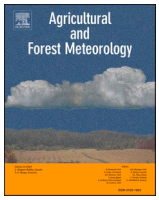
Agricultural and Forest Meteorology 373 (2025) 110754

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Canopy gap edge effects on overstory sap flux in a temperate mixed-hardwood forest

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ARTICLE INFO

Keywords:
Sap flow
Transpiration
Sapwood area
Vapor pressure deficit
Canopy gaps
Depth of edge

ABSTRACT

Canopy openings create gradients in microclimate and can increase transpiration of individual trees bordering the gaps. This study evaluates overstory tree water use in a mature, temperate, upland hardwood forest three and four years after the establishment of 0.1 and 1 ha experimental gaps. Sap flux density (J_s) was measured using thermal dissipation probes in 63 trees of dominant species groups, red maple (*Acer rubrum)*, hickory (*Carya* spp.), tulip-poplar (*Liriodendron tulipifera)*, and white oak and red oak groups (*Quercus* spp.), with increasing distance from experimental canopy gap edge (0 – 30 m). Diurnal, daily, and seasonal patterns of J_s showed no change with distance from gap edge and no difference between gap sizes, despite increased edge tree diameter growth. High tree-to-tree variability in J_s was prevalent within species, potentially intensified by steep slopes and rocky soils. There were clear differences in summer J_s between species with mesic species 43 % higher than oak and hickory species on average. As such, short-term effects of gap creation on local-scale water availability and stand-scale water use in mixed-hardwood forests will be largely driven by interactions between microclimate and vegetation dynamics within the gap, but not by canopy trees at the edge of the gap.

1. Introduction

Forest canopy gaps, created by natural disturbance or silvicultural practices, increase structural complexity and alter ecosystem processes, such as net primary production and evapotranspiration (Muscolo et al., 2014). With expected increases in the severity and frequency of drought and storms (USGCRP, 2017), a similar rise in canopy disturbance may occur (Munro et al., 2024). Forest structural complexity is an increasingly important focus for management when integrating ecological and economic objectives (Fahey et al., 2018; Franklin et al., 2002) due to positive correlations with biodiversity, wildlife habitat, and carbon sequestration (Gough et al., 2019; Greenberg et al., 2023; Muscolo et al., 2014). Harvested canopy gaps provide tree size class and age diversity within a stand and to an extent can resemble natural disturbances (Greenberg and McNab, 1998; Runkle, 1982).

Microclimatic gradients between the forest edge and interior forest arise after gap creation (Meeussen et al., 2021), typically in solar radiation (*Q*), wind speed, temperature, evaporative demand, vapor-pressure deficit (*D*), and soil moisture (Canham et al., 1990; Chen et al., 1995; Davies-Colley et al., 2000; Gehlhausen et al., 2000). The degree of change in microclimate is dependent on many factors, including aspect, gap size, and canopy height (Brown and Merritt, 1970; Ringger and Stearns, 1972). Overstory tree water use can be affected by canopy gaps in a variety of ways, depending on the physiological response to changes in external forcing factors. At the diurnal time scale, increased *D* and *Q* could result in increases in maximum J_s, with responses differing by species (Oren and Pataki, 2001). Resource limitations also vary in importance depending on the system and primarily include soil moisture (Pataki et al., 1998) and *Q*. Soil moisture limitations may cause a reduction in J_s sooner in the afternoon or decrease at the daily level (Hölscher et al., 2005; Oishi et al., 2010). In a dense canopy, increased light availability or intensity may boost peak J_s or shift peak J_s earlier in the day for edge trees (Ringgaard et al., 2012). At the seasonal scale, trees with more exposed positions receiving increased light availability or intensity may begin to move water sooner in the spring (Tian et al., 2019). At the annual scale, independent of changes to J_s, increased edge tree sapwood area due to increased diameter growth compared to forest interior trees has been commonly observed across many systems (Chen et al., 1992; Dyer et al., 2010; Gray et al., 2012; Herbst et al., 2007; Hernandez-Santana et al., 2011; Stan and Daniels,

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https://doi.org/10.1016/j.agrformet.2025.110754
Received 20 June 2024; Received in revised form 15 July 2025; Accepted 18 July 2025
Available online 28 July 2025

2014)., provided that the gap does not create other limitations (e.g., dryer soil). In theory, the increased tree-level carbon assimilation (i.e., photosynthesis) that supports tree growth requires an increase in leaf area, stomatal conductance, and/or water use efficiency (WUE). While increased WUE could result in greater assimilation without a change in water use, increased leaf area or conductance would require higher transpiration. Increases in forcing factors, i.e., D and wind speed, at edges have been shown to increase individual tree transpiration (Boggs et al., 2015; Giambelluca et al., 2003; Hernandez-Santana et al., 2011) potentially reducing available soil moisture for regeneration.

Management and disturbance impacts to local- and stand-scale eco-hydrology in mixed-species forests will vary by species-specific water use (Caldwell et al., 2016; Hölscher et al., 2005; Pataki et al., 1998), as well as the type of disturbance. Transpiration increases of 30 - 43 % have been observed for certain deciduous tree species in riparian buffers of clearcuts (Boggs et al., 2015) and agricultural fields (Hernandez-Santana et al., 2011; Taylor et al., 2001). Sap flow in Norway spruce (*Picea abies*) increased 8 – 16 % in trees positioned along the edge of gaps (Ozcelik et al., 2022), while the response of Scots pine (*Pinus sylvestris*) was not consistent, with large variability between trees (Cienciala et al., 2002). Sap flow in oak (*Quercus* spp.) was found to be less responsive to edge effects compared to ash (*Fraxinus* spp.) and diffuse-porous species such as maple (*Acer* spp.) and tulip-polar (*Liriodendron tulipifera*) (Boggs et al., 2015; Herbst et al., 2007). Reducing stand basal area by thinning typically increases individual tree transpiration and can mitigate impacts of low soil moisture on canopy conductance of the overstory (del Campo et al., 2019, 2022).

Our study objective was to compare whether and how sap flux density (J_s) of six deciduous species varies with proximity to canopy openings. We used two recently harvested gaps within a southern Appalachian mixed-oak forest to quantify overstory water use of trees bordering the canopy opening and extending up to 30 m into the surrounding closed canopy forest. We hypothesized that 1) individual trees would have higher J_s closer to the edge, 2) with stronger edge effects at the larger gap, and 3) species would differ in edge sensitivity with ring-porous species being less responsive than diffuse-porous species. These gaps were part of a harvest to promote structural complexity as well as oak and hickory regeneration, which often occurs in the highest abundance at gap edges (Lhotka and Stringer, 2013). Increases in overstory tree water use at gap edges may limit available resources, specifically soil moisture, for seedlings in the understory.

2. Methods

2.1. Site description

The study was conducted in a temperate deciduous stand in the Pisgah National Forest, North Carolina, USA (35°28′N, 82°40′W; Grover et al., 2023) within the Blue Ridge Physiographic Province of the Southern Appalachian Mountains. Elevation ranges between 700 and 1070 m. The soils are shallow to very deep, well-drained, moderately to extremely acidic Inceptisols and Ultisols, ranging in texture from fine sandy loam to gravelly loam with steep 10–90 % slopes (Soil Survey Staff). Precipitation is evenly distributed throughout the year, on average totaling 1300 mm annually and 533 mm from May to September. Monthly average temperatures range from 3.8 to 8.6 °C in January, and from 15.9 to 28.3 °C in July (NOAA, 2021). A station in a deciduous forest in the region (Coweeta Hydrologic Laboratory, NC) reported ~1080 mm per year of average potential evapotranspiration (PET) and actual evapotranspiration (AET) from 1986 to 2007, making this an energy limited system (Rao et al., 2011).

The stand is a secondary upland hardwood forest dominated (in rank order by basal area) by tulip-poplar, chestnut oak (*Q. montana*), northern red oak (*Q. rubra*), red maple, white oak (*Q. alba*), and hickory species (Grover et al., 2023). Age (range from 95 - 150 years old), basal area (37 m^2 ha^{-1}), and density (1086 stems ha^{-1}) are typical for this forest type in the region. The experimental site was harvested in the spring 2019 to increase light availability in the understory and stimulate oak and hickory regeneration at gap edges. Marked trees were hand-felled and removed via skidders, minimizing damage to remaining trees. Midstory removal via stem herbicide injection in the summer 2019 was conducted to terminate non-mast producing trees (< 20 cm DBH) and further increase light penetration to the understory from above and from gap edge (Loftis, 1990; Patterson et al., 2022). Gap boundaries were defined as the canopy gap plus the area extending to the stem of the surrounding trees (> 20 cm DBH; i.e., expanded gap, Runkle, 1982).

2.2. Study design

Treatments included gap size (small versus large), tree position relative to gap edge, and species group. Two gaps close in proximity (~170 m apart) with southwestern aspects were selected (Fig 1). The small gap was 0.14 ha in size with an average slope of 80 %. The large gap was 0.96 ha in size with an average slope of 65 %. Edge trees were defined as trees whose crowns are adjacent to gap edge and thus receive additional light compared to forest interior trees. A subset of overstory trees was selected, this included diffuse-porous species, red maple and tulip-poplar, ring-porous species, white oaks (*Q. alba, Q. montana*) and red oaks (*Q. rubra, Q. velutina*), and semi-diffuse porous species, hickory (*C. tomentosa, C. ovalis, or C. glabra*). A total of 60 selected trees were divided approximately evenly across gap size, position, and species group (Table 1). Trees ranged in diameter at breast height (DBH) from 14.8 to 91.8 cm and included dominant (40 %), codominant (43 %), and intermediate (17 %) crown classes. The site average dominant tree height is 25 m.

2.3. Environmental measurements

Environmental measurements were taken along the gap edge gradient along a transect northeast of gap center in three locations (edge at 0 m, 15 m into the forest, and 15 m into the gap) at both gaps (Fig 1). Air temperature (T_a) and relative humidity (RH) were measured at 15-minute intervals during the study period (2022–2023) using HOBO Temperature/RH data loggers in solar shields (ONSET, Bourne, MA). Vapor pressure deficit (D) was calculated with T_a and RH using standard equations (Campbell and Norman, 2000). Soil moisture was measured at 15-minute intervals at two depths (10 and 25–30 cm) in each location using Soil Moisture Smart Sensors SMx and HOBO Micro Stations H21 (ONSET, Bourne, MA) during the first measurement year.

2.4. Sap flux measurements

Granier-type thermal dissipation probes were used to measure J_s (Granier, 1987). Sensor length varied by species due to differences in the radial depth of the transition point from conductive sapwood tissue to non-conductive heartwood. Ring-porous species received 10 mm length probes and diffuse-porous species received 20 mm length probes. Hickory received 20 mm length probes, except the smallest tree (DBH = 14.8 cm) received 10 mm length probes. One sensor (paired probes) was installed per tree on the north side of the stem at a height of 1.4 m and covered with a reflective pan with insulating material. Sensors were installed in March 2022 before leaf out and collected data through October 2023, spanning two growing seasons 3 and 4 years post-harvest.

Sap flux sensors measured the difference in temperature (ΔT) between a heated upper probe and an unheated lower probe 5 cm apart. Change in temperature was measured in 1-minute intervals and recorded as 15-minute averages using CR1000X dataloggers (Campbell Scientific, Logan, UT, USA). To calculate J_s, the following equation was used:

$$J_s = 119 \times \left(\frac{\Delta T_{max}}{\Delta T} - 1\right)^{1.23} \quad (1)$$

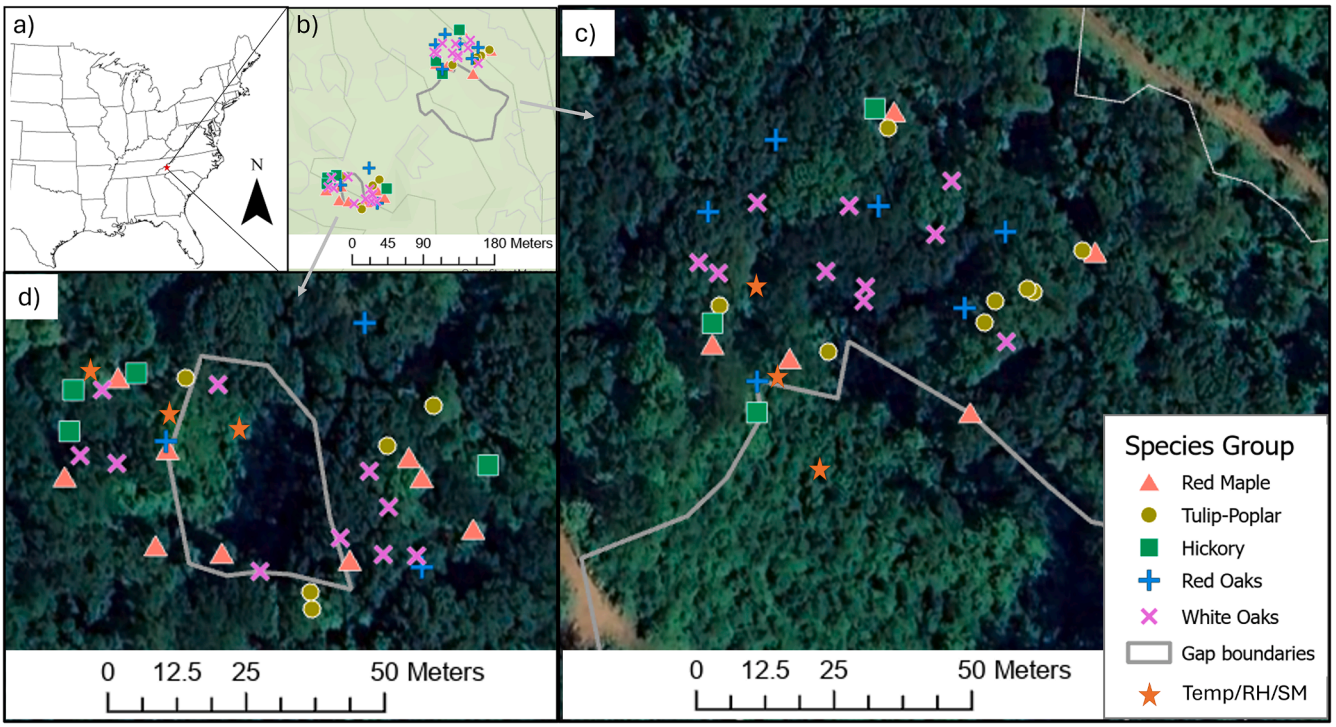

Fig. 1. Harvested canopy gaps of two sizes in a mature temperature upland hardwood forest in the Southern Appalachian Mountains, NC, USA. Gaps were located within 180 m of each other. Trees instrumented with sap flux sensors are shown by species. Approximate locations for temperature, relative humidity, and soil moisture sensors are shown as orange stars.

Table 1
Range of diameter at breast height (DBH) for each species. Count of measured trees varied by year based on sensor function.

	DBH (cm)	2022		2023	
		Small Gap	Large Gap	Small Gap	Large Gap
Red maple	22 – 56	9	5	6	2
Tulip-poplar	24 – 84	5	8	4	5
Hickory	15 – 45	4	3	4	1
Red oaks	49 – 92	3	6	2	6
White oaks	29 – 73	10	10	10	9

where the ΔT_{max} is the maximum temperature differential at which sap flux is assumed to be zero (Granier, 1987). Baseliner software was used to determine low flow values and the subsequent ΔT (Oishi et al., 2016). Occasional sensor failure resulted from wildlife damage to the sensors themselves or the datalogger box. Incomplete daily data was excluded from the analysis. Species- and size-specific calibration can improve accuracy of flux estimates (Sun et al., 2012), however, the generic Granier parameters were used as we did not have parameters for the species and size-classes in this study generated from a consistent calibration method.

To understand differences in sapflow during high D, summer days with data availability for 50 or more trees and with D over 0.6 kPa were selected ($n = 6$) and used to calculate peak J_s and centroid of diurnal J_s. Peak diurnal J_s per tree was calculated by selecting the highest 8 instantaneous J_s values (i.e., 2 h) per day and averaging those values across days per tree. The centroid, or the time of day half of total daily sap flow was reached, was calculated per day for each tree and averaged across days per tree.

To understand differences in the relationship between daily J_s and D, a reference sap flux density (J_{ref}) value was calculated per tree. For each tree and year, daily total J_s and D were fit with an exponential rise to maximum function:

$$J_s = a\left(1 - e^{-b \times D}\right) \quad (2)$$

where J_s is in units of g H_2O m^{-2} $_D$ $^{-1}$, a and b are coefficients for individual trees and years, and D is daily average vapor pressure deficit. The reference D value, 0.72 kPa, was defined as the 75th percentile across both years. Eq. (2) was solved using the reference D value to calculate J_{ref}. Values of J_{ref} were averaged across years, yielding one J_{ref} value for each tree. J_{ref} was calculated for the summer (June 1 – August 31) as well as for each month separately (May, June, July, August).

Whole-tree transpiration was estimated using tree wood anatomy, diameter, and probe length to calculate a scaling factor (Berdanier et al., 2016) for the summer J_{ref} value. This whole-tree transpiration value represents liters of water used per day per tree during reference D, 0.72 kPa, and accounts for radial decline in sap flow.

2.5. Analysis

Analysis of covariance (ANCOVA) was used to test the effects of species group, distance from edge, gap size, and all two-ways interactions on peak J_s, centroid, summer J_{ref}, and whole-tree transpiration. The effect of DBH was also included for whole-tree transpiration. A linear mixed model was used to test the effects of species group, distance from edge, gap size, month, and all two-ways interactions on monthly J_{ref}, including tree as a repeated random factor. Three-way and four-way interactions were not included in the models due to small sample size in some combinations of effects. A stepwise backward selection on full models was conducted using the 'stepAIC' function ('MASS' R package, Venables and Ripley, 2002) to reduce ANCOVA models and the 'step' function ('lmerTest' R package, Kuznestova et al., 2017) to reduce the linear mixed model. Model assumptions of residual normality and homoscedasticity were visually assessed using quantile-quantile plots and residual vs. fitted value plots. Response variables of summer J_{ref}, monthly J_{ref}, and whole-tree transpiration were log transformed to meet model assumptions. An alpha level of 0.05 was used to determine

significance. Model summaries were created using 'anova_test' function ('rstatix' package, Kassambara, 2023). Tukey HSD post-hoc tests were conducted on significant effects using 'glht' function ('multcomp' package, Hothorn et al., 2008) and least square means were reported using the 'lsmeans' function ('emmeans' package, Lenth R (2025)). All analyses were conducted in R (R Core Team, 2022).

3. Results

3.1. Microenvironment

Diurnal fluctuation of T_a and D was similar for both gaps, where higher variability and midday values were observed in the gap compared to the edge and forest (Fig 2a-d). For soil moisture both gap and edge dried down faster than the forest, though magnitude differed between gaps (Fig 2e-f). Soil water availability was fairly constant in the first year of the study (2022) and never became dry enough where it would be considered limiting, e.g. < 20 %. Precipitation for both 2022 and 2023 summers (June – August) summed to 395 and 264 mm of rainfall respectively (NOAA 2023), similar to the climate normal sum of 312 mm (SD = 82 mm; NOAA 2021, www.ncei.noaa.gov). Daily soil water loss in the top 30 cm on days without precipitation averaged 1.2 - 1.3 mm (Fig 2g-h).

3.2. Sap flux

The reduced model for peak J_s included species ($F_{4,41} = 3.88$, $P = 0.009$), gap size ($F_{1,41} = 0.86$, $P = 0.360$), distance from edge ($F_{1,41} = 1.16$, $P = 0.288$), and the interaction of gap size by distance from edge ($F_{1,41} = 3.18$, $P = 0.082$) (Table S1). Peak J_s varied by species where tulip-poplar was significantly higher than white oaks and hickory, and red maple and red oaks fell in between (Fig 3). The reduced model for centroid, i.e., time of day that half of the total daily sap flux occurred, included no parameters (Table S1). These findings are consistent with the similarities in T_a and D between the edge and forest (Fig 2) and also suggest a lack of effect of unmeasured diurnal forcing factors (e.g., increased light availability) and/or a change in sensitivity of J_s to forcing factors for edge trees.

Reference sap flux density (J_{ref}) for summer months was used as a simple metric to quantify the sensitivity of J_s to D (Fig 4a-e). The reduced model for summer J_{ref} included species ($F_{4,52} = 2.77$, $P = 0.037$) and distance from edge ($F_{1,52} = 2.18$, $P = 0.145$) (Table S1). Tulip-poplar had 93 % and 52 % higher J_{ref} than hickory, and white oaks, respectively, with red maple and red oaks in between (Table 2). Within species, there were no significant linear relationships between summer J_{ref} and distance from gap edge (Fig 4f-j). J_{ref} was also calculated per month to assess edge effects on green up timing, e.g. month by distance from edge. The reduced model for monthly J_{ref} included species ($F_{4,39} = 2.19$, $P < 0.088$) and month ($F_{3,129} = 34.4$, $P < 0.001$) (Table S2). Monthly J_{ref}

Fig. 2. Microenvironmental variable magnitude and variability across the gap edge gradient in 2022 was similar between small (left) and large (right) gaps. Summer (June and July, DOY 150–213) a-b) air temperature, c-d) vapor pressure deficit measure, e-f) soil moisture, and g-h) daily change in soil water are shown for each location, i.e., gap (−15 m), edge (0 m), forest (15 m). Soil moisture values are the average of probes at depths of 10 and 30 cm. Only a portion of available data is shown for temperature and vapor pressure deficit.

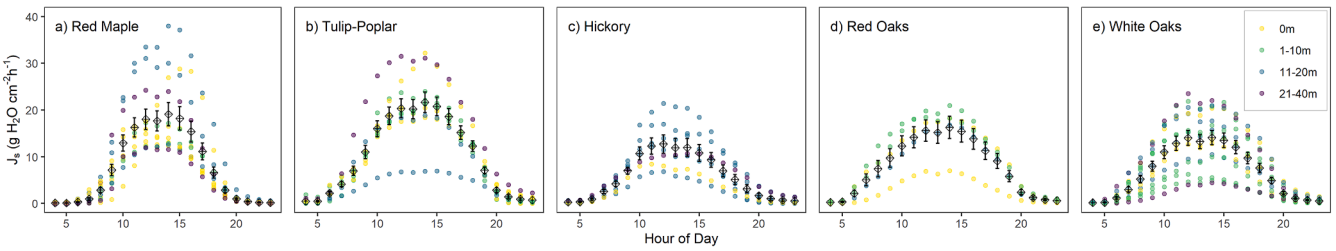

Fig. 3. Diurnal sap flux density averaged across six days with vapor pressure deficit greater than 0.6 by species. Color denotes distance from gap edge. Mean and standard error are shown in black.

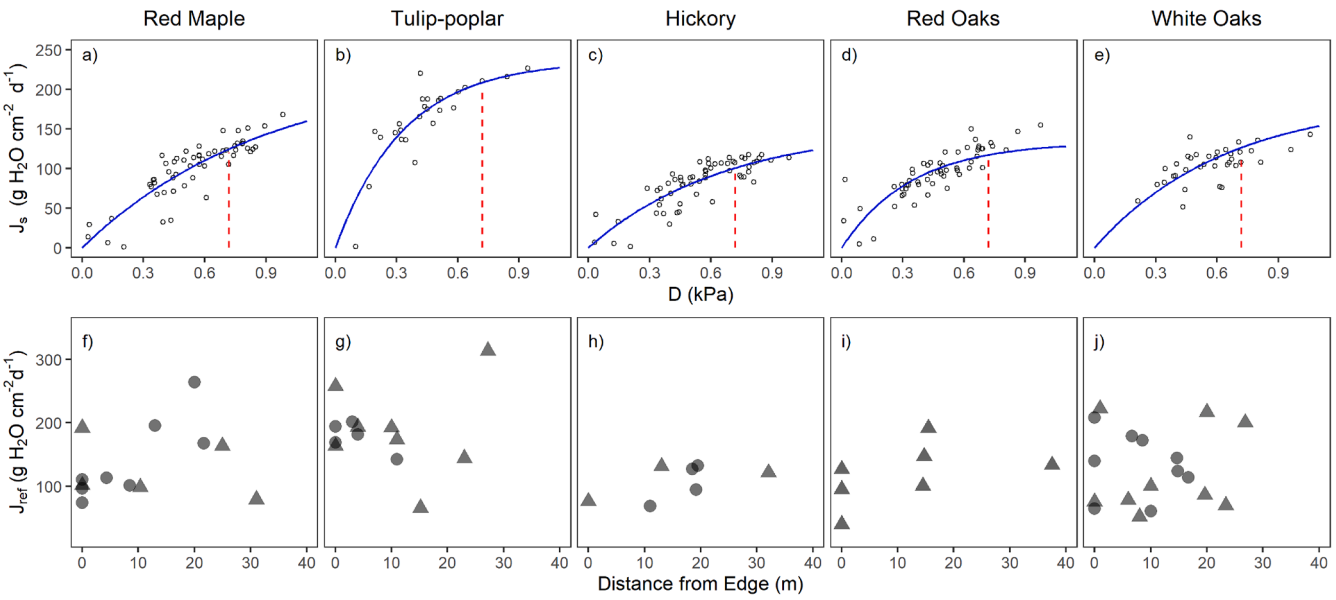

Fig. 4. a-e) Example tree sap flow (J_s) as a function of vapor pressure deficit (D), top row. Solving for reference sap flux density (J_{ref}) includes finding the daily total sap flux density (J_s) where daily average vapor pressure deficit (D) equals 0.72 kPa (red dotted line), which is the 75th quartile of D for the summer of both years. Example relationships are shown for one tree per species for the summer. f-j) J_{ref} averaged across summer months (June - August) for individual trees by species. Gap size denoted by point shape, large gaps (triangles) and small gaps (circles). Gap edge occurs at 0 m and the higher values represent increasing distance into the forest interior. In the full model, there were significant differences by species ($P = 0.04$), not by distance from edge ($P = 0.15$; Table S3).

Table 2
Reference summer sap flux density (J_{ref}) in g H_2O cm^{-2} D^{-1} summarized by species. Least squared means and standard error reported from reduced model. Tukey HSD ordered letters show significant differences between species groups.

Species	Mean	SE	
Red maple	136	15	AB
Tulip-poplar	197	15	A
Hickory	102	21	B
Red oaks	118	20	AB
White oaks	129	13	B

differences by species were similar to summer J_{ref}. Month most strongly influenced J_{ref} where May was significantly lower than July and August (Fig 5). Due to the lack of significant interaction between distance from edge and month, we found no evidence that the growing season began sooner for edge trees.

The reduced model for whole-tree transpiration included species ($F_{4,50} = 28.1$, $P < 0.001$), DBH ($F_{1,50} = 22.6$, $P < 0.001$), distance from edge ($F_{1,50} = 6.04$, $P = 0.018$), and gap size ($F_{1,50} = 0.245$, $P = 0.623$) (Table S3). Larger diameter trees had higher water use than smaller trees (Fig 6). Water use, and notably DBH, varied by species. Tulip-poplar had higher average water use (112 L D^{-1}) than other species. Red maple (52 L D^{-1}) had higher average water use than white oaks (33 L D^{-1}) and hickory (18 L D^{-1}), but similar to red oaks (43 L D^{-1}). Distance from edge had a relatively weak but positive influence on water use when accounting for other factors in the model, meaning edge trees used less water than interior trees. DBH and distance from edge were not correlated ($P = 0.99$).

4. Discussion

4.1. Species-specific edge tree sap flux density

We proposed that edge tree J_s would increase due to increases in D and resource availability (light and soil moisture). Contrary to our hypotheses, we found that J_s did not significantly increase sub-daily, daily, or seasonally nearer to gap edge within or across species. For some species, sample size was limited, e.g., hickory and red oaks, thus restricting comparisons of distance from edge by gap size. Hickory and red oaks, however, behaved similarly to the white oaks that had a large sample size. We did not have parameters for the many species and size-classes in this study generated from a consistent calibration method therefore we used generic Granier parameters for sap flux equations. Species- and size-specific calibration can improve accuracy of flux estimates (Sun et al., 2012). The primary focus of our analysis stayed on intra-specific differences in flow rates due to gap position and environmental drivers, so using different coefficients were not expected to affect the overall results. Species-specific parameters may be more important for computing total water budget values.

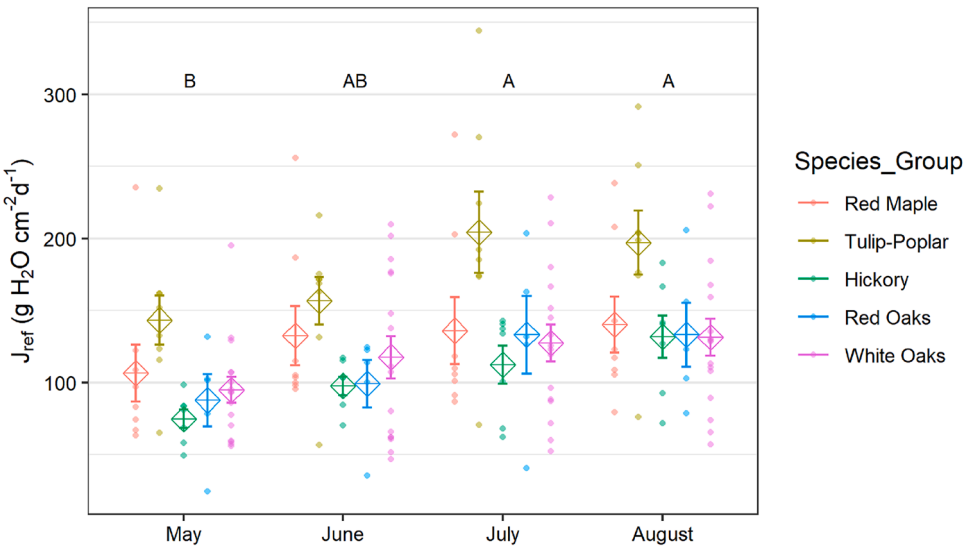

Fig. 5. Monthly reference J_s by species. Points represent individual trees. Mean and standard error shown for each species group. Tukey HSD ordered letters show differences between months, $P < 0.001$.

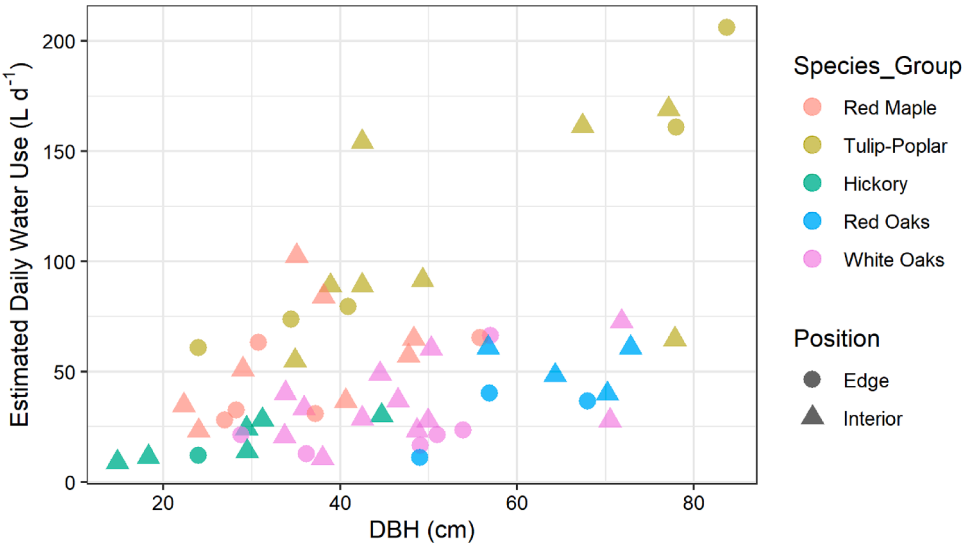

Fig. 6. Daily total water use for a reference day with vapor pressure deficit of 0.72 kPa. Calculated using scaled summer reference sap flux density (J_{ref}) per tree based on radial adjustment for sap flow (Berdanier et al., 2016). Water use varied strongly ($P < 0.001$) by species and diameter at breast height (DBH).

Species-specific values of J_s fell within expected ranges in mature forests (Wullschleger et al., 2001). Within species, we found no difference in edge effects on J_s. This can partly be attributed to high tree-to-tree variability which was a common reason cited for lack of statistical significance among other studies, even within a single species (Cienciala et al., 2002; Giambelluca et al., 2003). Inter-tree variability could have been compounded by the steep slopes and varied soil (Giambelluca et al., 2003). In a mature mixed hardwood stand in the UK with an existing edge, ash (*Fraxinus* spp.) sap flow was 30 – 82 % higher at the edge than forest, while oak showed no differences (Herbst et al., 2007). This was attributed to high tree-to-tree variability in the oaks, especially large (> 60 cm DBH) stems, due to crown size differences, i.e. leaf area per tree. Previous work by Bader et al. (2022) found that ring porous species, including oaks, maintained consistent J_s during drought conditions, enabled by deep roots and conservative water use (i.e., ~60–70 % of maximum J_s). It is also worth noting that because ring porous oaks have a lower sapwood to basal area ratio than diffuse porous species, their tree-level transpiration is lower, and this may also help oaks to maintain relatively consistent J_s when soil water limitations begin to affect other species. The trees in our study ranged in DBH from 15 to 92 cm, comparable to the stem sizes in Herbst et al. (2007). In trees ranging in DBH 13 – 39 cm, red maple and tulip-poplar J_s increased 2-years post-harvest, whereas oaks did not (Boggs et al., 2015). Smaller windward edge trees relative to those we measured, ranging in DBH 6 - 18 cm, responded with increases up to 69 % compared to the rate measured in closed canopy or leeward conditions (Hernandez-Santana et al., 2011; Taylor et al., 2001).

In another study at the same experimental site, we found edge trees had ~48 % greater radial ring width four years post-harvest compared to pre-harvest ring width, where forest interior trees did not see the same magnitude, ~9 %, of increased diameter growth (Reddy et al., in prep). The response was stronger for smaller stems, where magnitude varied by species. All of the gaps are larger in diameter than the height of the adjacent canopy likely contributing to the lack of radial growth differences by gap size (Gray et al., 2012). Previous studies have indicated an increase in edge tree transpiration due to increased basal area,

independent of J_s (Herbst et al., 2007; Hernandez-Santana et al., 2011). The difference in diameter growth between edge and forest interior trees will likely continue to diverge over time (Chen et al., 1992). As such, stand-scale water use in the first several years following gap creation will still be largely driven by species composition and sapwood area rather than edge effects in similar systems (Herbst et al., 2007; Hölscher et al., 2005; Wullschleger et al., 2001).

4.2. Understanding microclimate and resource gradients

The gradient of microclimate from gap edge to forest interior may have been less extreme than other edge studies. A study from an urban forest found no difference in sap flux for red maple in closed-canopy stands versus small clustered trees over turfgrass, with significantly higher sap flux only for red maple growing individually over turfgrass (Ponte et al., 2024). Large increases in water use of edge trees have been reported in young, planted stands adjacent to agricultural fields due to advection and increased soil water availability (Hernandez-Santana et al., 2011; Taylor et al., 2001). Sap flow rates of 16-year-old silver maple (*Acer saccharinum*) trees planted in a riparian area of a corn-soybean field exceeded what could be attributed to net radiation alone (Hernandez-Santana et al., 2011). Similarly, increase in edge tree water use per unit sapwood area was reported in a 7-year-old blue gum (*Eucalyptus globulus*) plantation established adjacent to wheat fields and sheep pastures in an area in southeastern Australia, a water limited region receiving less than 600 mm of annual rainfall (Taylor et al., 2001).

Gaps often have higher soil water availability than the surrounding closed canopy forest (Abd Latif and Blackburn, 2010; Ritter et al., 2005). At our sloped study site, however, we found that soil moisture was often lower in the gap than surrounding forest (Raymond et al., 2006). During the measurement period, 3- 4 years post-harvest, regrowth of understory vegetation was vigorous in the gaps (64 % total understory vegetation cover in gaps compared to 21 % in unharvested areas; unpublished data), potentially more so than other studies reporting results 1–2 years following disturbance (Boggs et al., 2015; Ozcelik et al., 2022), and likely mitigated the expected increase in soil moisture due to overstory removal (André-Alphonse et al., 2023; Gray et al., 2002).

While edge trees received increased light to the side of their canopy aboveground, they were also released from neighbor competition belowground. In addition, harvested canopy gaps can temporarily increase nitrogen availability, especially nearer to gap center (Thiel and Perakis, 2009). This access to nutrients could have altered carbon allocation patterns, where edge trees were supplying less carbon to their roots and more aboveground (Haynes and Gower, 1995), resulting in increased diameter growth with little change in water use (Albaugh et al., 1998). Increased water use efficiency through stomatal controls for edge trees during even part of the day may have yielded a similar response (Wright et al., 2012). Alternatively, mature overstory trees may already have had access to ample resources and were not limited by light or soil moisture. Trees could have also adjusted radial sap flow rates deeper within sapwood (Iida et al., 2024). We did not have sensors at multiple depths and were not able to assess that potential effect.

4.3. Management and future conditions

Oak-hickory abundance in forests across the eastern U.S. is in decline as mesic species like tulip-poplar and red maple are becoming more abundant (Fei et al., 2011; Nowacki and Abrams, 2008; Woodbridge et al., 2022). This shift in species composition has large implications for future stand water use in the region since mesic species have lower water use efficiency (Caldwell et al., 2016; Oren and Pataki, 2001). Much effort has been placed on increasing the recruitment of oak and hickory to maintain these species in forests due to the ecosystem services they provide such as increased drought and fire tolerance, high quality wildlife food source, increased water quality, and wood products (Caldwell et al., 2016; Cavender-Bares, 2016; Martin et al., 1961). Well-timed harvests in combination with midstory management are thought to promote advance regeneration of oak and hickory species (Patterson et al., 2022). Here, we show this type of management has minimal impact on the water use of remaining overstory trees four years post-harvest.

Daily soil water loss, 1.2 - 1.3 mm, was in the range of expected transpiration rates from stands with comparable species composition (Oren and Pataki, 2001; Wullschleger et al., 2001). If management to promote oak and hickory canopy recruitment is successful, the overstory will use less water both through the reduction of stems from gap harvest and through retaining oak and hickory dominance relative to mesic, diffuse-porous species (Wullschleger et al., 2001). Based on our assessment, trees bordering gaps are not diminishing soil water availability but instead maintaining water use, which leaves important resources for the regeneration and recruitment processes. This may become more important during drought conditions.

Several severe drought events with PDSI < -3 have been recorded in the region over the past century (1925–1926, 1985–1988, 2007–2008; Grover et al., 2023). While soil moisture did not seem to limit growth at our site during our measurement years, drought frequency and severity is projected to increase in the region despite a predicted overall increase in precipitation (Vose et al., 2015; Vose and Elliott, 2016). The interaction of edge effects and drought should be a topic of further research, as the edge tree response could vary by species during drought conditions (Oishi et al., 2010). At our study site, Grover et al. (2023) documented that ring-porous species had larger short-term growth declines but significantly faster growth in the decade following drought events compared to diffuse-porous species. This is inconsistent with patterns of responses by ring-porous and diffuse-porous species following drought in the region and elsewhere (Elliott et al., 2015; Bader et al., 2022), where diffuse-porous species have larger growth declines during drought years than ring-porous species. Understanding what conditions, such as site factors (topography, etc.), influence these responses is essential for projecting future forest productivity. Overall, we anticipate that in upland, mixed species forests, changes in water use at gap edges will be minimal, compared to those driven by vegetation dynamics occurring within the gap itself.

5. Conclusions

By measuring sap flux density (J_s) in trees with increasing distance from canopy gap edge, this study evaluated edge effects on overstory tree water use in a mixed-hardwood forest 3- and 4-years post-harvest. Contrary to our hypothesis, we found no increase in peak, daily, or seasonal J_s with proximity to gap edge and no difference between gap sizes. Because mature trees, the dominant source of transpiration in this system, are not increasing their individual water use at the gap edge, edge effects on stand-scale water use will likely be limited. In addition, these findings imply that under current climate conditions, overstory transpiration will not deplete soil water resources for forest regeneration at gap edge. However, this may change over time with increased edge tree diameter growth and potential interactions with drought.

Funding

This work was supported by the Agriculture and Food Research Initiative Foundation and Applied Science program, project award no. 2019–67,019–29,463, from the U.S. Department of Agriculture's National Institute of Food and Agriculture. Additional funding was also provided by the NC State University Goodnight Doctoral Fellowship and the USDA Forest Service Southern Research Station.

CRediT authorship contribution statement

Morgan L. Arteman: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation,

Conceptualization. **Jodi A. Forrester:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **A. Christopher Oishi:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Tara L. Keyser:** Writing – review & editing, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jodi Forrester reports financial support was provided by National Institute of Food and Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Chris Sobek, Molly Suminski, Phillip Whiting, Brandy Benz, Kevin McCarthy, and Amber Payne provided field support that made this work possible. A special thanks to Jason Rodrigue. This paper was written and prepared, in part, by U.S. Government employees on official time; and therefore, it is in the public domain and not subject to copyright. This research was supported the U.S. Department of Agriculture, Forest Service. The findings and conclusions in this publication are those of the author(s) and should not be construed to represent an official USDA, Forest Service, or U.S. Government determination or policy.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2025.110754.

Data availability

Data will be made available on request.

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