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INFLUENCE OF FOREST-TO-SILVOPASTURE CONVERSION AND DROUGHT ON COMPONENTS OF EVAPOTRANSPIRATION

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Abstract

The northeastern U.S. is projected to experience more frequent short-term (1-2 month) droughts interspersed among larger precipitation events. Agroforestry practices such as silvopasture may mitigate these impacts of climate change while maintaining economic benefits of both agricultural and forestry practices. This study evaluated the effects of forest-to-silvopasture (i.e., 50% thinning) conversion on the components of evapotranspiration (transpiration, rainfall interception, and soil evaporation) during the growing season of 2016. The study coincided with a late-summer drought throughout the northeastern U.S., which allowed us to also evaluate the effects of forest-to-silvopasture conversion on drought responses of multiple tree species, including *Pinus strobus*, *Tsuga canadensis*, and *Quercus rubra*. In the reference forest and silvopasture, we observed declining soil moisture and tree water use during the drought for all three tree species. However, the decline in *P. strobus* water use in response to declining soil moisture in the silvopasture was not as steep as compared with the reference forest, resulting in greater water use in the silvopasture for this species. In contrast, we did not detect different water-use responses between forest and silvopasture in *T. canadensis* or *Q. rubra*. This suggests that forest-to-silvopasture conversion via thinning can alleviate drought stress for *P. strobus* and that this species may be more sensitive to moisture stress when competition for water is high in denser stands. Evapotranspiration was 35% lower in the silvopasture compared with the reference forest, primarily a result of lower transpiration and rainfall interception. While soil evaporation was greater in the silvopasture, this was not enough to offset the considerably lower transpiration and interception. We observed greater radial tree growth 1-3 years following conversion in the silvopasture as compared with the reference forest for *T. canadensis* and *Q. rubra*, but not for *P. strobus*. Overall, our results suggest that forest conversion to silvopasture

(in lieu of clearcutting for new pasture) may mitigate the impacts of agricultural land use intensification and climate change on ecosystem services, especially in terms of sustaining hydrologic regulation functions. Further study is required to determine the generality of these results and whether these benefits extend beyond the first few years post-conversion.

1. Introduction

Land cover in New England has shifted from nearly 50 percent agricultural through the late 18th to mid-19th century to predominantly forests by the end of the 20th century (Foster, 1992; Foster et al., 2010; Nowak and Greenfield, 2012). Recently, however, agriculture in New England has experienced a resurgence, due in large part to increasing consumer demand for locally produced goods which enables a high percentage of farms to sell directly to consumers and retailers (e.g., restaurants, grocery stores) (USDA-NASS, 2014). At the same time, most farm properties in the region remain heavily forested, with as much as 65% of total farmland classified as woodland in some states (USDA-NASS, 2014). Hence, farmers in the region interested in expanding their agricultural land base to meet growing consumer demand will necessarily need to convert some of this forested land to agricultural uses (USDA-NRCS, 2001; Donahue et al., 2014).

While conversion of forested land to agriculture increases the land area available for food production, it also increases the risk of losing critical ecosystem services that forests provide to society, such as carbon sequestration and hydrological regulation. Agroforestry practices may offer a strategy that balances some of these ecological and economic trade-offs (Garrett and Buck, 1997; Shrestha and Alavalapati, 2004; DeBruyne et al., 2011; Nair, 2011; Orefice et al., 2019). In fact, the U.S. Department of Agriculture (USDA) has recently promoted agroforestry

to help mitigate the effects of climate change, provide resilience to agricultural landscapes, and offer improved food security throughout the U.S., while also recognizing that additional scientific research in agroforestry systems is needed (Schoeneberger et al., 2017). Given the New England region is projected to experience more frequent short-term (1-2 month) droughts interspersed among larger precipitation events (Hayhoe et al. 2007, Wake et al. 2014), identifying ways in which agroforestry practices can potentially mitigate climate change impacts while meeting the region's future agricultural goals is an important area of emerging research (Schoeneberger et al. 2012, Orefice et al. 2017).

Silvopasture is an agroforestry system that includes the simultaneous management of growing trees and livestock grazing on the same lands. Silvopasture systems vary widely depending on climate and resources, but the primary goals of silvopasture in New England are for production of sawtimber, firewood, and fruit production, in addition to livestock production (Orefice et al., 2017). Previous research has demonstrated silvopasture systems can provide important ecosystem services including carbon sequestration (Sharrow and Ismail, 2004; Dold et al., 2019) and improved water quality (Michel et al., 2007; Nair et al., 2007; Bambo et al., 2009), as well as providing favorable microclimate conditions for grazing animals (Karki and Goodman, 2015). A large collection of studies has also shown that forested catchments have greater evapotranspiration and lower water yield compared with open pastures (Bosch and Hewlett, 1982; Zhang et al., 2001; Brown et al., 2005; Beets and Oliver, 2007), suggesting that tree cover reduces runoff. However, less is known regarding how conversion of forested land to silvopasture affects ecosystem services that regulate runoff and streamflow, including tree transpiration, rainfall interception, soil evaporation, and evapotranspiration.

We evaluated how conversion of a mixed species forest to a silvopasture affected microclimate, stand structure (i.e., basal area and density), ecohydrology, and tree growth 1 to 3 years following conversion. The study coincided with extreme drought conditions that occurred throughout the northeastern U.S., with areas receiving 25-75% of normal precipitation (Coble et al., 2017; Sweet et al., 2017). This allowed us to additionally quantify drought responses in both the recently converted silvopasture and a reference forest. At the individual tree level, we hypothesized that following thinning, all species would experience greater increases in water use and tree growth and subsequent increases in water availability due to less competition. We also hypothesized that conversion of forest to silvopasture would alleviate water-stress and negative effects of drought on water use (i.e., sap flux density). Finally, we hypothesized that forest-to-silvopasture conversion would decrease total stand evapotranspiration one year following conversion via decreases in stand transpiration and intercepted precipitation. The primary target tree species for this study were *Pinus strobus* (white pine), *Tsuga canadensis* (eastern hemlock), and *Quercus rubra* (northern red oak).

2. Methods

2.1. Study site

The study site was a mixed *P. strobus*-*T. canadensis* forest located at the University of New Hampshire Organic Dairy Research Farm (43.0972 N, 70.9961 W; 30 m elevation) in Lee, New Hampshire. In the spring of 2015, two 1-ha (50 × 200 m) plots were converted to open pasture and silvopasture, herein referred to as ‘pasture’ and ‘silvopasture’, respectively. An additional 1-ha plot was left untreated, which served as the control, herein referred to as ‘reference forest’. These three plots were adjacent to each other, with the pasture located in

between the silvopasture and reference forest plots. The goals of the silvopasture conversion were to create sufficient light in the understory for forage production and cattle grazing (~50% reduction in canopy cover and removal of understory trees) by removing trees with lower timber value (e.g., *T. canadensis* and understory trees) while retaining trees with high timber value (e.g., primarily *P. strobus* and *Q. rubra*). All trees and understory were removed in the pasture treatment.

Orchard grass (*Dactylis glomerata*) seed was applied to the silvopasture and pasture plots immediately following conversion in 2015. Since there was very little establishment of orchard grass in 2015, seed was applied again in the spring of 2016. After seeding occurred in 2016, rotational grazing of Jersey heifers in the pasture and silvopasture plots over a ~13 week period was established to help scarify the soil and promote orchard grass germination and establishment. Ten heifers grazed in 15×100 m fenced paddocks that included portions of both the silvopasture and pasture. Within the paddocks, hay bales were evenly distributed to promote additional seeding and soil scarification. Paddocks initially started at the eastern end of the plots and were moved sequentially once per week to cover the entire area of the silvopasture and pasture plots. Grazing intensity was estimated to be $1.42 \text{ head ha}^{-1} \text{ day}^{-1} \text{ year}^{-1}$ (Stewart et al. 2019).

A complete tree inventory of the reference forest and silvopasture was conducted in May 2016. The total basal area of the reference forest and silvopasture were 49.5 and $20.5 \text{ m}^2 \text{ ha}^{-1}$, respectively (Table 1). *T. canadensis* and *P. strobus* were the dominant species in the reference forest with a basal area of 28.9 and $12.1 \text{ m}^2 \text{ ha}^{-1}$, respectively. Other major species in the reference forest included *Betula lenta* ($2.3 \text{ m}^2 \text{ ha}^{-1}$), *Carya ovata* ($2.1 \text{ m}^2 \text{ ha}^{-1}$), *Acer rubrum* ($1.4 \text{ m}^2 \text{ ha}^{-1}$), *Q. rubra* ($1.2 \text{ m}^2 \text{ ha}^{-1}$), and *Quercus alba* ($1.0 \text{ m}^2 \text{ ha}^{-1}$). *T. canadensis* and *P. strobus*

were the dominant species remaining in the silvopasture plot with a basal area of 5.7 and 10.0 m² ha⁻¹, respectively. Other major species in the silvopasture included *Q. rubra* (2.2 m² ha⁻¹), *Betula lenta* (1.5 m² ha⁻¹), *Acer rubrum* (0.5 m² ha⁻¹), *Carya ovata* (0.2 m² ha⁻¹), and *Quercus alba* (0.1 m² ha⁻¹).

All measurements in this study were made within one plot per treatment, which is a form of simple pseudoreplication with unreplicated treatments (Hurlbert 1984). One potential issue arising from simple pseudoreplication is that the experimental units may not be identical at the time of and following the treatment, apart from the treatment effect (Hurlbert 1984). Thus, pre-existing differences among plots can be mistaken for treatment effects. While the current study lacks pre-treatment data for most parameters reported in this manuscript, there is evidence for similar soil conditions between the reference forest and silvopasture. At the same site during the same year (2016), Stewart et al. (2019) found no significant differences in soil bulk density or soil particle size among the reference forest, silvopasture, and pasture plots. Stewart et al. (2019) also found that saturated hydraulic conductivity (K_{sat}) was not significantly different between the reference forest and silvopasture at three soil depths (0, 15, and 30 cm). The only difference in K_{sat} observed was between the reference forest and pasture at the 15 cm depth. Furthermore, we did not detect differences in 3-yr mean raw ring width between the reference forest and silvopasture for the pretreatment period for any of the tree species (see Section 3.4). Overall, these findings are consistent with the idea that pre-existing differences in site conditions across our plots are not the dominant drivers of the measured differences that we interpret as treatment effects.

2.2. Meteorological and microclimate measurements

One meteorological station was placed in the center of the reference forest, silvopasture, and pasture plots in October 2015. Each station continuously measured relative humidity (RH, %) and air temperature ($^{\circ}\text{C}$) using a HOBO U23 Pro V2 Temperature/Relative Humidity Data Logger (Onset Computer Corporation, Bourne, MA, USA). Photosynthetic photon flux density (PPFD, $\mu\text{mol m}^{-2} \text{s}^{-1}$) was measured using a HOBO PAR Smart Sensor. Relative humidity, air temperature, and PPFD were measured 1.5 m above the ground. We also measured RH and air temperature at 15 m above the ground in the silvopasture and reference forest canopies using two HOBO U23 Pro V2 Temperature/Relative Humidity Data Loggers, which were tied to parachute chord suspended by two large branches in two *P. strobus* trees. Relative humidity and air temperature measured at 1.5 and 15 m were used to calculate vapor pressure deficit (VPD, kPa) using the R-software package ‘plantecophys’ (Duursma, 2015). Soil temperature ($^{\circ}\text{C}$) was measured at a 0-15 cm depth at three locations around each tower with a HOBO 12-Bit Temperature Smart Sensor. Volumetric soil water content (VWC, $\text{m}^3 \text{m}^{-3}$) was measured at three locations around each tower and at three soil depths (0-15 cm, 15-30 cm, and 30-50 cm) using a HOBO 10HS Soil Moisture Smart Sensor. The analysis in this study includes VWC data at the 0-15 cm depth to simplify the analysis. Meteorological measurements were logged at an hourly time-step using a HOBO Micro Station Data Logger. Precipitation (mm) was also measured hourly in the pasture. However, there were a number of gaps in the data due to equipment malfunction. To fill in these gaps, we used hourly precipitation (mm) data from the National Oceanic and Atmospheric Administration USCRN meteorological station (WBAN #54795), located approximately 4 km from the study area.

In order to characterize light conditions throughout the reference forest and silvopasture plots, hemispherical photographs were taken at multiple locations throughout each plot, using a digital camera (NIKON E4500) with a fish-eye lens attached to a gimbal and telescoping pole. During the mornings and evenings of 17-18 August 2016, hemispherical photographs were taken directly above each throughfall collector (described below) in the reference forest and silvopasture plots for a total of 60 hemispherical photographs following the methods of Zhang et al. (2005) (Supplementary Material I). Hemispherical images were analyzed for gap fraction, indirect site factor, and direct site factor using HemiView v.2.1 software (Delta-T Devices, Ltd.; Cambridge, UK). Gap fraction is the fraction of the canopy not blocked by foliage from a viewpoint of 2 m above the forest floor. Direct site factor (DSF) is the proportion of direct light relative to open conditions, while indirect site factor (ISF) is the proportion of diffuse light under a standard overcast sky.

2.3. Throughfall measurements

Within each plot we measured net precipitation (i.e., throughfall) using 30 collectors. We randomly selected the locations of five transects (50 m length) within each plot. Transects were equally divided into six 8.3 m sections and one collector was randomly assigned a location within each section. We also included three equally spaced collectors in the reference pasture to measure gross precipitation for the same rain events. Throughfall collectors consisted of funnels (12 cm diameter) secured to the tops of the 3.8-liter plastic bottles. The bottles were secured to wooden stakes using parachute chord. Following each rain event, the quantity of water (mL) collected by the bottles was measured using a graduated cylinder. We measured throughfall for

rain events occurring from 6 June to 20 September 2016 for a total of 13 rain events at the silvopasture and reference plots, respectively.

2.4. Sap flux density measurements

Target species for sap flux density measurements included *T. canadensis*, *P. strobus*, and *Q. rubra* due to their high contribution to stand basal area in the silvopasture and reference forest, as well as the high timber value of *Q. rubra*. We selected five *T. canadensis*, five *P. strobus*, and two *Q. rubra* trees in each plot for a total of 24 trees. The mean diameter of these sample trees by species is shown in Table 1. Our objective in selecting sample trees was to select trees of similar diameter at breast height (DBH, cm) among treatments, which was accomplished for *P. strobus* and *T. canadensis*. However, due to the low number of *Q. rubra* trees in the reference forest, selecting trees with comparable diameters was not possible. Due to the greater diameter size of *Q. rubra* in the reference forest, we used sap flux density to compare water use patterns among individual species, which accounts for differences in the total sapwood area of each tree (Hernandez-Santana et al., 2015).

We used the heat-ratio method (HRM) for measuring sap flux density, which consisted of an upper and a lower temperature probe spaced 0.6 cm from a middle heater probe (Burgess et al., 2001; Vandegehuchte and Steppe, 2013). One set of temperature probes (i.e., upper, lower, and heater probe) per sample tree was installed in the tree sapwood after chiseling the bark and phloem from the sapwood. Bark thickness at each set of probes was measured with a depth gauge to account for bark thickness in diameter measurements and calculation of sapwood area. Probes were installed in trees at 2.7-3.0 m above the ground in the silvopasture plot to eliminate the potential for damage from cows that were grazing in the plot. Probes were installed 1.3 m

above the ground in the reference forest where heifers were not allowed to graze. For two *P. strobus* trees and one *Q. rubra* tree in the reference forest, we added additional probes at 3 m to assess whether vertical position along the bole affected sap flux density. For *P. strobus*, we observed strong correlations ($R^2 = 0.93-0.98$) between sap flux density at 1.3 m and at 3 m, and the slopes ranged from 0.95 to 1.11 for the linear models. For *Q. rubra*, we also observed a strong linear correlation ($R^2 = 0.99$) and a slope of 1.0. This analysis indicates that sap flux density measurements taken at 1.3 and 3 m can be compared directly.

Due to differing sapwood depth among species, two types of temperature probes that differed in length were constructed prior to installation: longer probes of 4 cm with thermocouples at depths of 1, 2.25, and 3.5 cm from the outer edge of the sapwood for *P. strobus* and large *T. canadensis* trees (> 32 cm DBH), and shorter probes of 2.5 cm with thermocouples at depths of 0.5, 1.0, and 1.5 cm for small *T. canadensis* (< 32 cm DBH) and *Q. rubra* trees. Appropriate probe length was based on sapwood depth observations in the three species included in the study (Daley et al., 2007; McIntire, 2018). Based on predicted sapwood depths using DBH (described below) and probe lengths, the proportion of sapwood depth covered by the probes was estimated to be 100% for *P. strobus*, 44% for small *T. canadensis* trees (< 32 cm DBH), 52% for large *T. canadensis* trees (> 32 cm DBH), and 92% for *Q. rubra*. Different probe lengths and depths into the sapwood were accounted for when conducting sap flow analysis at the tree level.

Each sap flow sensor set was wired to a channel relay multiplexer (AM16/32B-ST-SW, Campbell Scientific, Logan, UT) and datalogger (CR1000, Campbell Scientific, Logan, UT) powered by 12 volt batteries. Data loggers were programmed to collect consecutive measurements of sapwood temperature for 30 seconds prior to the heat pulse and for 100 seconds following the heat pulse, and these sets of measurements were collected every 15 minutes from 1

July through 1 October 2016. For each depth of the temperature probes, we calculated sap flux density using the methods described in Burgess et al. (2001). Sap flux density measurements at each depth were scaled to the tree using a weighted average based on of the proportion of sapwood area associated with each depth of the temperature probes (Hernandez-Santana et al., 2015).

For the purposes of estimating sapwood area and depth for each tree, tree cores were collected from outside and adjacent to the silvopasture plot from *T. canadensis* (10 trees) and *Q. rubra* (10 trees) in July 2017 using an increment borer. Sapwood depth was measured after the cores were stained with methyl orange (0.1%). Using the sapwood depth, we developed a regression equation for predicting sapwood depth using DBH as the independent variable. Regression equations relating DBH to sapwood depth were then used for predicting sapwood depth for the trees in the reference forest and silvopasture plots. DBH-sapwood depth regression equations for *P. strobus* were developed from another nearby study (4 km; McIntire, 2018). This method involved scanning tree discs and measuring sapwood depth and area using ImageJ software (Schneider et al., 2012).

2.6. Soil evaporation

We measured *in situ* soil evaporation to assess forest-to-silvopasture effects on soil evaporation during the late summer and to validate modeled soil evaporation (described below) relative to the reference forest and pasture treatments. We followed the methods of Jackson and Wallace (1999) for measuring *in situ* soil evaporation using microlysimeters with some modifications. Microlysimeters were constructed using polyvinyl chloride (PVC) pipe with a 10 cm diameter cut at 12 cm lengths, and equally spaced holes were drilled along the entire surface

of the pipe to allow for drainage of saturated soils. In the spring of 2016, prior to the study period, approximately 18 microlysimeters were inserted into the soil at a depth of 12 cm in an area adjacent to the silvopasture plot. Following three rain events in August, the microlysimeters were collected from the adjacent site in the morning at 0800 hours. Microlysimeters were carefully extracted to prevent soil loss from the soil collar. Three evenly spaced holes were dug within the reference forest, silvopasture, and pasture plots to a depth of 16 cm for the purpose of housing the microlysimeters, and lined with aluminum sheeting to form a microlysimeter holder. Immediately after extracting the microlysimeters, they were wrapped in plastic to prevent evaporation from the holes, weighed, and placed on a mounting platform within each microlysimeter holder. The mounting platform raised the soil core above bottom of the microlysimeter holder and kept the top of the microlysimeter at the same height as the soil surface. Microlysimeters were weighed immediately after extraction and measured at 0800 hrs and 1800 hrs each day for three days following each rain event in order to obtain daytime, nighttime, and 24-hour estimates of soil evaporation. In the analysis, we focus on the 24-hour measurements. We obtained six 24-hour estimates of soil evaporation for the three replicates in the reference forest and silvopasture for a total of thirty six 24-hour measurements of soil evaporation.

The rate of soil evaporation (E_s , $\text{kg m}^{-2} \text{s}^{-1}$) was modeled at an hourly time-step in all plots in order estimate total cumulative soil evaporation (mm) and evapotranspiration (mm) over the entire study period. Briefly, the modeling approach used in this study estimates the difference in partial water vapor pressures between the air and the soil, as well as the conductance of water vapor through the soil and boundary layers above the soil surface (see Supplementary Material I). This modeling approach is described by Duursma and Medlyn (2012), which is based on

models developed by Choudhury and Monteith (1988) and modified by Williams et al. (2001). We validated modeled soil evaporation with our *in situ* measurements.

2.8. Tree growth

Within the reference forest and silvopasture plots, sap flow trees and additional trees of similar diameter class were selected and cored in November 2017 for tree growth analysis. Ten trees for each species (*P. strobus*, *T. canadensis*, and *Q. rubra*) were selected in the reference forest and silvopasture plots, except for *Q. rubra* in the reference forest, which were limited to eight trees. Trees located near the edge of the pasture were excluded when possible. One core was collected from each tree at a height of 20-30 cm (to preserve future timber value, consistent with the management objectives). Samples were processed using standard dendrochronological techniques (Speer 2010). Due to the timing of the tree core collection, tree measurements were restricted to 3 years of growth following forest-to-silvopasture conversion.

While collecting short cores to assess radial growth three years before and after forest-to-silvopasture conversion was our primary objective, we also collected longer cores appropriate for cross-dating purposes. For instance, 78% of the chronologies were at least 25 years in length and 50% of the cores were at least 40 years in length. For *T. canadensis*, the series intercorrelation was 0.491 with an average mean sensitivity of 0.229. For *P. strobus*, the series intercorrelation was 0.365 with an average mean sensitivity of 0.252. For *Q. rubra*, the series intercorrelation was 0.684 with an average mean sensitivity 0.226.

2.9. Data Analysis

Statistical analyses were conducted using R statistical software v3.5.2 (R Core Team, 2018). We used ANCOVA to compare net precipitation (mm; i.e., throughfall) between the reference forest and silvopasture. Net precipitation was the dependent variable, and the independent variables were treatment, gross precipitation (covariate), and treatment \times gross precipitation. ANCOVA was also used to compare daily sap flux density ($\text{cm}^3 \text{cm}^{-2} \text{day}^{-1}$) between treatments and time periods (i.e., pre-drought, drought, and post-drought). The dependent variable was daily sap flux density, and the independent variables were treatment, time period, (ln)VPD (covariate), and all interaction effects. In comparing daily sap flux density-VPD slopes, we repeated this analysis after changing the default factor level (i.e., base case) for time period so that tests for differences in slopes could be made for all time periods. We used *t*-statistics to test whether slopes differ between treatments and time periods.

To further compare drought responses between treatments and species, we conducted a piecewise linear regression for the relationships between sap flux density and VWC for each species within each treatment. Data for this analysis includes days with above-average daily PPFD and that include VWC data in both the reference forest and silvopasture. Breakpoints for the piecewise linear regression were also estimated to identify the point, or threshold, at which sap flux density begins to decrease with decreasing VWC using the R package ‘segmented’ (Muggeo 2008). ANCOVA was used to compare the rate of decreasing sap flux density with decreasing soil moisture for values below the breakpoints. The dependent variable was daily sap flux density, and the independent variables were treatment, species, VWC (covariate), and all interaction variables. For this ANCOVA, we only included days that had above-average PPFD ($> 429 \text{ mol m}^{-2} \text{day}^{-1}$). The reason for not including cloudy, cooler days is that sap flux density is limited by these conditions and less likely to be influenced by soil moisture and crown

illumination, masking the effects of forest thinning or drought on tree water use. We only included days that contained soil VWC data in both the reference forest and silvopasture to avoid a biased comparison.

We used a linear mixed-effects model to compare daily sap flux density and tree growth between both treatments and among different time periods. For both linear mixed-effects models, tree was included as a random effect, and time (e.g., drought period or pre-/post-conversion), treatment, and time \times treatment were the fixed effects. Prior to running the models, mean daily sap flux density was averaged across each drought period (pre-drought, drought, and post-drought) for each tree, and ring width 3 years prior to and 3 years following the forest-to-silvopasture conversion were averaged for each tree to calculate 3-year mean ring width. Differences in 3-year mean ring width between pre- and post-conversion, as well as differences between reference forest and silvopasture, are reported along with corresponding 95% confidence intervals.

3. Results

3.1. Microclimate and soil moisture

As expected, daily photosynthetic photon flux density (PPFD) was greatest in the pasture, intermediate in the silvopasture, and lowest in the reference forest (Fig. 1a). Mean PPFD in the pasture, silvopasture, and reference forest over the study was 423 ± 17 , 103 ± 5 , 6 ± 1 mol m⁻² day⁻¹ (\pm SE). Vapor pressure deficit (VPD) was greater in the pasture and silvopasture than the reference forest (Fig. 1b). Mean VPD in the pasture, silvopasture, and reference forest, and was 0.67 ± 0.04 , 0.65 ± 0.04 , and 0.53 ± 0.02 kPa (\pm SE), respectively. The difference in VPD between the reference forest and silvopasture was much more apparent at 1.5 m than what was observed

in the canopy. Mean VPD in the silvopasture and forest canopies at 15 m above the ground were the same (0.75 ± 0.04 kPa for both).

During the study period at this site and throughout southeastern New Hampshire, a drought occurred from 23 August through 18 September (Fig. 1c), which was preceded by several months of below-average precipitation. The large rain event at the end of this drought occurred on 19 September, which resulted in 30 mm of gross precipitation. In the upper soil layer (0-15 cm), we observed a fairly constant and greater VWC in the pasture as compared with the reference forest and silvopasture (Fig. 1d). Declining VWC associated with drought was apparent in the reference forest and silvopasture and was likely associated with water uptake by trees and increased soil evaporation in the latter (see Section 3.2). Despite the greater number of trees present in the reference forest, VWC was similar between the reference forest and silvopasture.

3.2. Canopy interception and soil evaporation

We observed greater canopy interception by the reference forest as compared with the silvopasture (Fig. 2). The ANCOVA showed a significant treatment \times gross precipitation effect for predicting net precipitation ($p < 0.001$), indicating that the slope of the relationship between net precipitation and gross precipitation was significantly greater at the silvopasture than the forest. Approximately 83 and 92% of the precipitation falling onto the reference forest and silvopasture canopies (as throughfall), respectively, penetrated the canopies to reach the ground.

In situ measurements showed that soil evaporation was greatest in the pasture, intermediate in the silvopasture, and lowest in the reference forest in August 2016 (Fig. 3). The *in situ* measurements were similar to modeled estimates except for the pasture, where measured

soil evaporation was approximately 50% greater than the modeled estimate. The inconsistencies among measured and modeled estimates are discussed in Section 4.3.

3.3. Sap flux density and drought response

While daily sap flux density for *P. strobus* appeared to be greater in the silvopasture than the reference forest in early June and during the late-summer drought (Fig. 4a), we did not detect a significant treatment effect ($p > 0.05$) on mean daily sap flux density (e.g., averaged over each drought period) for any of the species or drought periods (pre-drought, drought, and post-drought). We did observe a significant ($p < 0.05$) drought period effect for all species. Mean daily sap flux density was significantly greater during the pre-drought than both the drought and post-drought periods for all species. Mean daily sap flux density was significantly greater during the drought period than the post-drought period for *Pinus strobus* and *Quercus rubra* in the silvopasture, but not in the reference forest.

In comparing seasonal differences in sap flux density between the silvopasture and reference forest, we calculated the ratio of the silvopasture to reference forest sap flux density (Supplementary Material II). For *P. strobus*, we observed a large increase in this ratio during the drought period, providing further evidence of decreased sensitivity to drought through thinning. This ratio slightly decreased during the drought period for *T. canadensis* and did not change for *Q. rubra*.

To better understand drought response and recovery following drought for the three species, we compared sap flux density and vapor pressure deficit (VPD) relationships among the pre-drought, drought, and post-drought time periods. Vapor pressure deficit is a key predictor in stomatal behavior. Thus, a diminished response (i.e., lower slope) indicates greater stomatal

closure. Sap flux density for all species displayed a non-linear response to VPD during all portions of the study period including pre-drought, drought, and post-drought (i.e., time period) (Fig. 5a-f). For the ANCOVA, a treatment and $(\ln)\text{VPD} \times \text{treatment}$ effect was detected for *P. strobus*, but not for *Q. rubra* or *T. canadensis*. For all species, we detected $(\ln)\text{VPD}$, time period, and $(\ln)\text{VPD} \times \text{time period}$ effects. For all species, the slopes of the sap flux density-VPD relationships were greater during the pre-drought period as compared with the drought and post-drought periods in both reference forest and silvopasture (Table 2). Within each time period, the slopes were not significantly different between the reference forest and silvopasture for all species, except for *P. strobus* during the pre-drought period (Table 2).

Breakpoints of the piecewise regression model were similar among treatments and species, ranged from 0.15 to 0.18 $\text{m}^3 \text{m}^{-3}$, and indicate that sap flux density declines with decreasing VWC below this range (Fig. 6). For all species, regressions between sap flux density and VWC were significant ($p < 0.001$) below the breakpoint and non-significant ($p > 0.05$) above the breakpoints (Fig. 6). For the ANCOVA that compared sap flux-VWC slopes below the breakpoint, we observed a significant treatment, VWC, and species effect ($p < 0.001$) on sap flux density. The 2-way and 3-way interaction effects on sap flux density were also significant ($p < 0.001$). In the reference forest, the slope (slope \pm SE) of the relationship between sap flux density and VWC (e.g., below the breakpoint) was greater for *P. strobus* (2403 \pm 254) than for *T. canadensis* (1100 \pm 208) and *Q. rubra* (604 \pm 134). This suggests that *P. strobus* was most sensitive to drought in the reference forest. In the silvopasture, the slope of the sap flux-VWC relationship was greater for *P. strobus* (977 \pm 93) and *T. canadensis* (782 \pm 62) as compared with *Q. rubra* (509 \pm 85). Thus, *P. strobus* was more sensitive to drought than *Q. rubra* in both treatments. Within species, the sap flux-VWC slopes were similar between treatments for *T.*

canadensis and *Q. rubra*, but not for *P. strobus*. We observed a greater sap flux-VWC slope in the reference forest as compared with the silvopasture for *P. strobus*. This suggests that for *P. strobus*, sap flux density was less sensitive to declining VWC in the silvopasture than in the reference forest. In contrast, forest-to-silvopasture conversion had no effect on the sap flux density response to decreasing VWC for *T. canadensis* and *Q. rubra*.

3.4. Tree growth

Mean ring widths were similar among the reference forest and silvopasture prior to forest-to-silvopasture conversion (Fig. 7a-c). Following conversion, we observed a consistent positive response in 3-year mean ring width in the silvopasture for all tree species (Fig. 7a-c). In the silvopasture, we detected a significant increase for *Q. rubra* from pre- to post-conversion, but not for *T. canadensis* (Table 3, Fig. 7a-c). For *P. strobus*, there was some evidence of an increase in 3-year mean ring width following conversion. The confidence limits did not straddle zero, yet the model output indicated non-significance (Table 3). In the reference forest, mean ring width did not change over time (e.g., pre- to post-harvest) for any species. After forest-to-silvopasture conversion, 3-year mean ring width was greater in the silvopasture compared to the reference forest for both *T. canadensis* and *Q. rubra*, but not for *P. strobus* (Table 3). Finally, changes in 3-year ring width that occurred from pre- to post-conversion were significantly greater in the silvopasture than the reference forest for *T. canadensis*, but not for *P. strobus* and *Q. rubra* (last row of Table 3).

3.5. Stand-level evapotranspiration

Total evapotranspiration (ET), evaporation of intercepted precipitation (E_i), and transpiration (E_t) were greater in the reference forest than the silvopasture over the study period (Fig. 8). Data for E_i and E_t in the pasture were not collected because vegetation in this treatment site was sparse at beginning of the study and increased over time, and we did not attempt to model transpiration. Thus, we report soil evaporation for the pasture only. Consistent with our *in situ* measurements of soil evaporation, modeled soil evaporation (E_s) was greater in the silvopasture and pasture as compared with the reference forest. In the reference forest, the contributions by E_i , E_t , and E_s were 21%, 67%, and 12%, respectively. In the silvopasture, the contributions by E_i , E_t , and E_s were 16%, 49%, and 35%. Thus, in the silvopasture, the relative contribution of E_s to ET was greater than E_i .

4. Discussion

4.1. Tree-level thinning and drought response

Our results provided partial support for our first hypothesis that forest thinning and conversion to silvopasture would increase water use on a sapwood area basis. Mean daily sap flux density was similar between the silvopasture and reference forest for all tree species examined. However, we detected treatment effects for *P. strobus* when VPD and soil moisture were included as covariates. Sap flux density for *P. strobus* was greater in the silvopasture during days with high VPD prior to the drought and during low soil moisture conditions during the drought. Opening the canopy through forest thinning reduces competition for light within the canopy and typically results in greater wind speeds lower in the canopy due to reduced leaf area index (Cionco, 1972). By exposing tree crowns to greater light conditions, greater absorption of shortwave radiation by leaves increases leaf surface temperature and conductance to water vapor,

and greater wind speed increase the conductance of water vapor through the leaf and canopy boundary layers (Campbell and Norman, 1998). Collectively, this may explain why *P. strobus* is more responsive to higher VPD in the silvopasture prior to the drought.

Our results also provide partial support for our second hypothesis that forest-to-silvopasture conversion would alleviate water stress and negative effects of drought on water use. Conversion to silvopasture alleviated the effect of drought on *P. strobus* as indicated by greater sap flux density in the silvopasture at low soil water content. Greater tree density in the reference forest likely resulted in greater competition for soil water, restricting water use for *P. strobus*. Similar to our findings, Skubel et al. (2017) observed an increase in *P. strobus* whole-tree water use after thinning (30% of trees removed) even during a severe drought in Ontario, Canada. In this study, thinning appeared to alleviate competition for soil water in the silvopasture for *P. strobus*.

While treatment effects were most evident for *P. strobus*, vapor pressure deficit and soil water content were important variables that explained seasonal variation in sap flux density for all three species. Vapor pressure deficit appeared to be the driving factor for sap flux density for all species earlier in the summer when soil moisture was not limiting. During the drought period for all species, sap flux density was less responsive to vapor pressure deficit (VPD) and appeared to more sensitive to declining soil moisture. Similarly, Bovard et al. (2005) observed a diminished response of transpiration to VPD in a northern hardwood forest during a drought, indicative of reduced stomatal aperture.

We detected a decline in sap flux density for all species as soil water content decreased, but these declines were not consistent among species. *Pinus strobus* displayed greater sensitivity to drought than *T. canadensis* in the reference forest and greater sensitivity than *Q. rubra* in the

silvopasture and reference forest. Our results suggest that the three species displayed different strategies for avoiding drought stress and dehydration. *Pinus strobus* may use more conservative strategies such as reducing stomatal aperture to avoid critical thresholds in leaf water potential (i.e., isohydric response). *Tsuga canadensis* was intermediate in drought sensitivity with respect to sap flux density, suggesting that this species may be intermediate along the isohydric-anisohydric gradient. Anisohydric species follow a riskier strategy that allows leaf water potential to decline as drought intensifies, subsequently sustaining stomatal conductance of water vapor. *Quercus rubra* is a ring porous species that tends to display anisohydric response to drought (Roman et al., 2015). Consistent with our results, transpiration of *Quercus* species, including *Q. rubra*, was found to be less responsive to drought than other species (Oren and Pataki, 2001; Bovard et al., 2005). *Quercus* species also tend to be more deeply rooted compared with co-occurring tree species (Lyford, 1980; Abrams, 1990), which may allow this species to sustain transpiration during drought.

Radial growth over a 3-year period immediately following conversion for *T. canadensis* and *Q. rubra* was greater in the silvopasture than in the reference forest. Previous work has found that thinning or selective logging increases radial growth for *P. strobus* (Bebber et al., 2004), *T. canadensis* (Marchand and Filion, 2014), and *Q. rubra* (Schuler, 2006). Bebber et al. (2004) found that increased stem growth was first detectable 3 years following thinning and continued to increase 8 years following harvest in a mature *P. strobus* stand. A delayed response to thinning may have also occurred for *P. strobus* in this study, which may partially explain why we did not detect greater ring width in the silvopasture 1-3 years following thinning. It is worth noting that 3 years of tree growth data is a short time to detect effects and draw conclusions about the growth and response of the three tree species.

4.2. Evapotranspiration

Consistent with our third hypothesis, we observed greater evapotranspiration in the reference forest as compared with the silvopasture. Our results are consistent with several studies that have observed decreased evapotranspiration following forest thinning (Simonin et al. 2006; Sun et al., 2017; Roche et al., 2018). Increases in streamflow following harvest has been widely reported across many forest types (Hornbeck et al., 1993; Stednick, 1996; Grace et al., 2006; Dung et al., 2012; Hawthorne et al., 2013). The greater evapotranspiration in the reference forest was primarily a result of greater transpiration and canopy interception. Greater canopy cover, basal area, and tree density, in the reference forest all contributed to greater stand-level transpiration and more interception of precipitation. While a shadier and cooler microclimate in the reference forest resulted in lower rates of soil evaporation, transpiration and interception were sufficiently large to maintain higher ET in the reference forest than in the silvopasture.

As a result of the forest-to-silvopasture conversion, we observed a decrease in the contributions of interception and transpiration to evapotranspiration and an increase in the contribution of soil evaporation to evapotranspiration. Similarly, Sun et al. (2017) observed similar trends in relative contributions to evapotranspiration as a result of thinning (i.e., 50% strip thinning) in a *Chamaecyparis obtusa* plantation in Japan. The increase in soil evaporation as a result of thinning was generally consistent with findings of microclimate and soil moisture. Greater absorption of shortwave radiation would increase soil temperature in the upper soil layer, which, in combination with higher VPD of the air would contribute to greater soil evaporation in the silvopasture. This interpretation can also be extended to the soil evaporation trends observed in the pasture.

The *in situ* measurements and modeled estimates of soil evaporation were similar except for the pasture where measured soil evaporation was greater. There are many potential sources of error associated with *in situ* measurements, including diameter and depth of microlysimeters, timing of core extraction and replacement of those cores used in the microlysimeter relative to the timing of a rain event, and material used for the microlysimeter (Daamen et al., 1993; Verhoef and Campbell, 2005). In our study, the microlysimeter diameter and depth was small compared with other studies (Daamen et al., 1993; Verhoef and Campbell, 2005), which may partially explain the greater soil evaporation rate as compared with modeled estimates in the pasture. Also, we used a simplified modeling approach to estimate soil evaporation. For example, we did not incorporate components of the soil surface energy balance or changes in the thickness of dry surface layer, both of which influence the conductance of water vapor from the soil to the air (Duursma and Medlyn, 2012). Regardless, our estimates of soil evaporation with respect to evapotranspiration agree with other studies. In this study, soil evaporation was 10% and 35% of evapotranspiration in the reference forest and silvopasture, respectively. Sun et al. (2017) estimated soil evaporation to be 13% and 31% of annual evapotranspiration and 14 to 28% of growing season evapotranspiration in an unthinned and thinned (50% strip thinning) *Chamaecyparis obtusa* plantation in Japan.

5. Conclusions

Our results suggest that conversion of a forest to a silvopasture through thinning may reduce the risk of losing important forest ecosystem services that mitigate the impacts of climate change. Forest-to-silvopasture conversion appeared to alleviate drought stress for *P. strobus* and increased radial tree growth for *T. canadensis* and *Q. rubra* in both drought and non-drought

years. Our results suggest that forest-to-silvopasture conversion can be an important land management strategy that improves overall tree health and vigor in the face of future climate change, which will likely include more frequent drought in the northeastern U.S. Our results also highlight the importance of identifying which tree species to retain during a conversion. In this study, one objective of the forest-to-silvopasture conversion was to increase light availability to the ground to promote forage production, while retaining overstory tree species with a high timber value (*P. strobus* and *Q. rubra*). Following conversion and substantial removal of *T. canadensis*, *P. strobus* was the dominant tree species, which greatly benefitted from the conversion in terms of its sensitivity to drought. Thus, the forest-to-silvopasture conversion applied in this forest will also help to mitigate drought effects on tree function.

Evapotranspiration decreased as a result of forest-to-pasture conversion, primarily a result of reduced transpiration and interception of rainfall. If high forest cover corresponds with greater evapotranspiration, which plays an important role in hydrologic regulation by increasing soil water storage capacity and reducing runoff (Duku et al., 2015), then land-use conversion to silvopasture rather than open pasture may offer added ecosystem services. For example, greater water uptake by vegetation during periods of high soil water availability in silvopastures compared to pastures may be particularly important in regulating streamflow dynamics and reducing flooding given the projected increases in extreme precipitation events in the northeastern U.S. Given our limited ability to make inferences beyond these specific treatment plots, additional research will be necessary to determine the generality of these results and the longer-term impacts of silvopasture conversions on the components of evapotranspiration described here.

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Table 1. Attributes of stand structure, sample trees, and light conditions of the reference forest and silvopasture (\pm SE).

Parameter	Reference Forest	Silvopasture
Stand basal area	49.5 m ² ha ⁻¹	20.5 m ² ha ⁻¹
Stand density	977 trees ha ⁻¹	245 trees ha ⁻¹
Mean DBH		
<i>Pinus strobus</i>	39.0 \pm 1.7 cm	41.9 \pm 1.8 cm
<i>Tsuga canadensis</i>	19.2 \pm 0.6 cm	20.8 \pm 1.4 cm
<i>Quercus rubra</i>	31.2 \pm 5.2 cm	27.3 \pm 1.6 cm
Stand	17.0 \pm 0.5 cm	25.0 \pm 0.9 cm
Mean DBH – sample trees (sap flux)		
<i>Pinus strobus</i>	47.5 \pm 4.0 cm	44.4 \pm 4.8 cm
<i>Tsuga canadensis</i>	38.3 \pm 3.4 cm	40.0 \pm 2.5 cm
<i>Quercus rubra</i>	39.5 \pm 5.9 cm	31.7 \pm 0.4 cm
All sample trees	42.3 \pm 2.6 cm	40.4 \pm 2.7 cm
Gap fraction	0.072 \pm 0.011	0.234 \pm 0.013
Indirect site factor	0.084 \pm 0.014	0.304 \pm 0.016
Direct site factor	0.036 \pm 0.004	0.385 \pm 0.026

Table 2. Slopes (\pm SE) of the relationship between sap flux density (SFD) and natural log-transformed (\ln) vapor pressure deficit (VPD) for *P. strobus*, *T. canadensis*, and *Q. rubra* for the reference forest and silvopasture. Slopes are shown for the pre-drought (30 June – 22 August), drought (23 August – 18 September), and post-drought period (19 September – 01 October). Different letters within each row indicate significant ($p < 0.05$) differences in slopes. *Significant ($p < 0.05$) difference in slopes between the reference forest and silvopasture within a given time period.

Species	Treatment	Slopes of SFD- \ln (VPD) relationship (\pm SE)		
		Pre-Drought	Drought	Post-Drought
<i>Pinus strobus</i>	Reference Forest	58.72 \pm 3.47 ^{a*}	23.02 \pm 4.57 ^b	34.68 \pm 6.99 ^b
	Silvopasture	74.24 \pm 5.26 ^a	37.86 \pm 6.73 ^b	37.61 \pm 10.46 ^b
<i>Tsuga canadensis</i>	Reference Forest	36.37 \pm 2.50 ^a	12.95 \pm 3.29 ^b	18.69 \pm 5.04 ^b
	Silvopasture	36.81 \pm 3.00 ^a	12.40 \pm 3.84 ^b	11.99 \pm 5.97 ^b
<i>Quercus rubra</i>	Reference Forest	37.29 \pm 2.75 ^a	16.82 \pm 3.62 ^b	18.14 \pm 5.54 ^b
	Silvopasture	36.33 \pm 2.40 ^a	15.79 \pm 3.08 ^b	14.82 \pm 4.78 ^b

Table 3. Differences in 3-yr mean ring width (mm) between pre- and post-conversion for the silvopasture (i.e., silvo) and reference forest (i.e., for), differences in 3-yr annual increment between silvopasture and reference forest for pre- and post-conversion, and differences of the differences described above. The lower and upper confidence limits of the 95% confidence intervals, based on the linear mixed-effects model, are also displayed. Bold numbers with asterisks indicate a significant difference in 3-yr mean annual increment (mm).

* $p < 0.05$, ** $p < 0.01$

[§]The confidence limits did not straddle zero, but the model output indicated non-significance.

Defined contrast	Difference in 3-yr mean annual increment (mm) (lower, upper confidence limits)		
	<i>Pinus strobus</i>	<i>Tsuga canadensis</i>	<i>Quercus rubra</i>
Post _{silvo} - Pre _{silvo}	0.74 [§] (0.01, 1.46)	0.24 (-0.15, 0.64)	1.35** (0.54, 2.16)
Post _{for} - Pre _{for}	-0.24 (-0.96, 0.48)	-0.38 (-0.77, 0.01)	0.19 (-0.70, 1.10)
Pre _{silvo} - Pre _{for}	-0.08 (-1.36, 1.20)	0.18 (-0.52, 0.88)	0.45 (-1.04, 1.93)
Post _{silvo} - Post _{for}	0.89 (-0.39, 2.17)	0.80* (0.10, 1.51)	1.60* (0.12, 3.08)
(Post _{silvo} - Pre _{silvo}) - (Post _{for} - Pre _{for})	0.97 (-0.05, 1.99)	0.62* (0.07, 1.18)	1.16 (-0.05, 2.37)

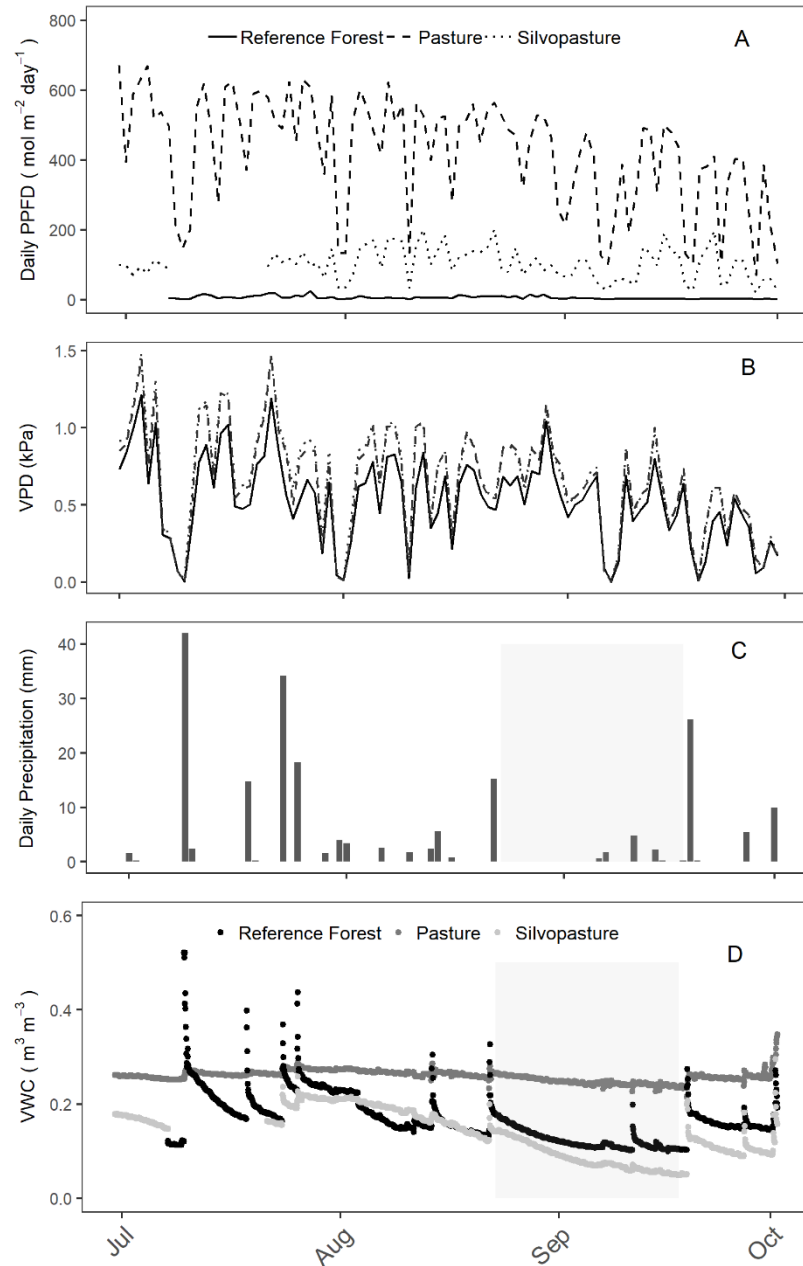


Figure 1. Daily photosynthetic photon flux density (PPFD, $\text{mol m}^{-2} \text{ day}^{-1}$; A), mean daily vapor pressure deficit (kPa, B), daily precipitation (mm; C), and soil volumetric water content at 0-15 cm ($\text{m}^3 \text{ m}^{-3}$; D) for the reference forest, pasture, and silvopasture at 1.5 m above the ground. The grey boxes represent the drought period.

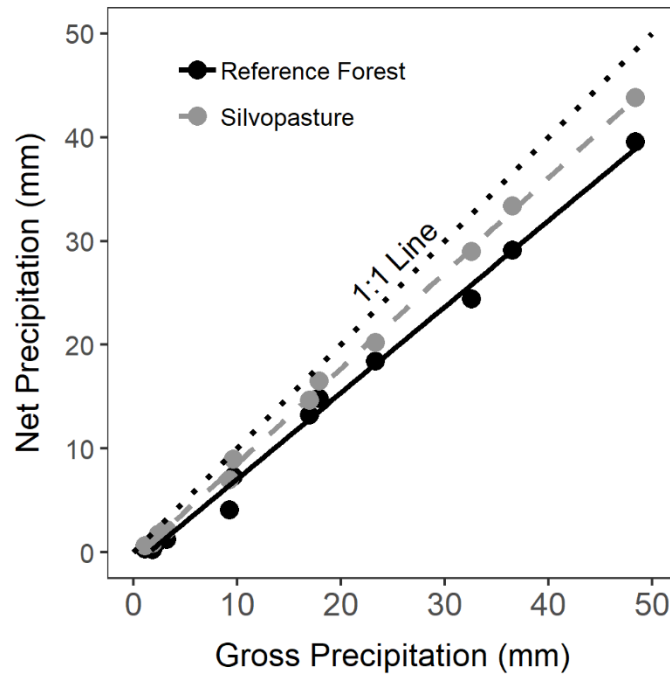


Figure 2. Net precipitation (P_n , mm) versus gross precipitation (P_g , mm) for the forest and silvopasture. Net precipitation was measured with throughfall collectors in the silvopasture and gross precipitation was measured with collectors in the pasture. Regression models: reference forest, $P_n = 0.83P_g - 1.29$; silvopasture, $P_n = 0.92P_g - 0.64$.

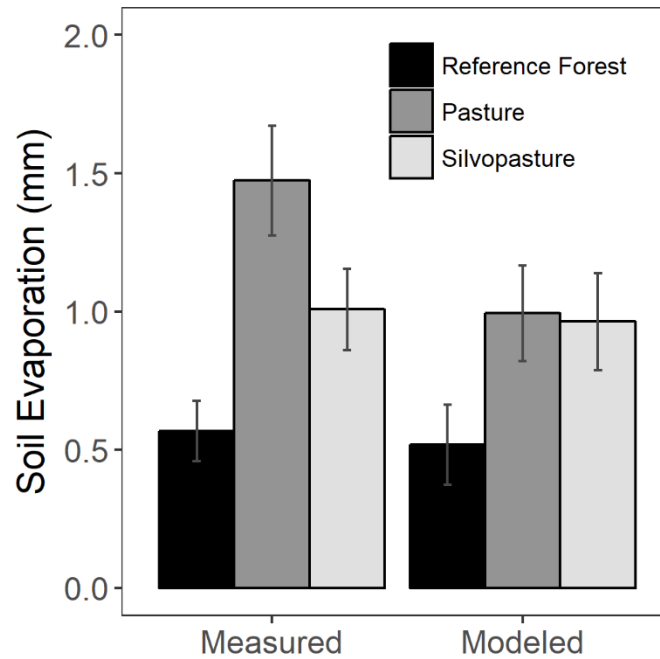


Figure 3. Measured and modeled mean daily soil evaporation (mm) of the reference forest, pasture, and silvopasture. Mean values represent soil evaporation for six 24-hr estimates. The error bar represents the standard error of the mean.

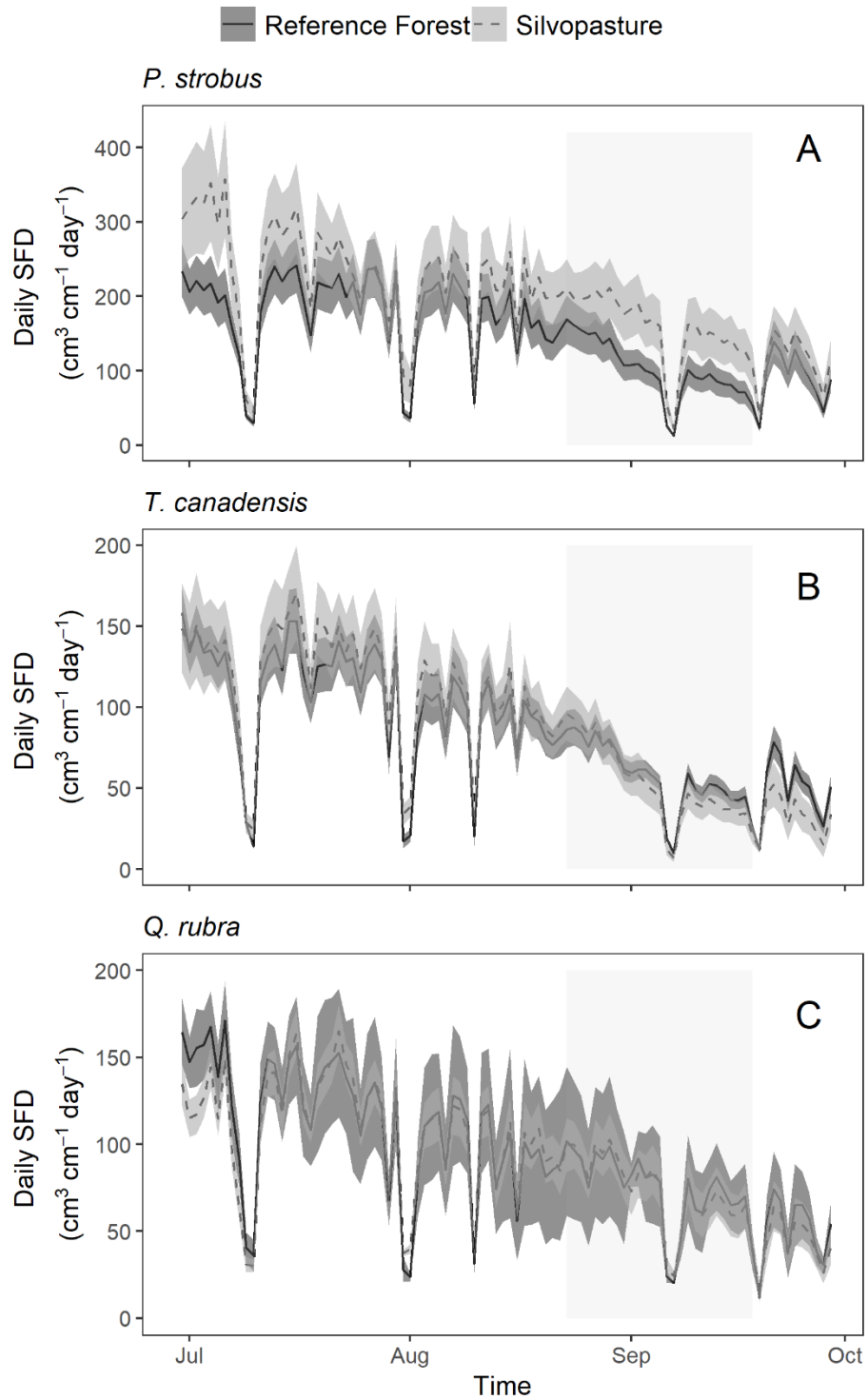


Figure 4. Daily sap flux density (SFD; $\text{cm}^3 \text{cm}^{-2} \text{day}^{-1}$) at the reference forest and silvopasture plot from June 30th to September 30th for *P. strobus* (A), *T. canadensis* (B), and *Q. rubra* (C).

The grey boxes represent the drought period.

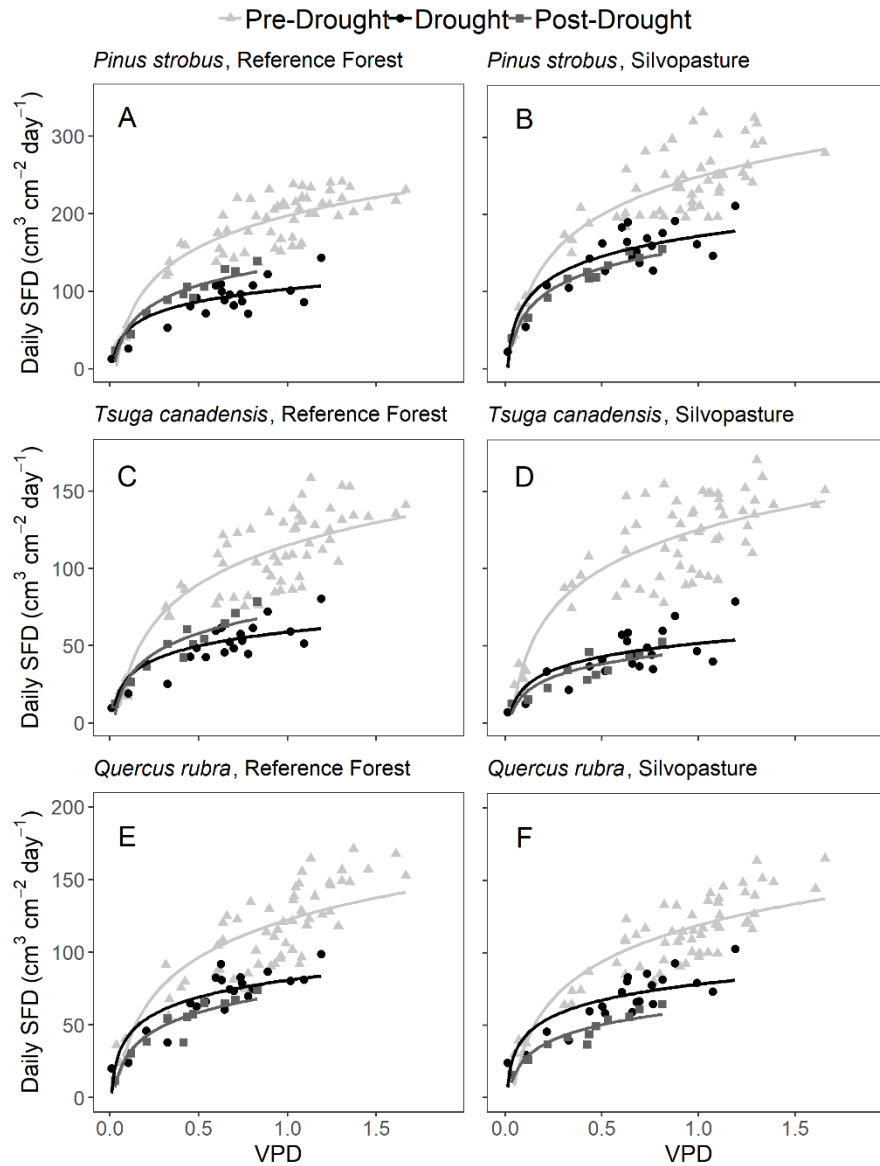


Figure 5. Daily sap flux density (SFD; $\text{cm}^3 \text{cm}^{-2} \text{day}^{-1}$) versus vapor pressure deficit (VPD; kPa) during the pre-drought, drought, and post-drought periods for *P. strobus* (A, B), *T. canadensis* (C, D), and *Q. rubra* (E, F) in the reference forest (A, C, E) and silvopasture (B, D, F).

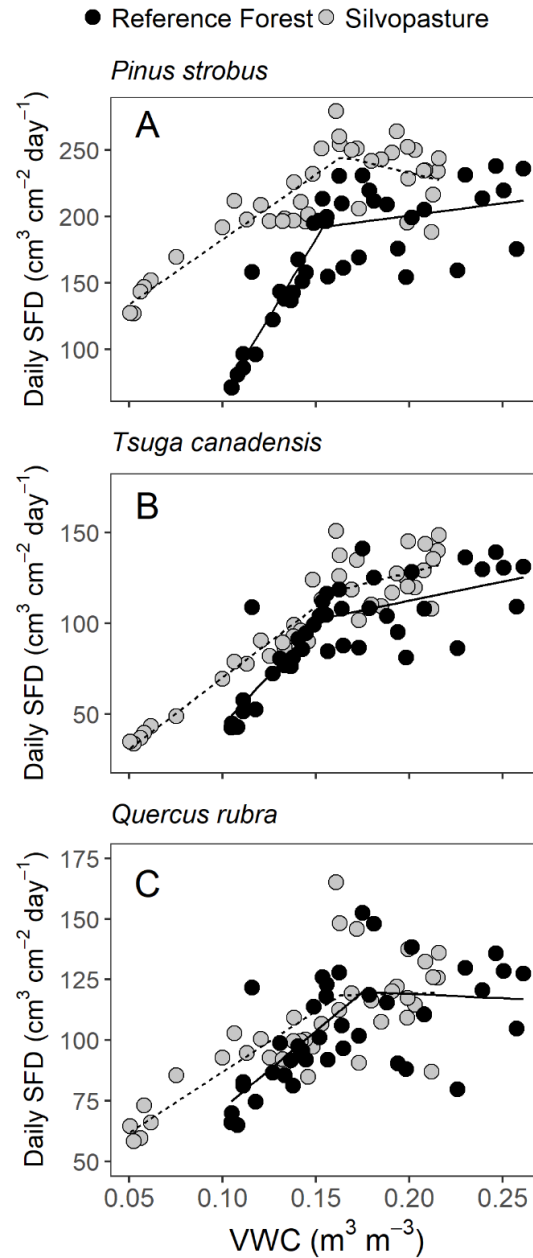


Figure 6. Daily sap flux density (SFD) versus soil volumetric water content (VWC, $\text{m}^3 \text{m}^{-3}$) for *P. strobus* (A), *T. canadensis* (B), and *Q. rubra* (C) during days with above-average PPFD ($> 429 \text{ mol m}^{-2} \text{ day}^{-1}$). Piece-wise linear regression models are fit to the data. Breakpoints ($\text{m}^3 \text{m}^{-3} \pm \text{SE}$): *P. strobus*, forest = 0.15 ± 0.01 , silvopasture = 0.16 ± 0.01 (A); *T. canadensis*, forest = 0.15 ± 0.01 , silvopasture = 0.16 ± 0.01 (B); *Q. rubra*, forest = 0.18 ± 0.02 , silvopasture = 0.16 ± 0.02 (C).

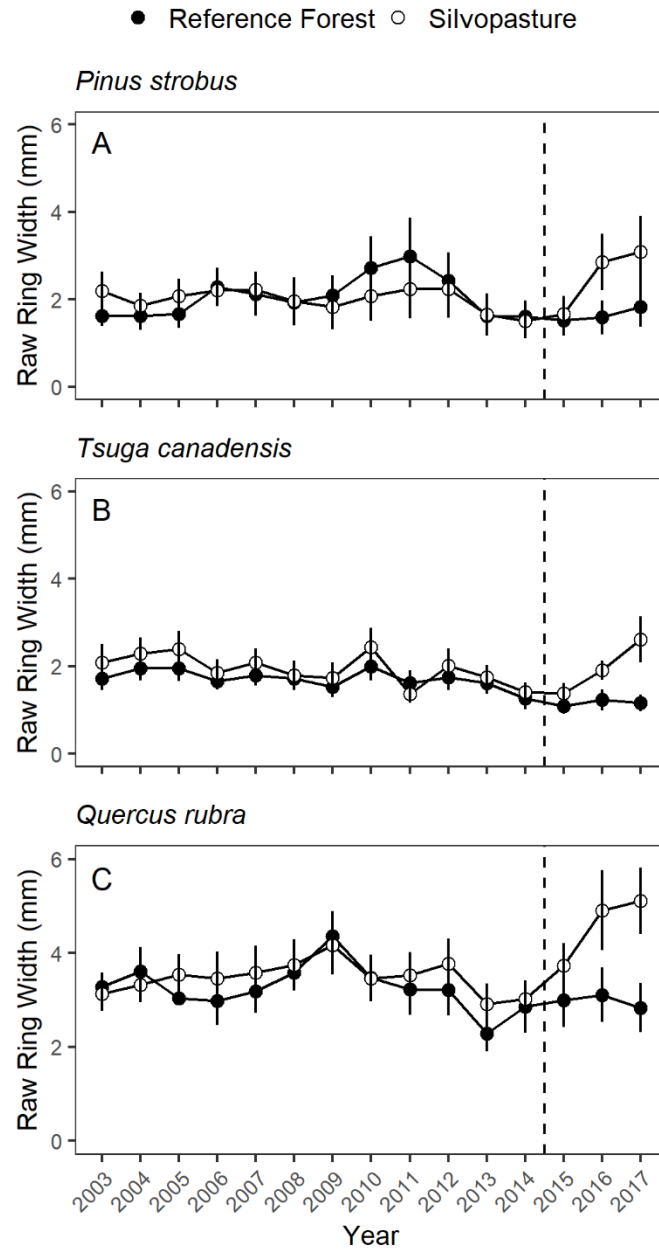


Figure 7. Ring widths of *P. strobus* (A), *T. canadensis* (B), and *Q. rubra* (C) for the reference forest and silvopasture prior to and after forest-to-silvopasture conversion. The vertical dashed line corresponds with the forest-to-silvopasture conversion.

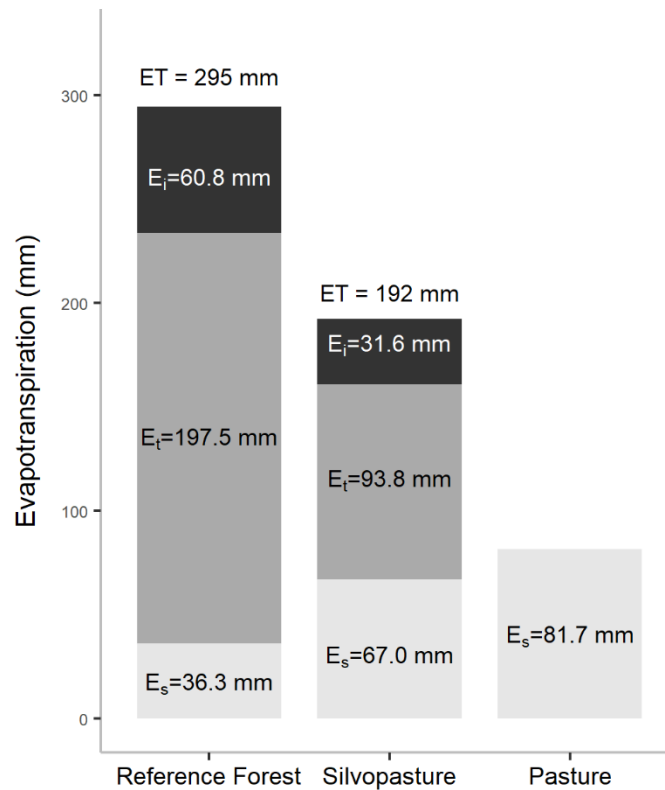


Figure 8. Evapotranspiration (ET; mm) and components of evapotranspiration (mm) for the reference forest and silvopasture over the study period (90) days. Components of evapotranspiration include interception (E_i), transpiration (E_t), and soil evaporation (E_s). Soil evaporation for the pasture is also included.