Mechanistic assessment of hillslope transpiration controls of diel subsurface flow: a steady-state irrigation approach

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ABSTRACT

Mechanistic assessment of how transpiration influences subsurface flow is necessary to advance understanding of catchment hydrology. We conducted a 24-day, steady-state irrigation experiment to quantify the relationships among soil moisture, transpiration and hillslope subsurface flow. Our objectives were to: (1) examine the time lag between maximum transpiration and minimum hillslope discharge with regard to soil moisture; (2) quantify the relationship between diel hillslope discharge and daily transpiration; and (3) identify the soil depth from which trees extract water for transpiration. An 8×20 m hillslope was irrigated at a rate of $3 \cdot 6$ mm h^{-1}. Diel fluctuations in hillslope discharge persisted throughout the experiment. Pre-irrigation time lags between maximum transpiration and minimum hillslope discharge were $6 \cdot 5$ h, whereas lags during steady-state and post-irrigation conditions were 4 and 2 h, respectively. The greatest correlation between transpiration and hillslope discharge occurred during the post-irrigation period, when the diel reduction in hillslope discharge totalled 90% of total measured daily transpiration. Daily transpiration of trees within the irrigated area remained relatively constant throughout the experiment. Diel fluctuations in soil moisture were greatest at a depth of $0 \cdot 9$–$1 \cdot 2$ m prior to irrigation and became more uniform throughout the soil profile during and post-irrigation. This study clearly demonstrates that when soil moisture is high, hillslope trees can be an important factor in diel fluctuations in stream discharge. We advance a conceptual model for the site whereby the relationship between transpiration and hillslope discharge is a function of soil moisture status and drainable porosity. Copyright © 2010 John Wiley & Sons, Ltd.

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INTRODUCTION

The hydrological cycle involves mutually dependent biological and physical processes that operate at multiple scales of time and space, and this principle is the foundation for research in Ecohydrology. Early studies of paired watersheds operated at the whole-basin spatial scale and at annual to decadal time scales—highlighting the importance of vegetation for streamflow, with demonstrations of increased streamflow (in most cases) following complete removal of vegetation (Bosch and Hewlett, 1982). While paired-watershed manipulations have been implemented in many regions, much of the work to date has focussed solely on inputs and outputs. These studies demonstrate strong influences of vegetation on streamflow, but this black-box approach fails to explain the mechanisms controlling water flow paths within the catchment. Mechanistic assessment of the relationships between transpiration and discharge is necessary to advance our understanding of catchment hydrology. One fruitful approach is to look at processes at smaller scales of time and space.

A number of recent studies have begun to explore the mechanistic link between transpiration and streamflow via the analysis of diel variations in streamflow. Vegetation-induced diel fluctuations in stream discharge have been noted for many decades, and this behaviour is especially pronounced during baseflow periods in mountainous, forested watersheds (White, 1932; Troxell, 1936). A growing body of work has suggested that the interaction between evapotranspiration (ET) losses from riparian zones characterized with shallow groundwater tables cause these diel fluctuations (Dunford and Fletcher, 1947; Federer, 1973; Kobayashi *et al*., 1990; Bren, 1997; Nachabe *et al*., 2005; Chen, 2007; Shah *et al*., 2007; Gribovszki *et al*., 2008; Loheide, 2008; Szilagyi *et al*., 2008). Many of these studies have reported time lags between the time of maximum transpiration and minimum stream discharge in the order of 4–6 h, and the authors infer that this is a manifestation of a strong hydrologic connection between riparian vegetation water use and water draining into the stream channel.

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Bond *et al.* (2002) found strong diel patterns in stream discharge in the spring that persisted through late summer in a small catchment in western Oregon. These observed diel patterns were hypothesized to be the result of extraction of water by vegetation in the riparian zone. Xylem water flux measurements indicated that transpiration within less than 0·3% of the total basin area accounted for the diel reduction in streamflow. Cross-correlations between transpiration and stream discharge were highest and the time lag between maximum transpiration and minimum stream discharge was shortest in the early summer, at which time transpiration explained nearly 80% of the daily variation in stream discharge. As summer drought conditions progressed, the apparent connectedness of the vegetation and the stream was greatly diminished; transpiration was not significantly related to discharge at any time lag by mid-August. Wondzell *et al.* (2007) conducted further analysis of diel fluctuations in the same stream examined by Bond *et al.* (2002) and suggested that shifts in time lags between transpiration and discharge were strongly dependent on stream flow velocity. Wondzell *et al.* (2007) found that high flow velocities occurring during high baseflow periods resulted in constructive wave interference that amplify the diel signal generated by ET along the stream channel. These various interpretations highlight the need for further experimental work to elucidate the first-order controls on transpiration–streamflow interactions. While prior studies have reported strong linkages between stream discharge and riparian vegetation dynamics, questions still remain concerning the mechanistic relationship between transpiration and water yield. By what mechanism does soil moisture influence the hydrologic connection between transpiration and subsurface flow? At what soil depth do roots take up water?

We know that diel fluctuations are not unique to streams with riparian vegetation and/or shallow groundwater tables. In a classic study by Dunford and Fletcher (1947), a damped diel signal persisted in stream discharge even after the complete removal of riparian vegetation. Since that study, however, little if any research has focused on the potential for hillslope transpiration to contribute to observed diel dynamics of streamflow. The role that hillslope transpiration plays in the diel subsurface flow (and hence streamflow) is difficult to identify in complex terrain with a hillslope–riparian area interface. Circumstantial evidence for hillslope control of stream diel dynamics is shown in the long-term stream discharge data from the H.J. Andrews Experimental Forest (HJA), the site of the field analyses presented in this paper. Long-term records at HJA demonstrate diel fluctuations in Watershed 10 (WS10), a first-order 10-ha headwater watershed devoid of any riparian zone (due to its excavation by debris flows—see Van Verseveld *et al.*, 2009 for details).

Resolving the mechanisms causing diel variations will reveal fundamental properties of vegetation-hydrological coupling in catchments. Examining the link between transpiration and subsurface flow at the hillslope scale is a necessary element of this research to further our understanding of the potential mechanisms that are likely to operate at the catchment scale. Here, we approach this issue experimentally, using a hillslope irrigation treatment to induce saturated conditions and then examine the relationships of soil moisture, transpiration and hillslope subsurface flow before, during and after the treatment. The overall goal of this experiment is to quantify the relationship between hillslope transpiration and diel hillslope discharge and how soil moisture modulates the timing and magnitude of the relationship. Our objectives are to: (1) examine the phase shift (time lag) between maximum transpiration and minimum hillslope discharge at different levels of soil moisture; (2) quantify the relationships between diel hillslope discharge and daily transpiration; and (3) identify the soil depths from which trees extract water for transpiration.

METHODS

Study site description

This study was conducted in a 10·2 ha headwater catchment (WS10), located on the western boundary of the HJA, in the western-central Cascade Mountains of Oregon, USA (44·2 °N, 122·25 °W). The HJA is part of the Long Term Ecological Research program and has a continuous meteorological and stream discharge data record from 1958 to the present. The HJA has a Mediterranean climate, with wet, mild winters and dry summers. Average annual rainfall is 2220 mm, of which about 80% falls between October and April during storms characterized by long duration and low rainfall intensity. Elevations in WS10 range from 470 m at the watershed gauging station to a maximum of 680 m at the southeastern ridge line. The watershed was harvested during May–June 1975 and is now dominated by naturally regenerated, second-growth Douglas-fir (*Pseudotsuga menziesii*). Dominant understory species include: western swordfern (*Polystichum munitum*), bear grass (*Xerophyllum tenax*), Oregon grape (*Berberis nervosa*) and salal (*Gaultheria shallon*). Several seep areas along the stream have been identified (Harr, 1977; Triska *et al.*, 1984). These seep areas are related to the local topography of bedrock, or to the presence of vertical, andesitic dikes (Swanson and James, 1975; Harr, 1977). Frequent debris flows at WS10 (most recently in 1996) have scoured the stream channel to bedrock removing the riparian area in the lower 200 m of the stream.

The study hillslope is located on the south aspect, 91 m upstream from the stream gauging station. The 125-m stream-to-ridge slope has an average gradient of 37°, ranging from 27° near the ridge to 48° adjacent to the stream (McGuire, 2004). The bedrock is of volcanic origin with andesitic and dacitic tuff and coarse breccia (Swanson and James, 1975). The soils vary across the watershed as either Typic Hapludands or as Andic Dystrudepts (Yano *et al.*, 2005), and are underlain by low-permeability subsoil (saprolite), formed from the
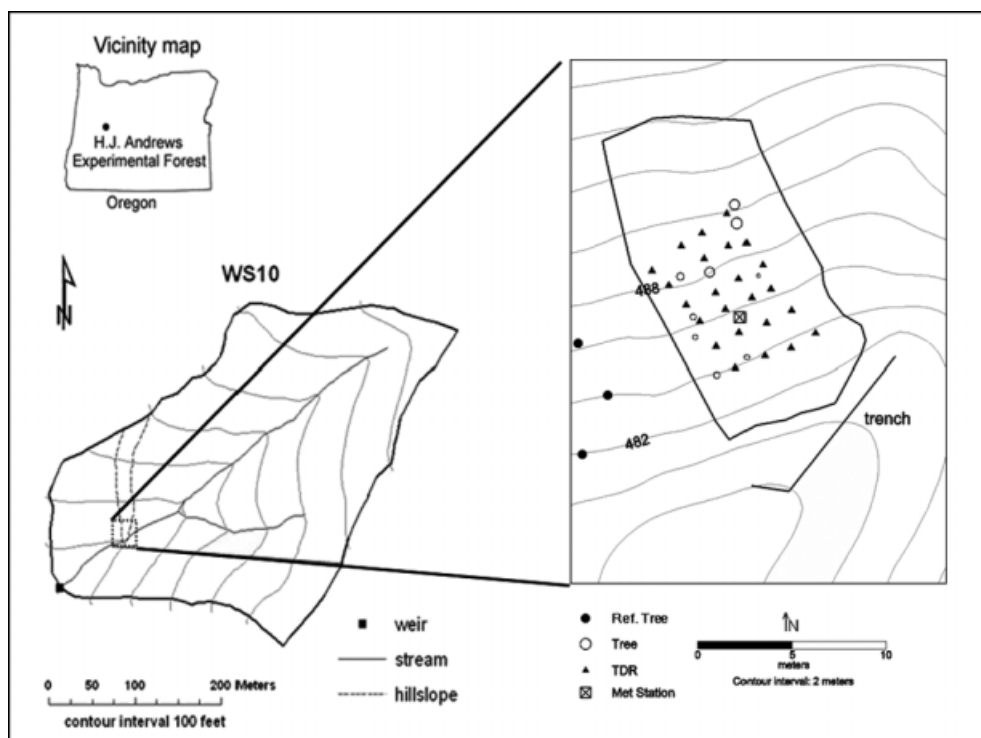
Figure 1. Location and map of study site with outline of irrigated area with 24 time domain reflectometry rods, meteorological station and instrumented trees. The relative size of circle symbol represents the diameter of the tree for trees within the irrigation area (minimum = 4·4 cm, maximum = 28 cm).

highly weathered coarse breccia (Ranken, 1974; Sollins *et al.*, 1981). Soil depth on the study hillslope ranges from 0·1 m adjacent to the stream, to 2·4 m at the upper limit of the irrigated area. Soils have distinct pore size distribution shifts at 0·3, 0·7 and 1·0 m, resulting in transient lateral subsurface flow at these depths (Van Verseveld, 2007; Harr, 1977). Soils are well aggregated, tending towards massive structure at depth (0·7–1·1 m) (Harr, 1977). Surface soils are gravelly loams, lower soil layers are gravelly, silty, clay loams or clay loams and subsoils are characterized by gravelly loams or clay loams (Harr, 1977).

Irrigation experiment

We conducted an irrigation experiment for 24 continuous days beginning on Julian day of year (DOY) 208 (July 27), 2005. Monitoring began one week before we began irrigating and continued for two weeks after irrigation stopped. The mean temperature at the hillslope during the experiment was 17·9 °C and natural rain events occurred on DOY 204 (~2 mm of rainfall) and DOY 242 (~0·5 mm of rainfall). The irrigation treatment area was located directly upslope from the soil–bedrock channel interface at the toe of the hillslope and was approximately 8×20 m (174·3 m^2) (Figure 1). A rectangular grid of 36 (9 rows of 4) 360° micro-sprinklers (with approximately 1 m spray radius) was installed on the hillslope, with sprinkler heads spaced 2 m apart and approximately 0·4 m above the soil surface. Sprinklers were controlled with an automatic timer to maintain a consistent application rate throughout the experiment. Sprinkler rate was measured by an array of 72 (5 and 10 cm diameter) cups

that were sampled every 4–12 h during days 12–19 of the experiment. Additionally, three tipping-bucket rain gauges (TruTrack, Inc., Pronamic Rain Guage) recorded irrigation rates throughout the experiment. The cups and tipping buckets were placed randomly in the sprinkled area, between 0·1 and 0·8 m from the sprinkler heads. We applied a total of 2107 mm of water at an average rate (±SD) of 3·6 (0·5) mm h^{-1} continuously except for minor malfunction periods on days 210, 225, 228, 229 and 230 (Figure 2(A)). Detailed information and analysis of the water balance throughout the experiment can be found in Graham *et al.* (2008).

Hillslope discharge and lateral subsurface flow

A 10-m trench consisting of sheet metal anchored 5 cm into bedrock and sealed with cement was constructed in 2002 to measure lateral subsurface flow at a natural seepage face (McGuire *et al.*, 2007). Intercepted subsurface water was routed to a calibrated 30° V-notch with stage recorded at 10-min time intervals using a 1-mm resolution capacitance water-level recorder (TruTrack, Inc., model WT-HR). Thirty-two manual measurements of discharge covered the range of values experienced during the irrigation experiment, and allowed for a stage–discharge relationship ($R^2 = 0.997$). We report hillslope discharge and lateral subsurface flow on a per unit irrigation area basis.

Xylem water flux, transpiration and canopy reference ET

Transpiration was estimated from xylem water flux measurements of the dominant trees located within or bordering the sprinkled area ($n = 9$) beginning 10 days
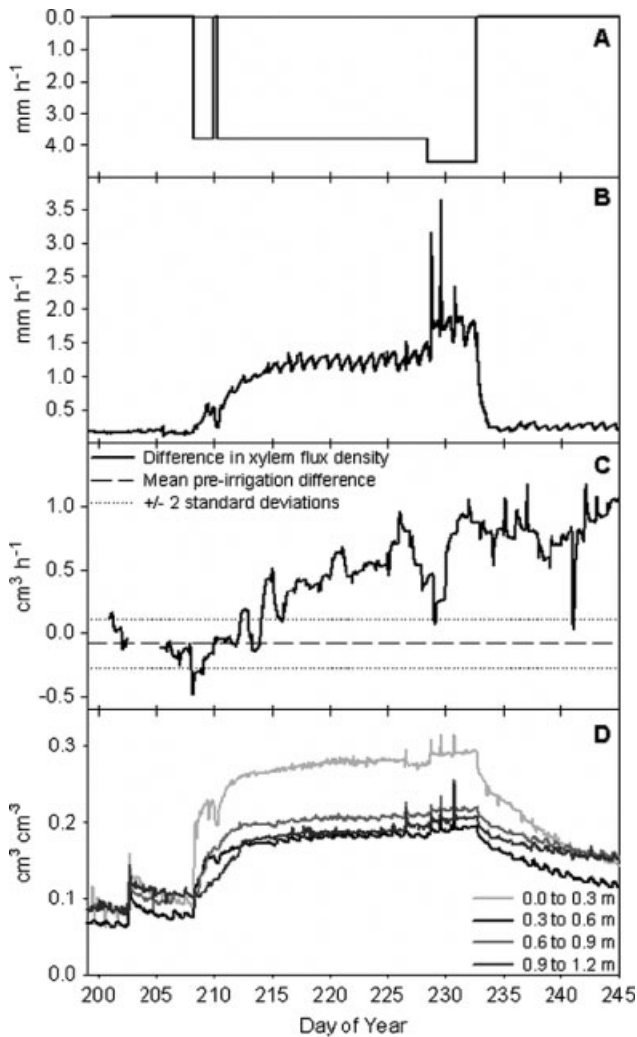
Figure 2. (A) Hillslope irrigation rate, (B) hillslope discharge, (C) difference in xylem flux density between irrigated and control Douglas-fir trees and (D) measured soil volumetric water content versus time.

prior to irrigation (DOY 199) and continuing for 60 days after irrigation stopped (DOY 293) (Figure 1). Of the mature trees located within the irrigation area Douglas-fir ($n = 6$), western hemlock (*Tsuga heterophylla*) ($n = 2$) and cascara (*Rhamnus purshiana*) ($n = 1$) represented 67, 27, and 6% of the total basal area, respectively. As a control for the trees in the experimental irrigation area, xylem water flux of three dominant Douglas-fir trees was measured 10–20 m outside the irrigation area. Xylem water flux was measured using the heat-dissipation method (Granier, 1985, 1987) every 15 s and data were stored in a CR-10x datalogger (Campbell Scientific, Logan, UT) as 15 min means. We used 2-cm probes for the flux measurements. Xylem depths were measured on tree cores extracted at the same height as the sap flux sensors on each tree. For trees with xylem depths greater than 2 cm, corrections for radial variations in flux were estimated from measured radial flux profiles of trees of the same species and age at another location (Moore *et al.*, 2004; Domec *et al.*, 2006).

We scaled measurements from individual sensors to water flux per unit ground area (mm day^{-1}). For each

tree, the total xylem area at each depth interval (0–2, 2–3, >3 cm) was calculated. The flux within each depth interval of xylem was calculated as the product of the area of that interval and the measured or predicted flux; we then summed the fluxes for each xylem depth interval to estimate total flux per tree. Last, we summed the fluxes of all the trees and divided by the ground area of the irrigation experiment to estimate mean water flux per unit ground area.

Meteorological conditions were monitored near the center of the irrigation treatment area from DOY 205 to 262 (Figure 1). Net radiation, relative humidity, air and soil temperature, and wind speed and direction were measured every 15 s and stored to a datalogger (CR-10x, Campbell Scientific) as 15 min means. To estimate total daily ET, we calculated canopy reference evapotranspiration (CRET) using the Penman-Monteith equation:

$$\text{CRET} = \frac{\Delta(R_n - G) + \rho c_p \{\text{VPD}\}/r_a}{\lambda(\Delta + \gamma(1 + r_c/r_a))} \qquad (1)$$

where Δ is the rate change of saturation vapour pressure with temperature (Pa K^{-1}), R_n is net radiation measured at the hillslope (W m^{-2}), G is the ground heat flux (W m^{-2}), ρ is the density of air (kg m^{-3}), c_p is the heat capacity of air (J kg^{-1} K^{-1}), VPD is vapour pressure deficit (Pa), r_a is the aerodynamic resistance of the canopy (s m^{-1}), λ is the latent heat of evaporation (J kg^{-1}), γ is the psychrometer constant (Pa K^{-1}) and r_c is the average canopy stomatal resistance (s m^{-1}). Average canopy stomatal resistance was estimated to be 150 s m^{-1} (Monteith and Unsworth, 2008; T. Pypker, personal communication). Relative to latent and sensible heat flux, G is usually small in forested ecosystems (Oke, 1992). Thus, we assumed G was only 10% of R_n. The aerodynamic resistance (r_a) was estimated using the following:

$$r_a = \frac{\ln[(z - d)/z_o]}{ku(z)} \qquad (2)$$

where z is the height of the canopy (m), d is the zone of zero displacement, k is von Karman's constant (0·41), z_o is the roughness length and $u(z)$ is the wind speed at the hillslope. In using Equations (1) and (2) we assumed that $d = 0.65h$, where h is canopy height ($h = 22$ m), $z_o = 0.1h$ (Campbell and Norman, 1998; Monteith and Unsworth, 2008).

Soil moisture

Soil volumetric water content (hereafter referred to as soil moisture) was measured at 24 locations within the irrigated area with a profiling time domain reflectometry (TDR) system (Environmental Sensors, Inc., model PRB-A). The system consisted of 1·2-m TDR probes that measured multiple depth segments (0·0–0·3, 0·3–0·6, 0·6–0·9 and 0·9–1·2 m) in a single profile. The probes have a manufacturer-reported precision within 3%. Since the probes were not calibrated for our site-specific soil

type, we examined relative changes in moisture content. Measurement locations were in a 4×6 sensor grid (parallel and perpendicular to the stream channel, respectively), with probes installed 2 m apart in each direction (Figure 1). Soil moisture was measured every hour for the duration of the experiment. Of the 96 measurements (locations × depth), 49 of the probe segments gave consistent results. Poor electrical connections or poor contact between the probe and soil caused inconsistent readings from the remaining 47 measurement segments. Only the data from consistently working segments were analysed.

Analysis

We took a statistical process control approach to evaluate differences between xylem water flux density within and outside the irrigation treatment throughout the experiment (Shewhart, 1933; Deming, 1950). Using this approach, we measured the difference in the 24-h running mean of xylem water flux density at 15-min intervals between treatment ($n = 6$) and control ($n = 3$) Douglas-fir trees prior to irrigation. A significant ($p \leq 0.05$) treatment effect was defined to occur when the difference between treatment and control trees exceeded the mean difference prior to irrigation plus two standard deviations.

We followed methods similar to those used by Bond *et al.* (2002) to examine the correlations between transpiration and hillslope discharge. Hillslope discharge and transpiration measurements were averaged over 30-min time intervals for statistical analysis. The correlations were analysed separately for three 4–7-day time periods: pre-irrigation (DOY 199–203), steady-state irrigation (DOY 218–223) and post-irrigation (DOY 238–245). For each period, the Pearson's correlation coefficient between transpiration and hillslope discharge was calculated for each 30-min lag (relating discharge to transpiration at progressively earlier time periods) from 0 to 12 h.

We estimated the diel reduction in hillslope discharge associated with ET for each day during the three irrigation periods. Following methods of Bond *et al.* (2002), we interpolated a straight line between successive daily maximum trenchflows. The difference between the interpolated line and the observed discharge was calculated at 10-min intervals and summed for each day to calculate the amount of water that was 'missing' from the actual daily discharge compared with the presumed potential discharge without ET.

RESULTS

Hillslope discharge

Hillslope discharge measured at the trench responded quickly to irrigation, with a detectable rise in discharge within an hour of initiation on DOY 208 (Figure 2(B)). Steady state was defined as the period when average discharge remained relatively constant and only diel fluctuations were recorded. Discharge rose from a pre-sprinkling average rate of 0·2 mm h^{-1} to a steady-state average rate of 1·2 mm h^{-1} within 8 days. Steady-state discharge was maintained for 13 days (with one malfunction that increased discharge on DOY 225), after which a series of sprinkler malfunctions increased discharge over the steady-state rate. Irrigation was terminated on DOY 232. Distinct diel patterns in hillslope discharge were apparent prior to the onset of irrigation. These became more pronounced as the system entered steady state during the treatment, (DOY 216) and persisted after irrigation ceased (Figures 2(B) and 3). The mean daily amplitude (±1 SD) of the diel fluctuation was 0·03 (0·002) mm h^{-1} prior to irrigation, 0·22 (0·03) during steady state and 0·08 (0·02) after irrigation ended.

The amount of diel reduction ('missing trenchflow') in hillslope discharge varied greatly between the three analysed time periods (Figure 4). During the 4-day pre-irrigation period, the calculated diel reduction averaged (±1 SD) 0·2 (0·1) mm day^{-1}. During steady-state irrigation, there was a 10-fold increase in the amount of 'missing trenchflow' with an average of 2·4 (0·5) mm day^{-1}. Post-irrigation diel flow reduction averaged 0·9 (0·3) mm day^{-1}. Minimum diel reduction occurred on days (DOY 202 and 241) when there were small (<2 mm) natural rain events supporting the idea that these daily reductions result from ET.

Xylem water flux, transpiration and canopy reference ET

The difference in xylem water flux density between irrigated and control Douglas-fir trees increased with time during irrigation and differences persisted after irrigation ceased (Figure 2(C)). The difference was significant ($p > 0.05$) within 7 days after irrigation began. The observed differences in xylem water flux density resulted from a decline in the xylem water flux density of the control trees through time that is likely a result in declining soil moisture outside the irrigation area.

Total daily transpiration of the nine dominant trees in the experimental plot showed little day-to-day variation before, during and after the irrigation treatment, averaging 1·1, 1·2 and 1·0 mm day^{-1} during the pre-treatment, treatment and post-treatment periods, respectively (Figure 4). These values of total daily transpiration are comparable to those measured in Douglas-fir of similar age at the HJA during high soil moisture conditions (Barnard, 2009). Daily maximum transpiration rates occurred at 1300, 1230 and 1315 h (Pacific Standard Time), respectively (Figure 3). These results contrast with diel reduction in hillslope discharge (i.e. 'missing trenchflow') which varied with irrigation. Prior to irrigation, transpiration was greater than the diel reduction in discharge by about 0·3 mm, but during the irrigation, the diel reduction was almost twice that of transpiration. Post-treatment, the two were similar in magnitude.

Estimated CRET within the irrigation plot varied from 0·1 mm h^{-1} at night to 0·7 mm h^{-1} during the day, with a daily average rate of 5·2 mm day^{-1} during the steady-state irrigation period. Post-irrigation rates averaged 4·2 mm day^{-1}. (Figure 4). Data were not available
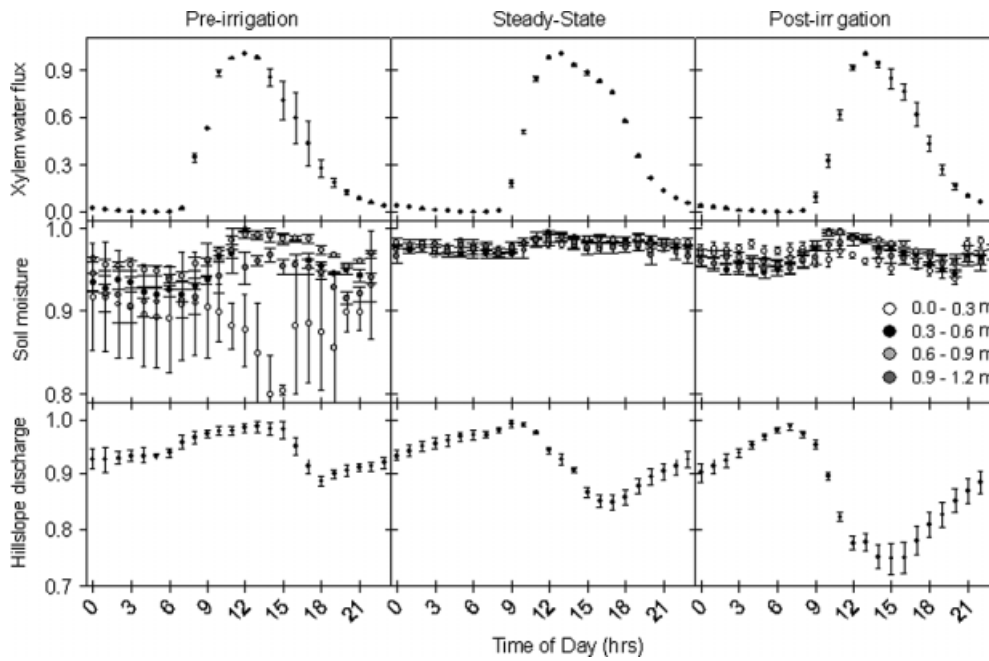
Figure 3. Average fluctuations in xylem water flux, soil moisture, and hillslope discharge relative to the daily maximum by time of day. Error bars = standard error.
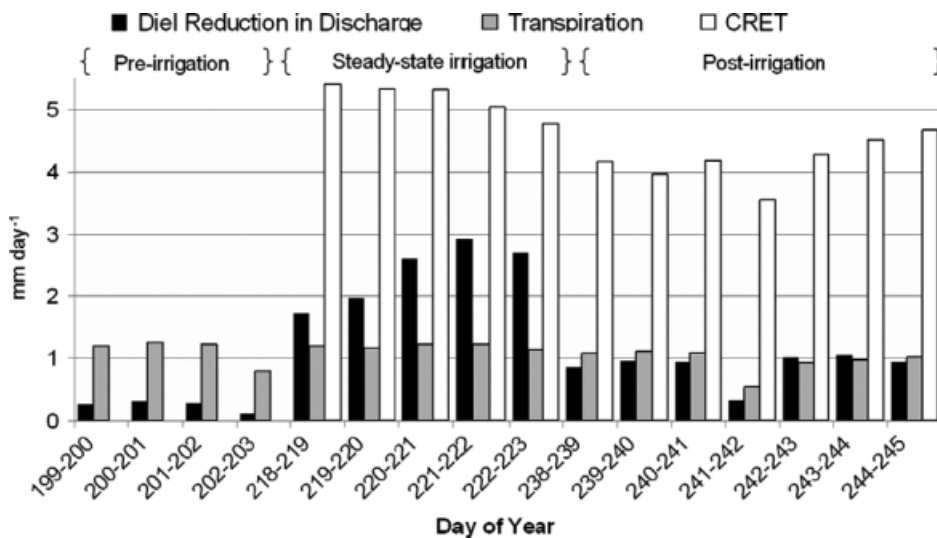

Figure 4. Total diel reduction in hillslope discharge (missing trenchflow), total daily hillslope transpiration and average daily canopy reference evapotranspiration for three irrigation periods.

to calculate hillslope-specific CRET for the pre-irrigation period; however, environmental data (temperature, relative humidity, and total solar radiation) from the HJA long-term meteorological sites suggest that CRET during this period was unlikely to differ greatly from post-irrigation period (data not shown).

Correlations between transpiration and hillslope discharge shifted through the experiment (Figure 5). Prior to irrigation, maximum transpiration was correlated ($r = -0.51$, $p < 0.01$) to minimum hillslope discharge with a 6·5-h time lag between the two variables. During the experiment at steady-state conditions, the correlation increased ($r = -0.89$, $p < 0.01$) and the time lag decreased to 4 h. For the 7-day period following irrigation, the time lag decreased further, with maximum

transpiration most highly correlated with minimum hillslope discharge 2 h later ($r = -0.86$, $p < 0.01$).

Soil moisture

Soil moisture increased rapidly in response to the onset of irrigation, with time lags at depth. Soil moisture in the upper 0·6 m of soil increased within the first 30 min of irrigation, whereas soil moisture in 0·6–0·9 m increased after 90 min, and below 0·9 m within 150 min. Soil moisture reached steady state within 5–6 days after irrigation was initiated (DOY 213–214), and steady-state conditions persisted until DOY 228, when the first of the sprinkler malfunctions caused an increase in soil moisture (Figure 2(D)). After irrigation ceased on DOY 232, the soil profile drained quickly for the first 8–12 h, followed
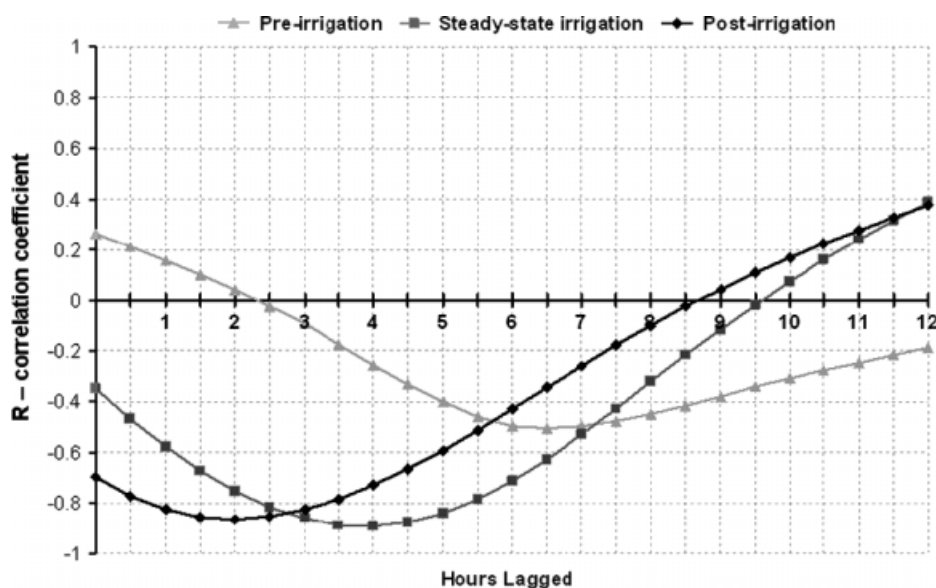
Figure 5. Phase (time lag) relationship between maximum transpiration and minmum hillslope discharge for three irrigation periods.

by a slower, more sustained water loss for the duration of monitoring.

Diel fluctuations in the soil moisture varied with soil depth and irrigation state. During the pre-irrigation period, the greatest fluctuations were at the 0·9–1·2 m depth where minimum soil moisture was 10% lower on average relative to the daily maximum (Figure 3). Diel fluctuations were present within 0·3–0·9 m as well, but were more damped. Diel fluctuations were not apparent during the steady-state period of the experiment (Figure 3). During steady state, minimum soil moisture for all depths was only 3% lower on average relative to their daily maximum. Post-irrigation diel fluctuations were 5–6% relative to the maximum with the upper 0·6 m being only slightly greater than the deeper soil.

DISCUSSION

Examining the link between transpiration and subsurface flow at the hillslope scale is necessary to further our understanding of the potential mechanisms that are likely to operate at the catchment scale. Irrigation experiments at the hillslope scale provide an opportunity to isolate the relationships between hillslope transpiration and runoff distinct from the complicating factors of riparian and instream processes. In addition, irrigation reveals transpiration-subsurface flow processes under controlled conditions that are difficult to capture for extended periods under natural conditions (e.g. prolonged soil saturation and rapid transition states).

By directly measuring hillslope discharge via a gauged trench at the hillslope–streambed interface, we observed time lags between maximum transpiration and minimum discharge on the hillslope scale that were similar to those reported by Bond et al. (2002) for the whole catchment scale in a nearby basin. In our study, pre-irrigation time lags were 6·5 h and lags during steady

state and post-irrigation were 4 and 2 h, respectively. These time lags correspond with measurements reported by Bond et al. (2002) for late July and June, respectively. The change in time lags we observed were not caused by increases in transpiration rate in response to soil moisture since these relatively high soil moistures were not limiting to transpiration. For the range of soil moisture conditions observed during this experiment, daily total transpiration remained relatively constant with the exception of reductions due to cloud cover. Wondzell et al. (2007) recently modelled the effects of stream flow velocity on time lags between transpiration and streamflow and found that as flow velocities decreased, time lags increased. Although increased flow velocity with increased soil moisture may be used to explain the shift in time lags from the pre-irrigation to the steady-state period, subsurface flow velocity is not likely to explain the shift to shorter lag times post-irrigation. The shortest time lag we measured (2 h) occurred post-treatment, not during the irrigation, when the highest flow velocities would be expected. While the result of shorter time lags after irrigation stopped is somewhat surprising, we postulate that the interaction of hillslope soil properties with tree roots under different moisture regimes are behind the variation in lag time.

Although total daily transpiration remained relatively constant throughout the irrigation experiment, the total amount of diel reduction in subsurface flow varied among the three irrigation periods. During the pre-irrigation period, transpiration exceeded the calculated amount of diel reduction in hillslope discharge. The average daily reduction in hillslope discharge was 17% of total daily transpiration. We propose two possible mechanisms to explain why transpiration would exceed the reduction in discharge. The first explanation corresponds with the conceptual model in Bond et al. (2002), which suggests that as soil moisture storage declines throughout rain-free periods, vegetation from locations farther upslope

become hydrologically disconnected from subsurface flow paths that contribute to discharge. As a result, only vegetation located in close proximity to the trench would influence diel fluctuations, so the rate of transpiration within the entire irrigation plot exceeds transpiration of the small zone of influence. A second explanation centers on the drainable pore space within the soil. In late July, the large-volume, fast-draining pore space within the shallow soil layers is generally air filled, and soil moisture within this area resides in small pore areas where it is tightly bound by adhesive and cohesive forces. While this tightly bound water is slow to move to the trench due to relatively low water potentials and low hydraulic conductivity in unsaturated soil, the water is available for uptake by roots located in this zone. Indeed, soil matric potentials in Douglas-fir stands have been known to reach values of -1200 kPa at shallow depths and -300 kPa at 1 m, while Douglas-fir roots can take up water at water potentials below -1500 kPa (Domec *et al.* 2004; Warren *et al.*, 2005; Brooks *et al.* 2006). This physical disconnection of water being taken up by trees versus water feeding subsurface flow, along with slow flow velocities at depth, may be responsible for the observed long lag times between transpiration and discharge.

During the steady-state irrigation period, the diel reduction in discharge was nearly double the daily total transpiration in the irrigated plot, suggesting potential limitations in the simple mass balance approach of the conceptual model advanced by Bond *et al.* (2002). The combination of very high soil moisture status and high ET during this period is unlikely to occur under natural conditions, but the experiment allowed us to identify mechanisms that would be difficult to observe otherwise. The diel reduction was likely larger than transpiration for several reasons: greater direct evaporation during the day and soil filling and draining processes. The CRET was on average seven times higher during the day compared to the night. The soil surface and understory vegetation were continually wet during the irrigation. Consequently, daytime evaporation greatly exceeded night time evaporation creating a greater diel reduction. Another reason for the large diel reduction in discharge was likely driven by the nonlinearity and hysteresis with filling and draining between soil water content and soil water potential. While the soils would be largely saturated during the irrigation period, preferential flow paths and heterogeneity within the soil would likely cause some areas to remain unsaturated where daily filling and draining processes could contribute to the diel reductions and lag times (Selker *et al.*, 1999). During the day, increased ET would reduce daily inputs and could allow for greater drainage and eventually reducing gravitational flow. At night when evaporative demand was lower, a greater proportion of irrigation inputs infiltrated into the soil, pores refilled, and ultimately subsurface flow and discharge increased. Because much of the soil pore volume was filled during steady-state irrigation, tree roots had a direct hydrologic connection to water that contributes to subsurface flow and discharge. This direct connection resulted in an apparent increased coupling between transpiration and discharge with time lags between the maximum transpiration and minimum hillslope discharge becoming much shorter than observed prior to irrigation. However, as a consequence to much of the soil pore volume being filled, hydraulic conductivity and flow velocity were both high and water within the profile was rapidly transmitted through the subsurface to the trench.

We observed the greatest coupling between transpiration and hillslope discharge in a 7-day period after irrigation. The time lag between maximum transpiration and minimum hillslope discharge was shortened to 2 h and the daily reduction in hillslope discharge was 90% of total daily transpiration. In our conceptual model of soil drainage, this period would correspond to large-volume soil pore space being fully drained while small pore volumes continue to contribute to discharge. Our conceptual model of soil drainage is consistent with measurements made of hillslope drainage by Harr (1977) at the same study site. Harr (1977) found a distinct decrease in hillslope discharge corresponding to the draining of larger soil pores 10 h after the end of natural rainfall events. We observed a rapid draining of the soil profile for 8–12 h after irrigation had stopped followed by a slower and more prolonged drainage for the duration of monitoring. Harr (1977) also observed that subsurface water flux was predominately in the vertical direction between rain events, in contrast to downslope flux during events. Tree roots intersecting these more slowly draining pore volumes are in direct competition with vertically draining water where soil-to-root water potential gradients work against the gravitational potential within the soil profile. Since a large proportion of the excess water in the hillslope has already drained, water losses via transpiration become even more apparent and coupled to the diel reduction in hillslope discharge. Presumably, this coupling would become progressively less pronounced (and time lags between maximum transpiration and minimum discharge longer) as the pore spaces within the rooting zone become air filled, and trees begin to rely on soil moisture within this area where water is very tightly bound by adhesive and cohesive forces. We conclude that the soil pore size distribution, hydraulic conductivity and the elevation gradient on the steep slope of the study site coupled with the ability of roots to take up water at low water potentials are responsible for the diel dynamics observed in hillslope discharge during the experiment.

CONCLUSIONS

A mechanistic understanding of the role forests play in controlling subsurface flow and streamflow patterns is needed to further our understanding of hydrologic processes in headwater catchments. This work represents one step forward in elucidating the linkages between vegetation water use and (sub) surface flow processes. By examining these linkages on an isolated hillslope that is lacking a riparian area, we have demonstrated the potential role

that hillslope vegetation plays in streamflow dynamics. In this paper, we found that transpiration on hillslopes plays an important role in diel variation in subsurface discharge. Although this role may be intuitive, this study is one of the first to quantify hillslope transpiration–stream discharge relationships. The amount of influence transpiration has on discharge is strongly dependent upon soil moisture properties and the greatest coupling of transpiration and discharge occurred after irrigation ended. During saturated conditions subsurface flow is characterized as a fast moving pool held at relatively weak matric tensions, making flow more subject to gravitational transport and preferential flow to streams when more water is added to the system. As soil moisture declines, water becomes more tightly bound to soil peds, and there is an increased likelihood that it will be taken up by plants rather than draining to the stream. Our study hillslope represents only one contributing unit to streamflow. Given the spatial heterogeneity of hillslope characteristics in watersheds, it is unlikely that transpiration signal inputs are synchronous at the watershed scale. Additional work is necessary to deconvolve hillslope, riparian, and in stream processes that contribute to diel fluctuations in low-order streams.

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