

| *Plot* | *Tree ID code* | *DBH (cm)* | *Sapwood Area (cm$^2$)* |
|---|---|---|---|

| | | | |
|---|---|---|---|
| *Maple untreated* | MC5 | 42.0 | 1078.90 |
| | MC7 | 49.3 | 1453.32 |
| | MC12 | 46.9 | 1324.56 |
| | MC16 | 21.4 | 308.03 |
| | MC20 | 26.7 | 464.78 |
| | MC21 | 32.7 | 677.49 |
| *Maple treatment* | MT01 | 31.5 | 632.00 |
| | MT02 | 37.6 | 878.28 |
| | MT04 | 55.8 | 1829.59 |
| | MT05 | 59 | 2029.43 |
| | MT23 | 49.3 | 1453.32 |
| *Oak untreated* | OC01 | 48.9 | 353.51 |
| | OC03 | 60.6 | 489.15 |
| | OC21 | 70.3 | 612.45 |
| | OC25 | 59 | 469.74 |
| | OC26 | 44.1 | 302.32 |
| | OC32 | 66.3 | 560.47 |
| *Oak treatment* | OT20 | 85.3 | 820.80 |
| | OT21 | 85.3 | 820.80 |
| | OT22 | 48.5 | 349.14 |
| | OT23 | 37.2 | 233.66 |
| | OT26 | 65.5 | 550.27 |
| | OT28 | 75.8 | 686.44 |

Table 4.S2: Summary of linear model results for modeling of future sap velocity.

| | Maple | Oaks |
|---|---|---|
| *Predictors* | *Estimates* | *Estimates* |
| (Intercept) | 105.89 *** | 66.08 *** |
| log(VPD) | 41.81 *** | 17.75 *** |
| Radiation | 0.13 *** | 0.06 ** |
| SM | 189.91*** | 3.08 |
| Observations | 126 | 252 |
| $R^2$ / $R^2$ adjusted | 0.881 / 0.872 | 0.639 / 0.635 |
| AIC | 1081.738 | 2002.580 |

- *p<0.05 ** p<0.01 *** p<0.001*

*Table 4.S3. Changes in Future Transpiration and percentage difference (% Δ) for two representative concentration pathways.*

| Species | 2018 transpiration (mm) | Future transpiration (mm) | % Δ |
|---|---|---|---|
| Maples | 308 | RCP 4.5: 407±15 | +32±5 |
| | | RCP 8.5: 429±17 | +39±6 |
| Oaks | 54 | RCP 4.5: 65±5 | +21±9 |
| | | RCP 8.5: 70±5 | +29±10 |

Table 4.S4. Basal areas by species for each plot.

| | Total Basal Area ($m^2$/ha) | Basal Area (%) |
|---|---|---|
| **Maple treatment** | | |
| *Acer rubrum* | 6.56 | 21 |
| *Acer saccharum* | 24.33 | 79 |
| Subtotal | **30.89** | **100** |
| **Maple untreated** | | |
| *Acer saccharum* | 30.24 | 59 |
| *Fraxinus americana* | 3.81 | 7 |
| *Quercus ruba* | 17.10 | 33 |
| | **51.15** | **100** |
| **Oak treatment** | | |
| *Acer saccharum* | 3.94 | 4 |
| *Carya ovata* | 0.99 | 1 |
| *Quercus ruba* | 14.45 | 16 |
| *Quercus velutina* | 68.08 | 75 |
| Unidentified | 3.03 | 3 |
| | **90.49** | **100** |
| **Oak untreated** | | |
| *Acer rubrum* | 1.16 | 2 |
| *Acer saccharum* | 4.06 | 7 |
| *Betula alleghaniensis* | 0.31 | 1 |
| *Betula lenta* | 0.39 | 1 |
| *Quercus ruba* | 8.13 | 14 |
| *Quercus velutina* | 44.53 | 76 |
| | **58.57** | **100** |

Table 4.S5: Leaf Area Index for 2018, based on scanning a sample of leaves collected from litterfall baskets and scaled by the amount of litterfall per area. Source: Raczka et al. unpublished data.

| **Plot** | **Mean LAI (*unitless*)** | **Standard deviation** |
|---|---|---|
| Maple untreated | 1.89 | 0.068 |
| Maple treatment | 1.98 | 0.027 |
| Oak untreated | 2.13 | 0.08 |
| Oak treatment | 2.79 | 0.38 |

# Chapter 5 Conclusions

This dissertation aimed to advance the understanding of the environmental controls of the water cycle in forested mountain ecosystems. In order to reach that goal, three investigations were designed and carried out and are presented in three standalone scientific manuscripts.

Overall, this body of work shows the importance of studying ecohydrological processes at different temporal and spatial scales, as they reveal the complexity of tree-soil-water-atmosphere relationships. For instance, empirically, we found how tree characteristics determine their water use and sensitivity to variations in the atmospheric water demand. Also, at regional and intra-regional scales climate controls played a more important role than vegetation or topography for evapotranspiration. Moreover, partitioning of precipitation can be modified due to changes in climate controls even in undisturbed areas such as reference catchments.

The specific conclusions from the three research questions were the following:

The first manuscript studied the hydrologic stability of reference catchments in the US. The methods included an analysis of trends in water balance components and an investigation of the evaporation sensitivities to the changes in precipitation, potential evaporation and catchment characteristics (Budyko's n). The main results were that that several catchments were hydrologically unstable, while other were hydrologically stable. The most unstable catchments were the most sensitive to the changes in Budyko's n, while the stable catchments can be more affected by the changes in long-term precipitation and potential evapotranspiration. Changes in climatic controls were associated with the changes in the catchment characteristics.

The second manuscript used the Budyko framework and statistics to analyze gridded data in order to understand how main precipitation partitioning controls differ across basins in the central Appalachian mountain region. The main results were that precipitation partitioning controls depend on scale and vary across the region due to complexity created by the eastern continental divide. Also, climate controls, in particular temperature and fraction of precipitation falling as snow, were more important than landscape controls. Finally, among the landscape controls, elevation was the most influential to partition precipitation.

The third manuscript studied the sap velocity rates of *Acer saccharum* and *Quercus velutina* in two forest stands of West Virginia. The main conclusions were that the sap velocity of the two tree species studies was mainly controlled by vapor pressure deficit, and that soil moisture levels were not low enough to importantly modulate transpiration. Modeling of transpiration and species dominance based on two scenarios indicated that higher atmospheric water demand could bring increases in future transpiration rates in the case of high soil moisture levels. Hence, the importance of the dominance of tree species types, atmospheric conditions and soil moisture level is determinant for future water resources during summer months.

This dissertation contributes to the forest hydrology sciences in bringing attention to lasting assumptions about reference catchment's hydrologic behavior. Also, it advances the knowledge about the environmental controls that influence the important water resources provided by the central Appalachian mountain region. Finally, it highlights the importance of looking at the small scale, as trees and their water use, fundamentally linked to the water balance, will be affected by climate and landscape change with cascading effects on future water resources.

Moreover, important outcomes from the research process behind this dissertation are the learning experiences from the numerous challenges that were encountered during its duration. These lessons are also a general answer to the question "What could have been done differently?" and will serve to improve the quality, efficiency and scientific value of future research project. Although there are many, some valuable lessons that can help other junior researchers are the following: i) the writing and publishing process can be longer than any good estimation, start early, meaning, years in advance. ii) Although, self-learning is imperative to the process, sometimes, specific highly technical skills should be learned from experts. Hence, understand, as soon as possible, the limitations of your own knowledge to apply a certain method (e.g. lab, field, coding, stats) and get external help or training; doing this will advance, speed up and improve the quality of the research. iii) Time should be devoted to understanding the data needs of specific methods in order to reduce uncertainty as this can later become a larger problem (e.g. parameters that could not be measured in the field leads to dependence on allometric equations with higher uncertainty). iv) Finding the data's story is crucial, but difficult when done in isolation. Instead, discussion and collaboration are a better strategy. The largest breakthroughs in the research and story development happen at meetings when teamwork and different viewpoints are exposed; carrying out this process earlier, more often and in a scheduled fashion can bring better results in future projects.

**Future Directions**

The conclusions and challenges of the investigations serve as a starting point to future studies that can continue to further the knowledge on the environmental controls of the water cycle. Three main future research questions are proposed:

1) Are vegetation changes influencing long term precipitation partitioning in reference catchments? The study of vegetation controls in reference catchment can complement our results about the influence of climatic controls over partitioning. The research could include variables, such as, phenology, growing season length, species composition, NDVI, leaf area index, forest type.
2) What are the partitioning controls at intra-basin scales in the central Appalachian region? Given the importance of the region as a water source to the eastern US and the dependence of controls on scale, studying small scales controls can improve decision making. Moreover, it is important

that hydrologic studies are closer to the scales in which watershed management decisions take place. A study of smaller catchments would also increase the sample size improving the capacity of making more meaningful statistical inferences.

3) How are sap velocity rates for *Acer saccharum* and *Quercus velutina* influenced by drier atmospheric and soil moisture conditions? Measurement of sap velocity and environmental variables we also carried during the summer of 2019, which was characterized by lower precipitation and lower soil moisture than the summer of 2018. A main hypothesis for this study is that higher limitations in soil moisture could reduce sap velocities at daily and intra-daily scales.

## Chapter 6 References


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