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Clearcutting upland forest alters transpiration of residual trees in the riparian buffer zone

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Abstract:

Our objectives are (1) to compare tree sap flux density (J_s in $g\,cm^{-2}\,d^{-1}$) and stomatal conductance (G_s in $mmol\,m^{-2}\,s^{-1}$) across five dominant species, red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), loblolly pine (*Pinus taeda*), and oak species (*Quercus* spp.), (2) to quantity riparian buffer stand transpiration (E_s in $mm\,d^{-1}$), and (3) to link riparian buffer E_s of residual trees to stream discharge. In June 2010, the above species were instrumented with sap flow sensors in a pair (HF1 and HF2) of 12 hectare gauged watersheds. HF1 was clearcut, leaving a 15.2-m riparian buffer around the stream, and HF2 was the reference. Trees were harvested in the riparian buffer reducing HF1 riparian buffer basal area by 27%. The riparian buffer growing season net radiation increased from $11.9\,W\,m^{-2}$ preharvest to an average of $24.3\,W\,m^{-2}$ postharvest. HF1 stream growing season discharge increased dramatically (150%) from the preharvest to postharvest period. HF1 2010 preharvest growing season soil moisture was 22.5%. HF1 postharvest growing season soil moisture was 28.5% in 2011, 26.5% in 2012, and 27.2% in 2013. HF2 canopy cover, energy input, and soil moisture showed little change over the same period. From preharvest to postharvest, mean daily growing season J_s of trees in HF1 increased in all species. A reduction in HF1 G_s was less evident over the study vapour pressure deficit range in loblolly pine, red maple, and tulip poplar than in oak and sweetgum during the postharvest period. HF1 residual trees in the riparian buffer used 43% more water in growing season postharvest (314 mm) than growing preharvest (220 mm) period. This resulted in an 8% reduction in stream discharge because of an increase in riparian buffer E_s. Although clearcutting increased stream discharge, we conclude that the increase in transpiration by the residual trees in the riparian buffer will, at least, partially mitigate the hydrologic effects of forest removal through increased transpiration. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS sap flux density; riparian buffer; transpiration; stomatal conductance; Best Management Practice (BMP); North Carolina

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INTRODUCTION

Forestry Best Management Practices (BMPs) require that vegetated riparian buffers are left around streams and lakes during forest harvest to protect water quality and stream ecological equilibrium. This practice has been shown to be an effective management option to trapping sediment, protecting stream banks from scouring and erosion, and taking up nutrients (Gilliam *et al*., 1997; Lakel *et al*., 2010; Fraser *et al*., 2012). The effectiveness of riparian buffers relies heavily on the width of the riparian buffer, structure of vegetation (i.e. presence of understory and windfirm trees), soil properties, other factors that control the flow path of water from uplands to the stream networks, and nutrient uptake by the remaining riparian forests. Water and nutrient cycles are expected to change after clearcutting in upland areas. For example, upland forest removal reduces evapotranspiration, elevates soil moisture, raises groundwater table level, and increases overall watershed discharge (Sun *et al*., 2001; Brown *et al*., 2005). The increase of soil water and nutrient availability in uplands is likely to influence soil water and nutrient dynamics in the downslope riparian zones. Tree water use is controlled by environmental factors such as radiation, air temperature, wind speed, and soil water and the amount of leaf area present (Sun *et al*., 2011).

Variations in tree water use across space and time are a function of interactions among species, environmental conditions, stand age, and management practices (Baldocchi *et al*., 2004; Moore *et al*., 2004; Bond *et al*., 2008). Stand-level estimates of water use by forest trees are often determined indirectly using either the catchment

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water balance, the eddy covariance technique, or more simply the Bowen ratio energy balance (Herbst, 1995; Ford *et al*., 2007; Sun *et al*., 2010). These estimates represent an integration of the main components of stand evapotranspiration including tree transpiration, soil evaporation, and canopy interception. In addition, individual tree size and species play a dominant role in determining stand water balance (Granier, 1987; Meinzer *et al*., 2001). Therefore, a more accurate and reliable estimate of tree water use has been obtained using direct measurements of tree sap flow (Wullschleger *et al*., 1998). Direct measurements of tree sap flow are very useful to examine the effect of changes in forest structure on stand water balance and to provide information on the physiological regulation of transpiration. Forest ecologists can utilize those estimates of tree water uptake derived from sap flow to evaluate the role of transpiration in forest hydrology (Barrett *et al*., 1996; Ewers *et al*., 2002), to quantify the water requirements of coexisting species (Granier *et al*., 1996; Oren *et al*., 1998), and to address issues of water resource management (Schiller and Cohen, 1995; Oishi *et al*., 2008). For example, previous studies have suggested that under a forest soil water deficit, management techniques such as tree thinning or controlling shrub layers to reduce competition for water may be necessary in some stands to increase water availability for plant growth (Breda *et al*., 1995; Moore *et al*., 2004; Domec *et al*., 2012). Besides tree water use, sap flow technique can also be used to indicate the forest physiological response to changing environmental conditions and canopy development (Kostner, 2001; Buchmann, 2002) and to determine the role of stomatal conductance in regulating water loss (Hinckley *et al*., 1994; Martin *et al*., 1997; Domec *et al*., 2009).

The sap flow technique has been used in a range of plant environments. However, little data has been generated about changes in water use (i.e. tree sap flux density and riparian buffer stand transpiration) and ecophysiology (i.e. stomatal conductance) by riparian buffer species after sivilcultural activities in the upland. Limited literature suggests that remaining trees in the riparian buffer will increase transpiration because of increased available solar radiation, wind speed, and soil moisture (Hernandez-Santana *et al*., 2011). To date, no study has linked these transpiration changes in riparian buffer area trees to the water balance and discharge rates during postharvest. Our objectives are (1) to compare tree sap flux density (J_s in $g\,cm^{-2}\,d^{-1}$), and stomatal conductance (G_s in $mmol\,m^{-2}\,s^{-1}$) across five dominant species, red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), loblolly pine (*Pinus taeda*), and oak species (*Quercus* spp.), (2) to quantity riparian buffer stand transpiration (E_s in $mm\,d^{-1}$), and (3) to link riparian buffer stand transpiration of residual trees to stream discharge.

MATERIALS AND METHODS

Site description

Study paired watersheds (HF1 and HF2) are characterized as 35 year-old mixed pine–hardwood stands located within the Piedmont region of North Carolina (NC, Figure 1). The catchments are in the Flat River watershed at North Carolina State University's Hill Demonstration Forest in northern Durham County, NC. HF1 and HF2 are 12 hectares in size, and dominated by red maple (*A. rubrum*), pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), white oak (*Qurecus alba*), northern red oak (*Qurecus rubra*), American beech (*Fagus grandifolia*), sweetgum (*L. styraciflua*), tulip poplar (*L. tulipifera*), sourwood (*Oxydendrum arboreum*), and loblolly pine (*P. taeda*). The perennial stream in HF1 and HF2 are generally shallow and connected to a narrow floodplain by a rocky substrate. Stream identification and rating were determined based on geomorphic, hydrologic, and biological indicators described in the North Carolina Stream Identification Manual (North Carolina Division of Water Quality, 2005). The stream channels have steep upland slopes ranging from 15% to 40%, and the watersheds have a Carolina Slate Belt (CSB) soil substrate. Upland soils are defined as well drained with depth to water table greater than 6 ft and tend to function in a similar capacity in growing season (i.e. May–October) and dormant season (i.e. November–April). The NC Geological Survey (1998) reported that the CSB is comprised mostly of rocks formed through volcanic activity and deposits. Total land surface in CSB covers 8.5% of NC and extends into surrounding states of Virginia and South Carolina (Cleland *et al*., 2007). Soil series is dominated by Tatum and Appling. Additional soil and watershed descriptive details can be found in Boggs *et al*., 2013. Upland trees were harvested in HF1 watershed from 29 November 2010 to 19 January 2011 as part of a Timber Harvest study, leaving a 15.2-m riparian buffer on either side of the stream. HF1 is the treatment watershed, and HF2 is the reference watershed. Therefore, no logging activities occurred in HF2. Although HF1 and HF2 are paired and share a watershed boundary line, the clearcut edge in HF1 is 130 m from HF2 monitored riparian buffer trees and poses little chance to create changes in HF2 riparian buffer soil or canopy conditions that would influence their water use. The riparian buffer covers about 8% of the watershed area in both HF1 and HF2.

Stream discharge, meteorological, and soil moisture data

Measurements for the Timber Harvest project began in November 2007 and continued through December 2013. Data for this manuscript covers June 2010 to December 2013. A 2-H flume was used as flow control structure at the outlet of HF1 and HF2. A Sigma 900 Max water

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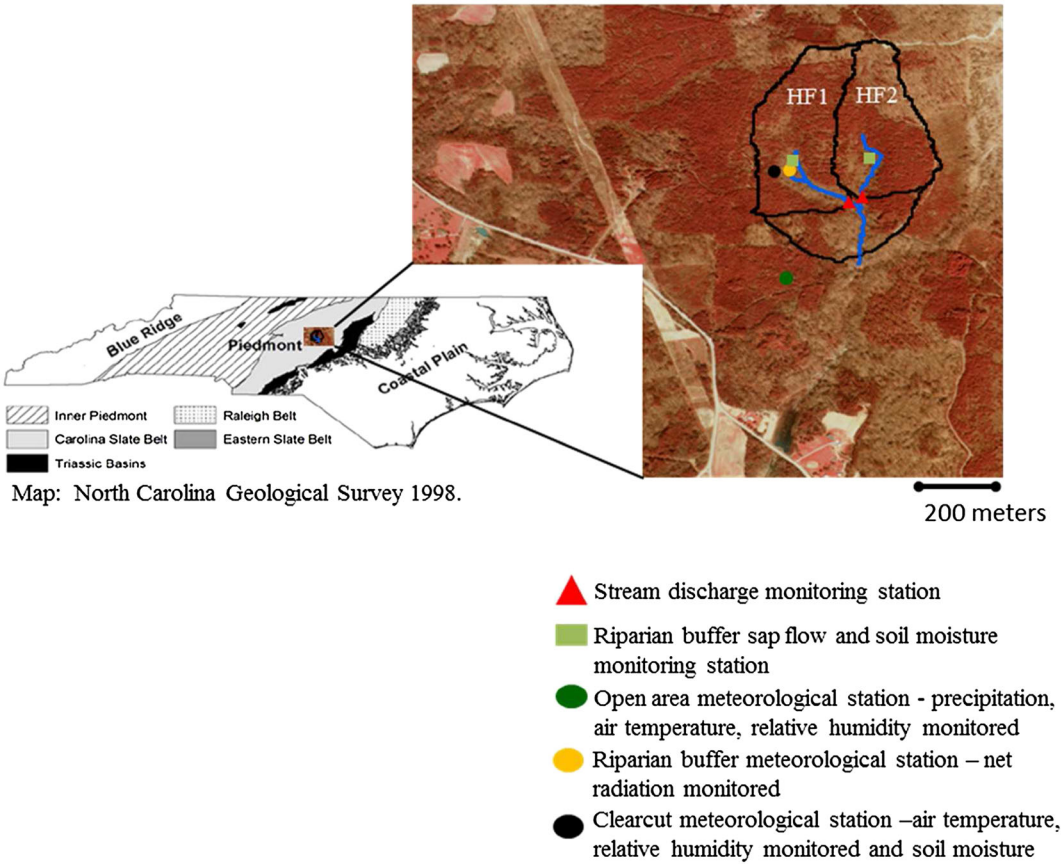


Figure 1. Location of North Carolina Piedmont mixed pine-hardwood study watersheds (treatment watersheds = HF1 and reference watersheds = HF2), stream discharge, sap flow, soil moisture, and meteorological stations

sampler and a depth sensor were used to measure and log discharge data every 10 min at the flume (Hach Company, Loveland, CO). Stream discharge values were divided by watershed size to normalize stream discharge data, and converted from cubic feet per second (cfs) to millimetres (mm), so units were comparable to precipitation. Precipitation was measured in an open area with a Hobo Data Logging Rain Gauge—RG3 (Onset Corporation, Bourne, MA) approximately 450 m from the watershed outlet. Relative humidity and air temperature measurements were taken with a Hobo Micro Station (Onset Corporation, Bourne, MA) next to the rain gauge (referred to as open area) and in the clearcut (referred to as clearcut area) near monitored trees every 10 min and averaged every hour. Hourly vapour pressure deficit (VPD) was calculated from relative humidity and air temperature data and reported in kilopascal (kPa) at both open and clearcut areas. The riparian buffer volumetric soil moisture (%) readings were taken in the riparian buffer zone near the monitored trees and clear cut area using water content reflectometer (CS 615) that were installed parallel to ground surface at 10-cm and 30-cm depths and logged every 10 min using a CR1000 (Campbell Scientific, Logan, UT). We report the average value between the two locations and depths to capture integrated soil moisture across space and with depth. Because of missing soil moisture data at the beginning of the monitoring period, 15% of our HF1 2010 growing season data (June and July 2010) was supplemented with moisture readings measured reported in Dreps *et al.*, 2014. The riparian buffer net radiation was measured next to the monitored trees every 10 min with a Kipp & Zonen long and short wave net radiometer (CNR2-L) (Campbell Scientific, Logan, UT). The radiometer was installed below the forest canopy, 3.7 m above the forest floor. From 2010 to 2013, annual hemispherical photos were taken from a series of 150-m^2 riparian buffer vegetation survey plots to determine percent canopy cover. In 2013, leaf area index (LAI) was measured at least monthly at the riparian buffer edge and in the middle of the riparian buffer using LAI 2000 (LI-COR, Lincoln, NE) to assess additional canopy conditions in the treatment and reference watersheds.

Sap flow measurements

In June 2010, three to five of each overstory riparian buffer tree species (American beech, loblolly pine, oak,

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red maple, sweetgum, and tulip poplar) were instrumented with sap flow sensors (heat dissipation probes) to measure tree transpiration. This resulted in 25 monitored trees in HF1 and 23 in HF2. Each 20-mm sap flow sensor was installed 1.4 m above ground surface on the north face to avoid direct sun influence. Sensor signals were converted from temperature difference to tree sap flux density (J_s, $g\,m^{-2}\,d^{-1}$, gram of sap per square meter sapwood area per day) according to computation outlined in Granier (1987). Sap velocity is dependent on probe depth and species (Wullschleger and Norby, 2001). We adjusted sap velocity for depth beyond the measured 20 mm for monitored species according to percent pattern of outer/inner sapwood reported by Phillips *et al*. (1996) to account for variation in water use across sapwood depth. For example, a sap velocity ratio at >20-mm sapwood depth was 60% of the sapwood velocity of the ≤20-mm sapwood depth for loblolly pine (Phillips *et al*., 1996). Not accounting for this variation in radial profile can result in a scaling error of 28% (Ford *et al*., 2007). Additional information about the sap flux density calculation, sap flow design, and installation can be found in Granier (1987) and Pataki *et al*. (1998).

In each watershed, an increment borer was used to extract two corers from 15 trees outside of the sap flow monitoring area to determine sapwood area. Once J_s was computed, monitored tree sapwood area was used to compute tree transpiration (E_t in $kg\,d^{-1}$). Stand tree density and sapwood area (Table I) from six 152-m^2 vegetation survey plots in HF1 and four plots in HF2 were then used to estimate preharvest riparian buffer stand transpiration (E_s in $mm\,d^{-1}$). The number of trees in HF1 riparian buffer decreased from 544 trees ha^{-1} preharvest to about 400 tree ha^{-1} postharvest (data used to compute postharvest riparian buffer stand transpiration are not shown in Table I). Scaling from tree sap flux density to stand transpiration has inherent challenges related to accurate sap flux measurements, total stand sapwood area, and tree composition (Moore *et al*., 2004; Kumagai *et al*., 2005; Ford *et al*., 2007). Careful consideration was taken to minimize error at each step in the scaling process which included adjusting sap velocity for depths beyond 20 mm for all species to account for variation in water use across sapwood depth.

American beech, hickory, and sourwood accounted for 26% of dominant or co-dominant canopy species in HF1

Table I. Characteristics of 2009 dominant and co-dominant canopy tree species in treatment (HF1) and reference (HF2) watersheds that were used to calculate preharvest riparian buffer stand transpiration rates (E_s, $mm\,d^{-1}$) of residual trees in the riparian buffer. Data were collected from 152 m^{-2} plots

Species	Trees ha	dbh cm	Sapwood, from bark to end of probe, 20 mm ----cm^2----	Sapwood, from end of probe to pith ----cm^2----	Total sapwood ----cm^2----
HF1					
Loblolly pine	94 (52)	24.9 (3.5)	71.9 (33.6)	224.8 (113.2)	296.8 (146.4)
Oak spp.	122 (42)	29.7 (3.1)	144.9 (32.9)	305.6 (81.2)	450.5 (113.5)
Red maple	28 (22)	16.4 (1.2)	30.1 (19.1)	63.7 (41.1)	93.7 (60.2)
Sweetgum	47 (31)	15.2 (1.3)	41.6 (18.9)	55.9 (26.3)	97.6 (45.2)
Tulip poplar	113 (44)	25.1 (2.1)	120.6 (26.3)	301.2 (75.1)	421.8 (100.9)
American beech	56 (41)	25.5 (1.5)			
Hickory spp.	28 (32)	21.1 (0.0)			
Sourwood	56 (24)	20.8 (2.7)			
Total	544 (36)	22.3 (2.2)*			
HF2					
Loblolly pine	230 (82)	26.9 (1.7)	108.0 (37.2)	280.2 (100.3)	388.2 (137.2)
Oak spp.	16 (16)	16.7 (0.0)			
Red maple	49 (31)	39.0 (15.5)	110.1 (74.0)	280.7 (205.4)	390.8 (137.2)
Sweetgum	131 (46)	15.8 (0.3)	64.6 (1.8)	78.5 (4.8)	143.1 (6.6)
Tulip poplar	164 (124)	23.4 (2.9)	63.7 (37.4)	120.2 (75.3)	183.9 (112.2)
American beech	49 (49)	19.7 (0.0)	26.2 (26.2)	50.7 (50.7)	76.9 (76.9)
Hickory spp.	16 (16)	13.0 (0.0)			
Total	655 (52)	22.1 (2.9)*			

Trees in bold are monitored species. Data from these trees were used to compute preharvest riparian buffer stand transpiration (Es, $mm\,d^{-1}$). The number of trees in HF1 riparian buffer decreased from 544 trees ha^{-1} preharvest to about 400 tree ha^{-1} postharvest (data used to compute postharvest riparian buffer stand transpiration are not shown). Tree transpiration (Et, $kg\,d^{-1}$) of non-monitored dominant and co-dominant trees (Hickory spp., American beech, sourwood, and Oak spp.) were estimated from a linear model developed from dbh and Et, $y = 3.6x - 37$, $r^2 = 0.80$, $p < 0.001$. These Et data were incorporated in final *E*s analysis.

*= Mean value for diameter at breast height (dbh). Spp. = species. Standard error is in parenthesis.

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riparian buffer, but were not monitored for water use because of limited field resources and long distance between trees. Hickory and oak trees in the HF2 riparian buffer were not monitored for the same reasons and accounted for 5% of dominant or co-dominant species. Mean E_t by these non-monitored species was quantified based on a linear model developed from dbh and E_t from monitored trees:

$$y = 3.6x - 37,\ r^2 = 0.80,\ p < 0.001$$

American beech, hickory, oak, and sourwood modeled E_t data were integrated in the final mixed pine–hardwood E_s analysis in HF1 and HF2. Reduction in stream discharge by riparian buffer E_s was computed based on the following equation:

$$(\text{Post_}E_s - \text{Pre_}E_s)*A_b/D_a + (\text{Post_}E_s - \text{Pre_}E_s)*A_b$$

where Post_E_s is growing season postharvest riparian buffer stand transpiration (314 mm), Pre_E_s is growing season preharvest riparian buffer stand transpiration (220 mm), A_b is riparian buffer area of total watershed (0.08 or 8%), and D_a is additional growing season water added to the stream because of harvest (84 mm, Boggs *et al*., 2015).

Based on calculation for this study, aerodynamic or boundary layer resistance (G_A) was much larger than stomatal conductance (G_S), meaning the resistance is very low and thus G_A can be ignored (Phillips and Oren, 1998; Ewers and Oren, 2000). Over a 6-day period in the summer where mean daytime wind speed was greater than 0.7 m s^{-1}, we computed mean G_S to be 0.20 mm s^{-1} and mean G_A to be 220 mm s^{-1}. In addition, our calculated aerodynamic resistance was 8% which is considered negligible. Therefore, stomatal conductance (G_s in mmol m^{-2} s^{-1}) was calculated from evaporation at the leaf (EL) and vapour pressure deficit (D) based on the simplified approach suggested by Monteith and Unsworth (1990) and Ewers *et al*. (2001):

$$G_s = K_G(T)*E_L/D$$

$G_s = K_G(T) \times E_L / D$ where $K_G(T)$ is the conductance coefficient $115.8 + 0.42\,T$ (kPa m^3 kg^{-1}). E_L was computed as follows: sap flux density × sapwood area / leaf area × molecular weight (Oren *et al*., 1998). This resulted in a unit of mmolm^{-2} s^{-1}. Literature sapwood area / leaf area values (Blanche *et al*., 1985; Pataki and Oren, 2003) were used in the computation because we did not develop these ratios in this study. When D was ≤0.6 kPa, it was excluded from the analysis to avoid errors in estimating G_s (Ewers and Oren, 2000).

We analysed canopy cover and basal area data in the preharvest and postharvest periods using one-way analysis of variance (JMP, 2011). A *t*-test was selected, and significance level was set to $\alpha \leq 0.05$ in JMP 11.0 to determine which group values were statistically different from each other. Statistics (slope, standard errors, and sample size) from bivariate plots were put into the equation below to determine *t*-statistic values and significant differences between slopes at $\alpha \leq 0.05$:

$$t = \frac{b_1 - b_2}{\sqrt{s_{b_1}^2 + s_{b_2}^2}},\ df = n_1 + n_2 - 4$$

where b_1 and b_2 are the slopes of lines 1 and 2, s_{b1} and s_{b2} are the standard errors for lines 1 and 2, and n_1 *and* n_2 are the sample sizes for lines 1 and 2. If preharvest *versus* postharvest slopes were significantly different, this indicated that the species were not regulating stomatal closure (not sensitive to VPD) after harvest. If preharvest and postharvest slopes were not significantly different, this indicated that species were regulating stomatal closure (sensitive to VPD). *D*-statistic was computed to determine to the effect size of treatment using the following equation:

$$d = \frac{|\overline{X}_1 - \overline{X}_2|}{S_p}$$

where X_1 and X_2 are the observed means of samples 1 and 2 and S_p is the pooled estimate of the population standard deviation (Cohen, 1992). *D*-statistic equals 0.20 for small effect, 0.50 for medium effect, and 0.80 or > for large effect. The effect test indicates the degree of practical importance of the response.

RESULTS

Basal area, canopy cover, and LAI

Trees were removed from the riparian buffer according to the Neuse River Riparian Buffer Rule for forestry where some trees can be selectively harvested from the riparian buffer. Selective removal of trees reduced treatment watershed (HF1) riparian buffer basal area 27%, 31.8 m^2 ha^{-1} to 23.2 m^2 ha^{-1} (Figure 2). Reference watershed (HF2) riparian buffer basal area increased from 30.5 m^2 ha^{-1} to 34.5 m^2 ha^{-1} (i.e. 13%) from 2009 to 2013. HF1 canopy cover was reduced significantly from 90% preharvest to 69% postharvest. HF2 canopy cover did not change significantly over the monitoring period, ranging from 92% to 95%. Mean growing season (May–October) LAI declined from 5.5 m^2 m^{-2} to 2.6 m^2 m^{-2} (i.e. 53%) in HF1 riparian buffer after clearcut harvest (Figure 3).

Growing season atmospheric, soil moisture, and stream discharge

Growing season precipitation, VPD, soil moisture, riparian buffer net radiation, and stream discharge patterns

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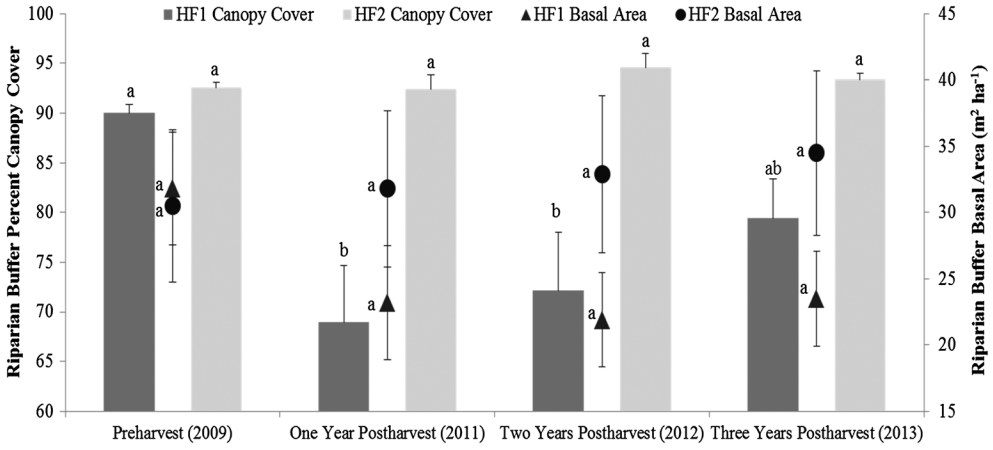


Figure 2. Preharvest and postharvest riparian buffer percent canopy and basal area in treatment (HF1) and reference (HF2) watersheds. Means with same letters are not significantly (t-test, $p < 0.05$) different within watersheds across years

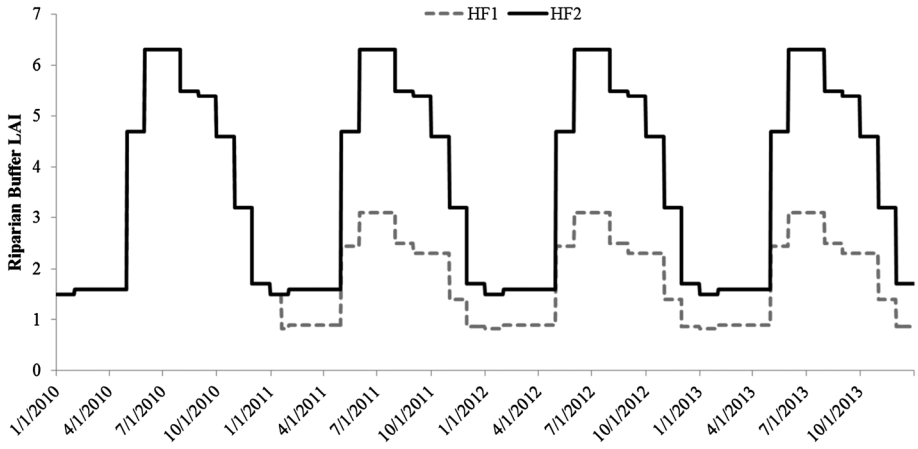


Figure 3. Preharvest (2010) and postharvest (2011–2013) riparian buffer leaf area index (LAI) in treatment (HF1) and reference (HF2) watersheds. Riparian buffer LAI was only measured in 2013. As indicated in Figure 2, riparian buffer percent canopy cover did not change significantly in reference watersheds (HF2) from 2009 to 2013 and in treatment watersheds (HF1) from 2011 to 2013. Therefore, we applied 2013 LAI values to previous years to depict canopy openness

varied in HF1 and HF2 watersheds between preharvest (2010) and postharvest (2011–2013) periods (Figure 4). Growing season precipitation was 717 mm preharvest and 583 mm, 667 mm, and 657 mm postharvest in 2011, 2012, and 2013, respectively. Growing season preharvest VPD was 0.77 kPa in the open area and 0.67 in the area to be clearcut. Mean growing season VPD during the postharvest periods was 0.62 kPa in the open area and 0.71 kPa in the clearcut area. Open area VPD reached a daily mean maximum of 2.4 kPa on 7 July 2010, and clearcut area VPD reached a daily mean maximum of 2.2 kPa on 29 July 2011. Growing season riparian buffer net radiation increased from 11.9 W m^{-2} preharvest to an average of 24.3 W m^{-2} during postharvest periods. Preharvest growing season soil moisture in HF1 and HF2 were similar, 21.3% and 22.4%, respectively. HF1 preharvest growing season soil moisture was 28.5% in 2011 then decreased below this level in 2012 and 2013, 26.5% and 27.2%, respectively. In converse, HF2 postharvest growing season soil moisture was 16.5% in 2011 then increased to 21.4% in 2012 and 23.0% in 2013. HF2 mean growing season soil moisture followed precipitation pattern, while HF1 mean growing season soil moisture did not. HF1 preharvest stream discharge was 52.3 mm, while HF2 preharvest stream discharge was higher at 99.8 mm. HF1 growing season stream discharge increased dramatically from preharvest (52.3 mm) to postharvest (averaging 132 mm). This is a 150% increase from the preharvest period to the postharvest period. These headwater streams are naturally flashy and respond rapidly to precipitation events.

Daily sap flux density, J_s

Greater changes in mean daily growing season J_s from the preharvest to postharvest period were observed in the HF1 riparian buffer trees when compared to HF2 riparian buffer trees, with tulip poplar and red maple showing the

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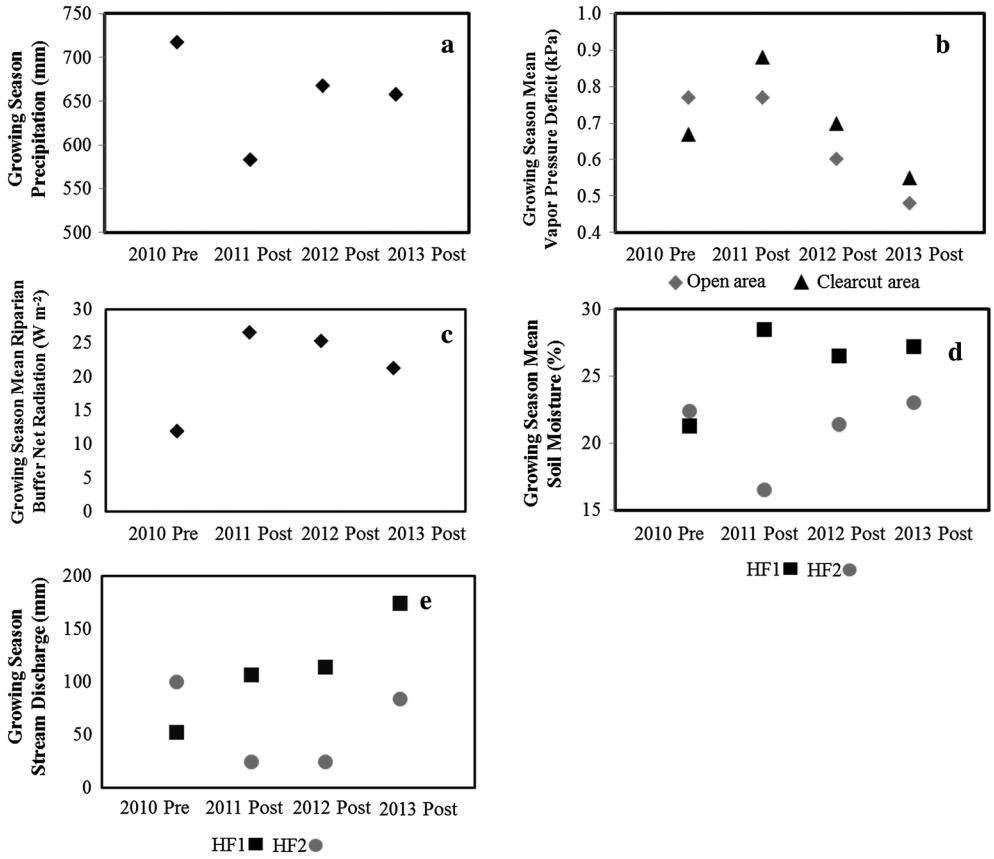


Figure 4. Growing season (May–October) (a) precipitation, (b) open area and clearcut area vapour pressure deficit (VPD), (c) riparian buffer net radiation, (d) soil moisture, and (e) stream discharge in treatment (HF1) and reference (HF2) watersheds over preharvest (2010) and postharvest (2011–2013) periods. Soil moisture sensors were installed in June 2010; thus, 2010 preharvest soil moisture growing season data covers June–October. Pre = preharvest; Post = postharvest

largest increases (Figure 5). From preharvest to postharvest, mean daily growing season J_s of trees in HF1 increased 88 g cm^{-2} d^{-1} in tulip poplar, 49 g cm^{-2} d^{-1} in red maple, 45 g cm^{-2} d^{-1} in oak, 32 g cm^{-2} d^{-1} in sweetgum, and 29 g cm^{-2} d^{-1} in loblolly pine. From preharvest to postharvest mean daily growing season J_s of trees in HF2 increased 43 g cm^{-2} d^{-1} in tulip poplar, and 25 g cm^{-2} d^{-1} in American beech (American beech not shown in Figure 5) but decreased 24 g cm^{-2} d^{-1} in loblolly pine, 13 g cm^{-2} d^{-1} in red maple, and 4 g cm^{-2} d^{-1} in sweetgum.

VPD was related to J_s in both HF1 and HF2 watersheds during preharvest and postharvest periods (Figure 6). These data cover a wet period when moisture conditions were favourable for transpiration. Regression slopes between VPD and HF1 J_s for all species increased significantly ($p < 0.05$) from preharvest period to postharvest period (98.7 to 232.8 in loblolly pine; −24.9 to 118.7 in oak; 40.2 to 307.0 in red maple; 19.2 to 111.5 in sweetgum; and 94.3 to 321.6 in tulip poplar). Regression slopes between VPD and HF2 J_s for all species also increased significantly ($p < 0.05$) from preharvest period to postharvest period (71.6 to 157.9 in loblolly pine; 104.1 to 149.9 in red maple; 56.6 to 114.0 in sweetgum; and 95.5 to 154.8 in tulip poplar). However, HF2 regression slope was statically lower than HF1 regression slopes for all species. HF1 red maple and tulip poplar J_s (Figure 6c and 6e) showed a greater response to VPD postharvest than HF1 loblolly pine, oak, and sweetgum (Figure 6a, 6b, and 6d). At a VPD of 0.8 kPa, HF1 postharvest J_s continued to increase in all species except sweetgum.

Effect size of treatment on J_s in HF1 was medium in loblolly pine and large in oak, red maple, sweetgum, and tulip poplar species (*d*-statistic in Figure 6). Effect size of J_s in HF2 was small in red maple and tulip poplar, medium in loblolly pine, and large in sweetgum species.

Stomatal conductance, G_s

HF1 stomatal closure (i.e. decrease in G_s) was less evident over the study VPD range in loblolly pine, red maple, and tulip poplar than in oak and sweetgum during the postharvest period (Figure 7). Regression slopes between VPD and HF1 G_s decreased significantly ($p < 0.05$) from the preharvest period to the postharvest period in loblolly pine, red maple, and tulip poplar, (−43.1 to −68.9 in loblolly pine; −57.9 to −159.5 in red maple; and −33.7 to −181.1 tulip poplar). Regression

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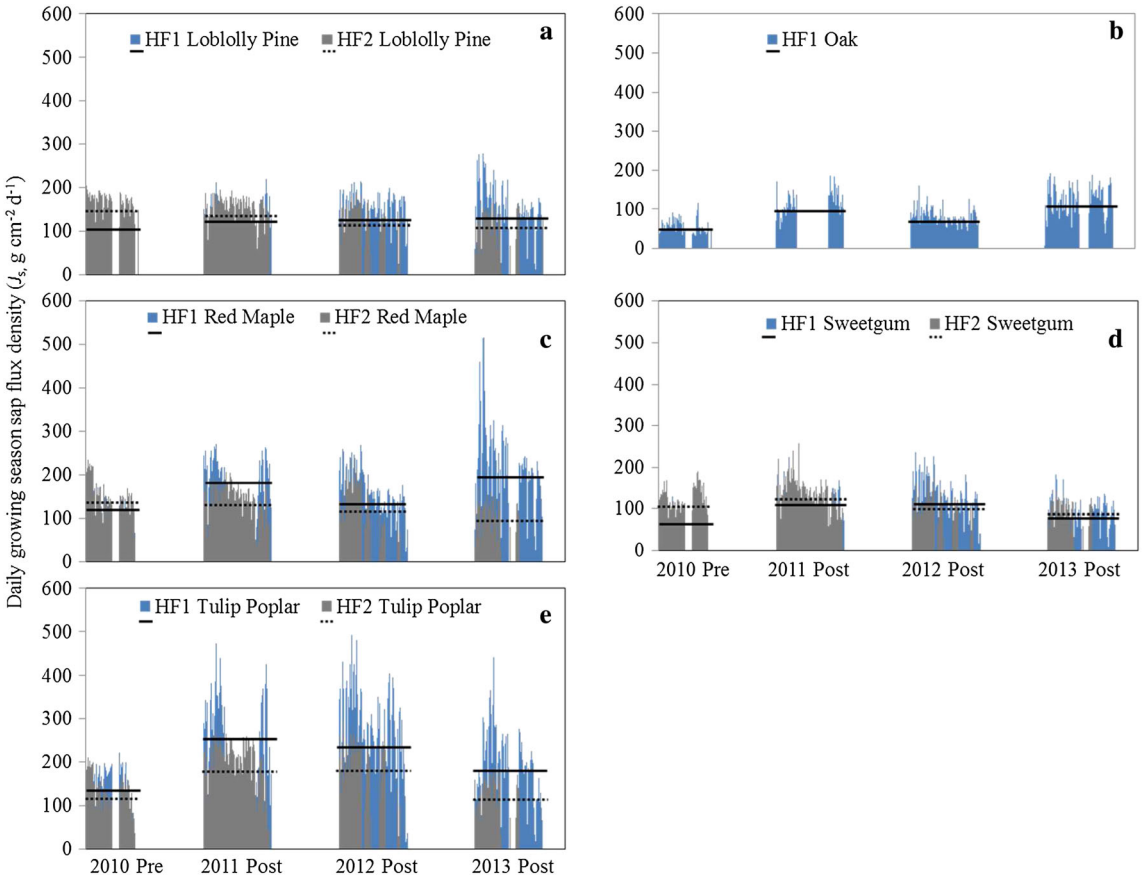


Figure 5. Daily growing season sap flux density between treatment (HF1) and reference (HF2) watersheds during preharvest (201) and postharvest (2011–2013) periods across (a) loblolly pine, (b) oak, (c) red maple, (d) sweetgum, and (e) tulip poplar. Solid line is growing season (May–October) mean J_s in HF1, and dash line is growing season mean J_s in HF2. Gaps in data are because of sap flow sensor errors or battery recharge issues. Pre = preharvest; Post = postharvest

slopes between VPD and HF1 G_s in sweetgum and oak did not change significantly (−30.1 to −26.1 in sweetgum; and −33.21 to −29.7 in oak). Unexpectedly, regression slopes between VPD and reference watershed (HF2) G_s decreased significantly ($p < 0.05$) from the preharvest period to the postharvest period in tulip poplar (−69.6 to −214.8). Loblolly, red maple, and sweetgum regression slopes between VPD and HF2 G_s showed no significant difference (−72.5 to −74.0 in loblolly pine; −67.3 to −74.1 in red maple; and −172.1 to −171.9 in sweetgum) between the two periods.

Effect size of treatment on G_s in HF1 was large in all species. Effect size of G_s in HF2 was small in loblolly pine and sweetgum and large in red maple and tulip poplar species.

Riparian buffer stand transpiration, E_s

The riparian buffer covered about 8% of the watershed area in both HF1 and HF2 and varied in the amount of growing season water used (riparian buffer stand transpiration, E_s) between preharvest and postharvest monitoring periods (Table II). HF1 residual trees in the riparian buffer used 43% more water in growing season postharvest period (314 mm) than growing preharvest period (220 mm). This resulted in an 8% reduction in discharge because of an increase in riparian buffer E_s. HF2 riparian buffer tree growing season water use remained about the same during preharvest period (330 mm) and postharvest period (327 mm). HF1 growing season riparian buffer E_s was estimated to be 30.7% of precipitation preharvest and a maximum of 60.0% of precipitation postharvest in 2011. The riparian buffer E_s showed a strong relationship with VPD where HF1 postharvest riparian buffer used more water than HF1 preharvest riparian buffer (Figure 8a). In HF2, riparian buffer E_s also showed a strong response to VPD with postharvest riparian buffer trees using similar amounts of as preharvest riparian buffer trees (Figure 8b).

DISCUSSION

Few studies have quantified water use (i.e. tree sap flux density, J_s and riparian buffer stand transpiration, E_s)

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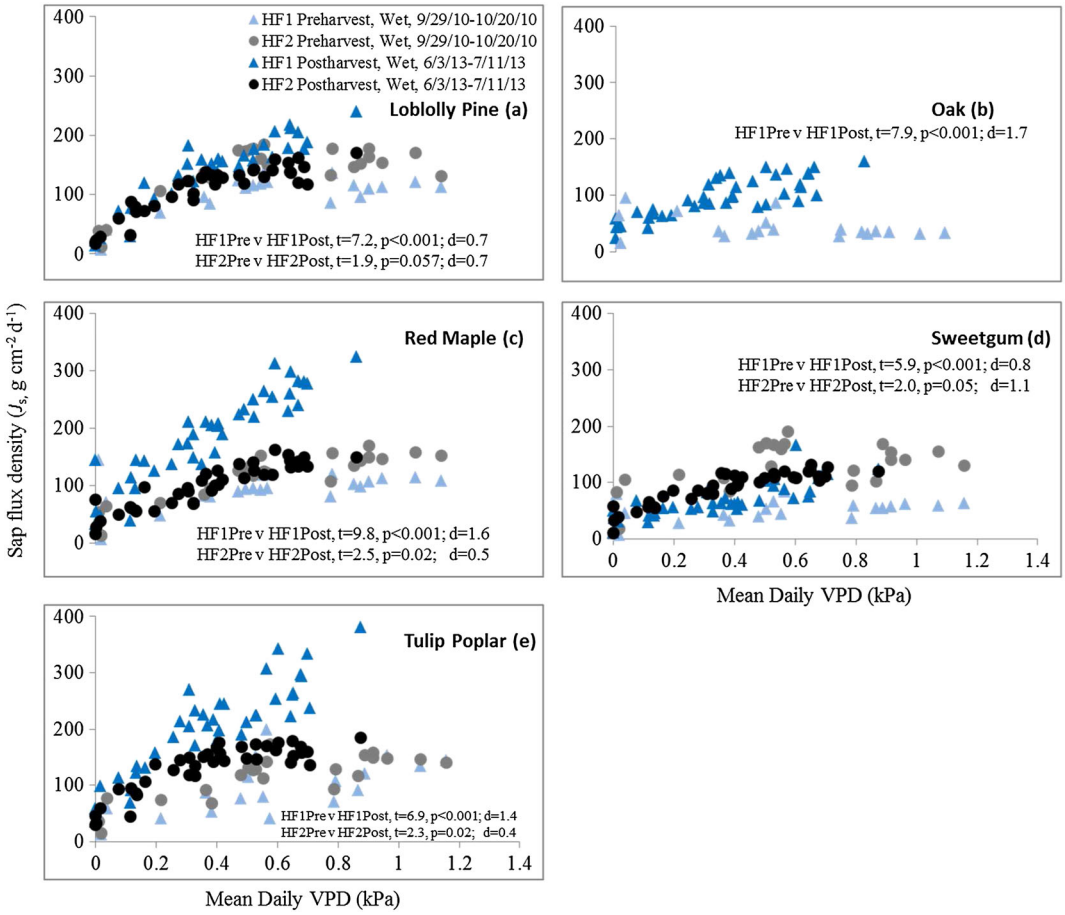


Figure 6. Relationship between growing season (May–October) vapour pressure deficit (VPD) and sap flux density (J_s) during the preharvest (2010) and postharvest (2013) periods in treatment (HF1) and reference (HF2) watersheds across five species—(a) loblolly pine, (b) oak, (c) red maple, (d) sweetgum, and (e) tulip poplar. Soil moisture conditions were wet ($\Theta = 20$–30%). *T*-statistics and *p* values are shown to indicate statistical differences between preharvest and postharvest slopes. Slopes with *p* values <0.05 are significantly different. Effect size of treatment is shown as *d*-statistics; 0.20 is small effect, 0.50 is medium effect, and 0.80 or $>$ is large effect. There were no oak trees monitored in HF2. Pre = Preharvest, Post = Postharvest

by riparian buffer species and ecophysiological changes (i.e. canopy stomatal conductance, G_s in mmol m^{-2} s^{-1}) after silvicultural activities in the upland. There are no data on how tree transpiration changes might reduce stream discharge. In this study, we compared tree J_s and G_s across loblolly pine, oak, red maple, sweetgum, and tulip poplar trees that were part of the riparian buffer left after the watershed clearcut. We then scaled those data to the riparian buffer area to assess E_s and linked transpiration to stream discharge. Changes in stream discharge, riparian buffer meteorology, and soil moisture condition are typical after a timber harvest and can increase evaporative demand in cut areas (Swank *et al.*, 1989; Breda *et al.*, 1995; Bladon *et al.*, 2006). The degree to which these changes mitigate impacts of upland harvesting on discharge and alter tree transpiration may vary by species (Wullschleger *et al.*, 2001) and by tree density (Hernandez-Santana *et al.*, 2011).

Daily sap flux density, J_s

Difference in J_s across species is likely linked to tree anatomy (diffuse porous *vs* ring porous) where there are differences in efficiency of tree water conduction (Bladon *et al.*, 2006; Gebauer *et al.*, 2008; Takahashi *et al.*, 2013). In general, diffuse porous species (e.g. red maple, tulip poplar, and sweetgum) have the capacity to use more water than ring porous (e.g. oaks) and non-porous (e.g. loblolly pine) species (Bush *et al.*, 2008; Taneda and Sperry, 2008). Tulip poplar and red maple in HF1 were the only species that had significant changes in J_s and G_s and a large effect size (*d*-statistic) across VPD (Figure 6c and 6e; Figure 7c and 7e). The large effect size (0.80 or $>$) indicates that the treatment had a practical effect on J_s and G_s in tulip poplar and red maple, while the low *p* value ($p < 0.001$) indicates that the effect was not attributable to chance. In other words, the results are practically important and statistically

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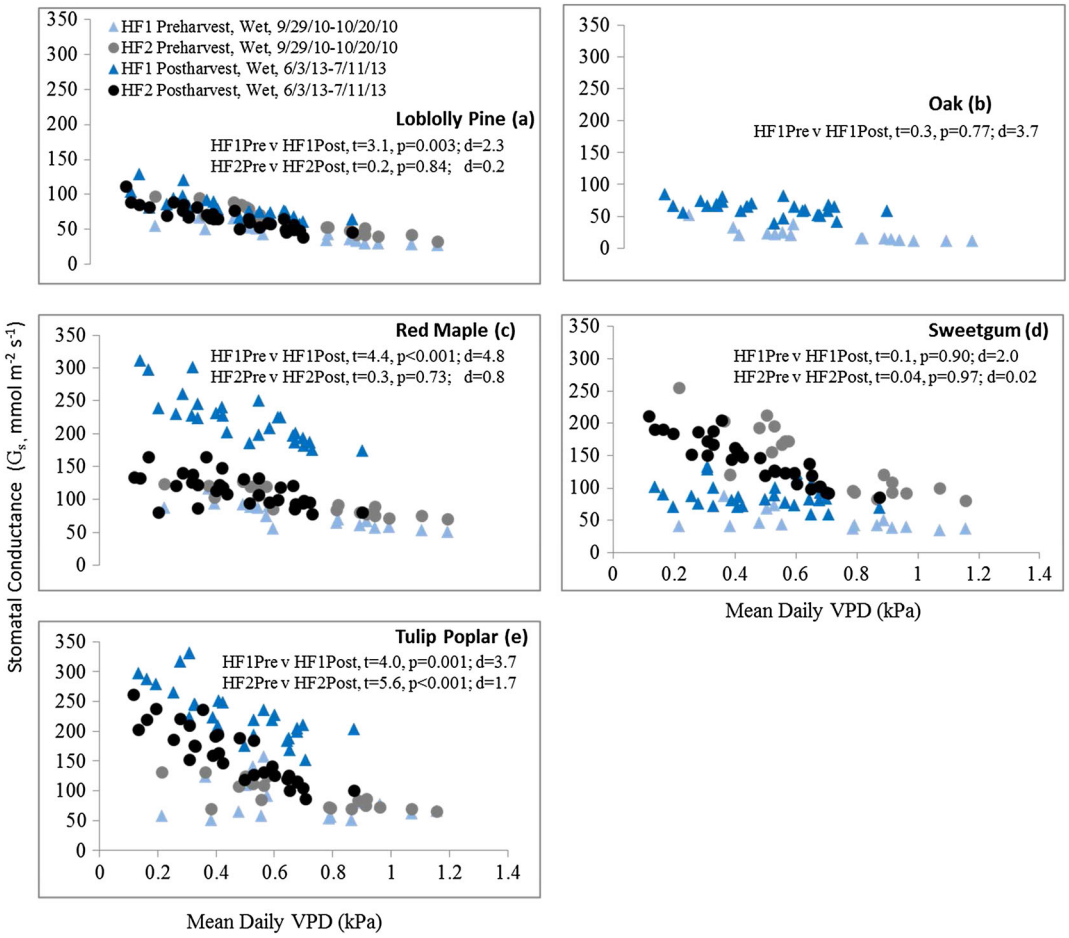


Figure 7. Relationship between growing season (May-October) vapour pressure deficit (VPD) and stomatal conductance (G_s) during the preharvest (2010) and postharvest (2013) periods in treatment (HF1) and reference (HF2) watersheds across five species—(a) loblolly pine, (b) oak, (c) red maple, (d) sweetgum, and (e) tulip poplar. Soil moisture conditions were wet ($\Theta = 20$–30%). *T*-statistics and *p* values are shown to indicate statistical differences between preharvest and postharvest slopes. Slopes with *p* values <0.05 are significantly different. Effect size of treatment is shown as *d*-statistics; 0.20 is small effect, 0.50 is medium effect, and 0.80 or $>$ is large effect. There were no oak trees monitored in HF2. Pre = Preharvest, Post = Postharvest

significant in regards to how VPD controls certain tree physiological conditions in tulip poplar and red maple trees (Ellis, 2010).

High J_s or transpiration values postharvest in HF1 tulip poplar and red maple trees likely caused the observed decrease in HF1 percent mean growing season soil moisture from 2011 to 2013 (Figure 4d), even though precipitation increased over this period (Figure 4a). This suggests that tulip poplar and red maple utilized shallow soil water which could lead to a reduction in the amount of water available for streamflow generation. This close coupling between tree water use and soil moisture can reduce the time it takes for postharvest discharge rates to match preharvest discharge rates, partially mitigating the hydrologic effects of forest removal on watershed water balance at the watershed level (Moore and Owens, 2006). Moore *et al.* (2011) found that soil moisture typically correlates significantly with streamflow and can mediate the influence of transpiration on streamflow.

The effect of reduced net radiation over the growing season on J_s was apparent preharvest and postharvest in both HF1 and HF2 tree species. Late growing season J_s was about half that of early growing season maximums (Figure 5). J_s tended to peak in early growing season and then decreased as the year moved toward dormant season, because of seasonal controls on available energy, VPD, and soil moisture (Bond *et al.*, 2002). In forests, soil moisture tends to be highest in early growing season and then declines as the season progresses until storage is recharged during precipitation events (Moore *et al.*, 2011).

Stomatal conductance, G_s

Although J_s of all species in HF1 were significantly linked to VPD, we found that oak and sweetgum G_s was less coupled to VPD than other species in this study (Figure 7b and d) (i.e. *t*-statistics = 0.3, $p = 0.77$ in oak and *t*-statistics = 0.1, $p = 0.90$ in sweetgum) (Ford *et al.*, 2011).

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Table II. Growing season (May–October) riparian buffer stand transpiration (E_s), precipitation, and transpiration/precipitation ratio preharvest and postharvest in treatment (HF1) and reference (HF2) watersheds

	HF1 riparian buffer sand transpiration (E_s) mm	HF2 riparian buffer stand transpiration (E_s) mm	Precipitation mm	HF1 transpiration/ precipitation ratio %	HF2 transpiration/ precipitation ratio %
Preharvest (2010)	220	330	717	30.7	46.0
Postharvest (2011)	350	364	583	60.0	62.4
Postharvest (2012)	315	340	667	47.2	51.0
Postharvest (2013)	276	276	657	42.0	42.0
Mean postharvest	314	327	636	49.4	51.4

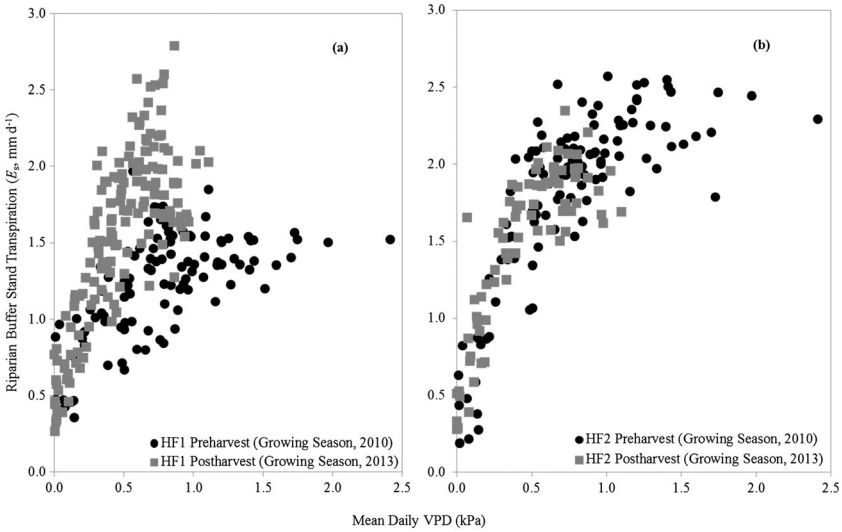


Figure 8. Relationships between mean daily vapour pressure deficit (VPD) and riparian buffer stand transpiration (E_s) in (a) treatment (HF1) and (b) reference (HF2) watersheds during growing season (May–October) in preharvest (2010) and postharvest (2013) periods

This suggests that oak and sweetgum species regulated stomata conductance more than other the other monitored species. Given the increase in available energy and soil moisture in the treatment riparian buffer, a regulation of stomata should not occur unless the trees are guarding against anatomical damage. For example, oak water transport capacity is driven by the vulnerability to cavitation that may induce stomatal closure to limit further formation of vapour cavities and leaf tissue damage (Taneda and Sperry, 2008). Oak stomatal regulation also creates a more constant flow of water in roots and tissues in growing season than maple species (Taneda and Sperry, 2008). Pataki and Oren (2003) found in a bottomland oak-hickory forest in Duke Forest, NC that oak had the lowest G_s across VPD when compared to other species. Although sweetgum is a diffuse porous species, in HF1 during the postharvest period, its G_s under favourable moisture conditions for transpiration was lower than the other diffuse porous species, red maple, and tulip poplar (Figure 7c, d, and e). Sweetgum also demonstrated stomatal closure in the reference watershed (HF2) where regression slopes of VPD *versus* G_s in HF2 preharvest were not significantly different than slopes in HF2 postharvest, t-statistics = 0.04, $p = 0.97$ (Figure 7d). This suggests a lower variant in leaf transpiration in sweetgum under study specific soil moisture and VPD conditions when compared to the other diffused porous trees. Species location within the buffer landscape may impact sap flow rates (Hernandez-Santana *et al.*, 2011); however, studies do show that landscape position does not consistently impact tree transpiration and conductance (Bosch *et al.*, 2014).

On the other hand, loblolly pine, red maple, and tulip poplar in HF1 did not demonstrate stomatal closure under wet conditions. Their preharvest and postharvest slopes were significantly different from each other (Figure 7a, c, and e), indicating that these species regulate stomatal closure less and were less sensitive to VPD than oak and sweetgum. G_s rates during the postharvest period in HF1 red maple and tulip poplar trees, in particular, seem to illustrate a lack of species specific stomata control and maximized photosynthesis at the expense of large transpiration losses that could lead to reduction in water use efficiency over time (Phelps *et al.*, 1976; McConathy

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and McLaughlin, 1978; Bush *et al*., 2008). If these trees expressed similar G_s relative to VPD on a drier site, this could lead to tissue moisture deficits and limit growth rates (McConathy and McLaughlin, 1978).

We did not expect HF2 preharvest regression slope of tulip poplar VPD *versus* G_s to be significantly different than HF2 postharvest regression slope (t-statistic = 5.6, $P < 0.001$) (Figure 7e). However, a 2013 windstorm event, where the tops were broken from a few non-monitored trees that were next to monitored tulip poplar trees, seems to have influenced tulip poplar G_s. This influence likely created higher G_s rates than would not have been observed if the canopy had not changed. This is another anecdotal event that suggests that tulip poplar G_s will respond to changes in canopy structure.

Riparian buffer stand transpiration, E_s

There was a clear divergence between HF1 preharvest riparian buffer E_s and HF1 postharvest riparian buffer E_s above a VPD of about 0.2 kPa with HF1 postharvest riparian buffer E_s displaying a linear trend up to a VPD of 1.0 kPa (Figure 8a). This divergent was driven in large part by water use and stem density (i.e. trees per hectare) of tulip poplar riparian buffer trees. Tulip poplar occupied 21% of the riparian buffer stand area and used 40% of the stand water, while oak occupied 22% of the riparian buffer stand area and used 20% of the stand water. HF1 riparian buffer E_s was estimated to be 30.7% of precipitation preharvest and 49.4% of precipitation postharvest (Table II), even though 27% of the riparian buffer tree basal area ($m^{-2}\,ha^{-1}$) was selectively harvested during logging. In contrast to HF1, as expected, HF2 preharvest and postharvest riparian buffer E_s relationships with VPD (Figure 8b), and preharvest and postharvest transpiration/precipitation ratios (Table II) were very similar. Overall, HF1 residual trees in the riparian buffer used 43% more water in the postharvest period (314 mm) than the preharvest period (220 mm). This resulted in an 8% decrease in discharge because of an increase in riparian buffer E_s. With a 150% increase in HF1 growing season discharge above precut hydrologic conditions, an 8% reduction from this value will obviously not produce peakflows, sediment, and nutrient loads that match preharvest exports. However, the increase in transpiration by the residual trees in the riparian buffer will, at least, partially mitigate the hydrologic effects of forest removal on in-channel sediment flows through increased transpiration. In addition, catchments with large riparian buffers (i.e. 30.5 m or more) (Georgia Environmental Protection Division, 2009), high presence of tulip poplar trees, and less flashy discharge peaks will likely reduce stream discharge rates by a larger percentage than what we found. This could lead to sediment and nutrient flow loads that closely mimic preharvest levels within a few years after harvest.

Boggs *et al*. (2015) found that tulip poplar trees located at streambank edge were least likely to be blown down during high wind events (more windfirm than other species) in forests located on Triassic soils in the Piedmont of North Carolina. Most to least windfirm species in that study was Tulip poplar > Sweetgum > Pine spp. > Hickory spp. = Oak spp. Residual tulip poplar trees in the riparian buffer seem to serve the following mechanistic functions to reduce loss of sediment from streams: (1) decrease the amount of water available for sediment transport and (2) mitigate windthrow and uprooting of streambanks in the Piedmont region. Given the differences in tree J_s, G_s, and species-specific percent contribution to E_s in this study, species selection for riparian buffer harvesting and enhancing riparian zone design and function appears to be an important management option to consider (Hernandez-Santana *et al*., 2011). This study also offers foundational and species-specific water use research that can enhance the potential for scaling transpiration from the tree to watershed scale and can lead to a better understanding of water use dynamics of Piedmont riparian buffers after harvest and how they function.

CONCLUSIONS

This study quantified changes in meteorological data, riparian buffer tree composition, below riparian buffer canopy net radiation, soil moisture, and stream discharge from preharvest to postharvest periods and linked these values to species-specific water use (i.e. tree sap flux density, J_s and riparian buffer stand transpiration, E_s) and ecophysiological changes (i.e. stomatal conductance, G_s). We found that treatment watershed J_s in red maple and tulip poplar showed the largest increases from preharvest to postharvest period compared to loblolly pine, oak, and sweetgum J_s. Stomatal closure (G_s) in oak and sweetgum trees was evident even under wet soil moisture postharvest period, suggesting a lower variant in leaf transpiration under study soil and climatic conditions when compared to the other species. Residual trees in the treatment riparian buffer stand used 43% more water postharvest than preharvest. Although clearcutting increased growing season stream discharge by 150%, we conclude that the increase in transpiration by the residual trees in the riparian buffer will, at least, partially compensate for the cutting through increased transpiration and a reduction in the amount of water available in the stream to transport sediment downstream. Quantifying changes in J_s, G_s, and E_s in riparian buffer areas, particularly ones dominated by red maple and tulip

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popular will expand our current knowledge of riparian buffer functions as it relates to discharge controls and estimates of the water budget. Use of riparian buffer best management practices (BMPs) to help with flow control rates is not generally practiced in forestry. However, as we improve our knowledge about forestry BMP functions and designs, this practice could gain practical application in the future. In addition, species selection for harvesting and enhancing riparian buffer function appears to be an important management options to consider.

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