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Changes in hillslope hydrology in a perched, shallow soil system due to clearcutting and residual biomass removal

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Abstract

Sustainable fuels legislation and volatility in energy prices have put additional pressures on the forestry sector to intensify the harvesting of biomass for "advanced biofuel" production. To better understand how residual biomass removal after harvest affects forest hydrology in relatively low slope terrain, a Before-After-Control-Impact (BACI) study was conducted in the USDA Forest Service's Marcell Experimental Forest, Minnesota, USA. Hydrological measurements were made from 2010–2013 on a forested hillslope that was divided into three treatment blocks, where one block was harvested and residual biomass removed (Biomass Removed), the second was harvested and residual biomass left (Biomass Left), and the last block was left as an Unharvested Control. The pre-harvest period (2 years) was 2010–11 and post-harvest (2 years) was 2012–13. Water table elevation at the upslope and downslope position, subsurface runoff, and soil moisture were measured between May–November. Mixed effect statistical models were used to compare both the before-after and "control" treatment ratios (ratios between harvested hillslopes and the Unharvested Control hillslope). Subsurface runoff significantly increased ($p < .05$) at both harvested hillslopes but to a greater degree on the Biomass Left hillslope. Greater subsurface runoff volumes at both harvested hillslopes were driven by substantial increases during fall, with additional significant increases during summer on the Biomass Left hillslope. The hydrological connectivity, inferred from event runoff ratios, increased due to harvesting at both hillslopes but only significantly on the Biomass Left hillslope. The winter harvest minimized soil disturbance, resulting in no change to the effective hydraulic conductivity distribution with depth. Thus, the observed hydrological changes were driven by increased effective precipitation and decreased evapotranspiration, increasing the duration that both harvested hillslopes were hydrologically active. The harvesting of residual biomass appears to lessen hydrological connectivity relative to leaving residual biomass on the hillslope, potentially decreasing downstream hydrological impacts of similar forestry operations.

KEYWORDS
BACI, forest hydrology, forestry, Minnesota, perched water table, runoff, silviculture

1 | INTRODUCTION

The effects of forest harvesting on hydrology have been long documented, with studies going back as far as the late 1800s (Grip, 2015; Hibbert, 1967). Following forest harvesting, typical hydrological responses include increases in water yield/runoff and peak flow duration (Buttle, Webster, Hazlett, & Jeffries, 2019; Dung et al., 2012; Dung, Hiraoka, Gomi, Onda, & Kato, 2015; Monteith et al., 2006; Moore & Wondzell, 2005; Schelker, Kuglerová, Eklöf, Bishop, & Laudon, 2013). These effects are largely driven by soil compaction, decreased transpiration, and increased effective precipitation, which enhance runoff from uplands to downgradient aquatic and wetland systems (Buttle, Creed, & Moore, 2009; Moore & Wondzell, 2005; Thompson, Devito, & Mendoza, 2018). The increased runoff typically results in higher suspended sediment loads and changes in downstream solute yields (Ampoorter, de Schrijver, van Nevel, Hermy, & Verheyen, 2012; Eklöf, Lidskog, & Bishop, 2016; Oda et al., 2018; Vance et al., 2018). These impacts potentially lead to the degradation of aquatic and wetland habitats, resulting in a loss of ecosystem services at local and watershed scales (Pohjanmies et al., 2017; Tahvonen, Rämö, & Mönkkönen, 2019). Underpinning these broader landscape impacts are the changes to hillslope runoff generation processes. Thus, it is critical to properly assess changes in hydrology at the hillslope scale to better contextualize environmental impacts resulting from forest harvesting.

Hillslope hydrology is governed by slope, vegetation cover, soil type, macropore density, soil depth and stratigraphy, as well as climate and underlying geology (Dung et al., 2012; Moore & Wondzell, 2005; Vance et al., 2018; Weiler, 2017; Ziegler, Negishi, Sidle, Noguchi, & Nik, 2006). Forest harvesting leads to a number of important hydrological changes that are particularly apparent at the hillslope scale. For example, the heavy machinery used in commercial forestry operations can disturb the soil through compaction and the creation of ruts (Ebeling, Lang, & Gaertig, 2016; Holub, Terry, Harrington, Harrison, & Meade, 2013). These disturbances alter the partitioning of water between surface runoff and infiltration, often generating increased overland flow events and surface erosion (Buttle et al., 2019; Ebeling et al., 2016; Schelker et al., 2013; Sørensen et al., 2009). Soil disturbance and compaction can be mitigated if harvesting occurs during the winter on frozen soils (Kolka, Steber, Brooks, Perry, & Powers, 2012). Large reductions in transpiration and interception due to the removal of the overstory canopy (Dung et al., 2012; Ide, Finér, Laurén, Piirainen, & Launiainen, 2013; Thompson et al., 2018) leads to a surplus of soil moisture, resulting in higher water tables and increased runoff generation (Buttle et al., 2019; Dung et al., 2012; Ide et al., 2013; Thompson et al., 2018). These hydrological effects can last for several years to tens of years, depending on the local hydroclimatic conditions and the regeneration rate of the forest (Buttle et al., 2018; Buttle, Oswald, & Woods, 2005; Ebeling et al., 2016; Moore & Wondzell, 2005; Oda et al., 2018; Thompson et al., 2018).

In North America, residual biomass is typically left on site in an effort to retain nutrients for regrowth, but in recent years, there has been more interest in residual biomass harvesting (Dirkswager, Kilgore, Becker, Blinn, & Ek, 2011; Yemshanov et al., 2014). Residual biomass is commonly comprised of branches, treetops, and other organic matter that is not suitable for timber or pulp production, and can be used as renewable biofuels for power generation (Dirkswager et al., 2011; Yemshanov et al., 2014). Removal of residual biomass may alter ecosystem services or the function of certain environmental processes (Dirkswager et al., 2011; Hakkila, 1989; Janowiak & Webster, 2010; Vance et al., 2018; Yemshanov et al., 2014; Yemshanov, McKenney, Hope, & Lempiere, 2018). The added heavy machinery traffic associated with residual biomass removal can lead to greater soil disturbance and increased runoff generation (Ampoorter et al., 2012; Vance et al., 2018). However, depending on the harvesting techniques (e.g., winter harvest), these effects can be minimized (Labelle & Jaeger, 2011; Vance et al., 2018). Additionally, the removal of residual biomass can decrease wildfire risk because it reduces potential fuel load and increases habitat for herbaceous understory vegetation (Nakamura, 1996; Vance et al., 2018). Residual biomass harvesting also increases the amount of incoming solar radiation reaching soil (Mazur et al., 2014) and can alter the atmospheric mixing at the soil-atmosphere boundary (Runyan, D'Odorico, & Lawrence, 2012; Sun et al., 2001), typically increasing soil evaporation (Buttle & Murray, 2011; Runyan et al., 2012). However, there remain few experimental studies comparing hydrological effects, such as runoff generation, between sites where residual biomass is harvested or not, particularly at the hillslope scale.

Although changes to post-harvesting hydrological processes are known to occur, there is limited information on the direction and magnitude of these responses on the relatively low slope hillslopes that cover large areas of northern, post-glacial latitudes where forest management is widespread and vital to local and regional economies (P. C. Bates, Blinn, Alm, & Perala, 1989; Perala & Verry, 2011). Using a full Before-After-Control-Impact (BACI) hillslope experimental manipulation design, we aimed to (a) compare the hydrological impacts of residual biomass removal following clearcutting with no residual biomass removal and (b) elucidate the governing hydrological mechanism(s) driving changes in hillslope runoff dynamics due to these harvesting practices.

2 | METHODS

2.1 | Study site, experimental design and harvest

We studied a north-facing hillslope of the S7 headwater watershed at the USDA Forest Service's Marcell Experimental Forest (MEF) in north-central Minnesota (47° 31′ 21″ N, 93° 28′ 7″ W) (Sebestyen et al., 2011). The MEF is located in a sub-humid continental climate with an average daily temperature of 4.2°C and annual precipitation of approximately 780 mm, of which 156–195 mm falls as snow water equivalent (Sebestyen et al., 2011). The hillslope overstory vegetation was primarily comprised of sugar maple (*Acer saccharum*), trembling aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), and balsam poplar (*Populus balsamifera*). The study site has a mean slope of ~18°

and mean slope length (ridge to peatland) of ~55 m (Figure 1), which is a relatively high slope in the low topographic relief setting of the surrounding area.

The north-facing hillslope was delineated into three adjacent hillslope plots (Biomass Removed hillslope, Biomass Left hillslope, and Unharvested Control hillslope), each draining through a separate trench that collected subsurface runoff at the toe slope landscape position (Figure 1). The organic horizon in the soil profile is relatively shallow (generally <2 cm) with little year-to-year litter persistence due to consumption by invasive earthworms (Hale, Frelich, & Reich, 2005; Holdsworth, Frelich, & Reich, 2008). Soils are composed of an upper, permeable loess sandy loam horizon with a mean depth of 50 ± 27 cm and vertical hydraulic conductivity of between 4×10^{-3} and 1×10^{-6} cm s^{-1} over low-permeability Koochiching clay loam till, with a vertical hydraulic conductivity of approximately 5×10^{-7} cm s^{-1} (Mitchell, Branfireun, & Kolka, 2009; Verry, Brooks, Nicholas, Ferris, & Sebestyen, 2011). The sandy loam had an average depth of 45 ± 21, 46 ± 24 and 58 ± 35 cm for the Biomass Removed, Biomass Left and Unharvested Control hillslopes, respectively (Haynes & Mitchell, 2012). Overland flow on these hillslopes can occur after snowmelt and large rainfall events, yet overland flow was almost never observed and only rarely during snowmelt when soil frost limited the downward percolation of water (Haynes & Mitchell, 2012). The low-permeability till precludes most deep vertical percolation, leading to the development of a shallow perched groundwater system, resulting in saturated throughflow downslope (Nichols & Verry, 2001). Elsewhere on the MEF, overland flow is a small fraction (~10%; Kolka, Grigal, Nater, & Verry, 2001) of the annual runoff (subsurface stormflow plus overland flow) from uplands to peatlands.

The study began April 1, 2010 and ended November 20th, 2013. The experimental design follows a BACI approach wherein all hillslopes were simultaneously monitored for nearly 2 years (April 2010 through March 2012) before any harvest, and again for approximately 1.75 years after harvest (April 2012 through November 2013).

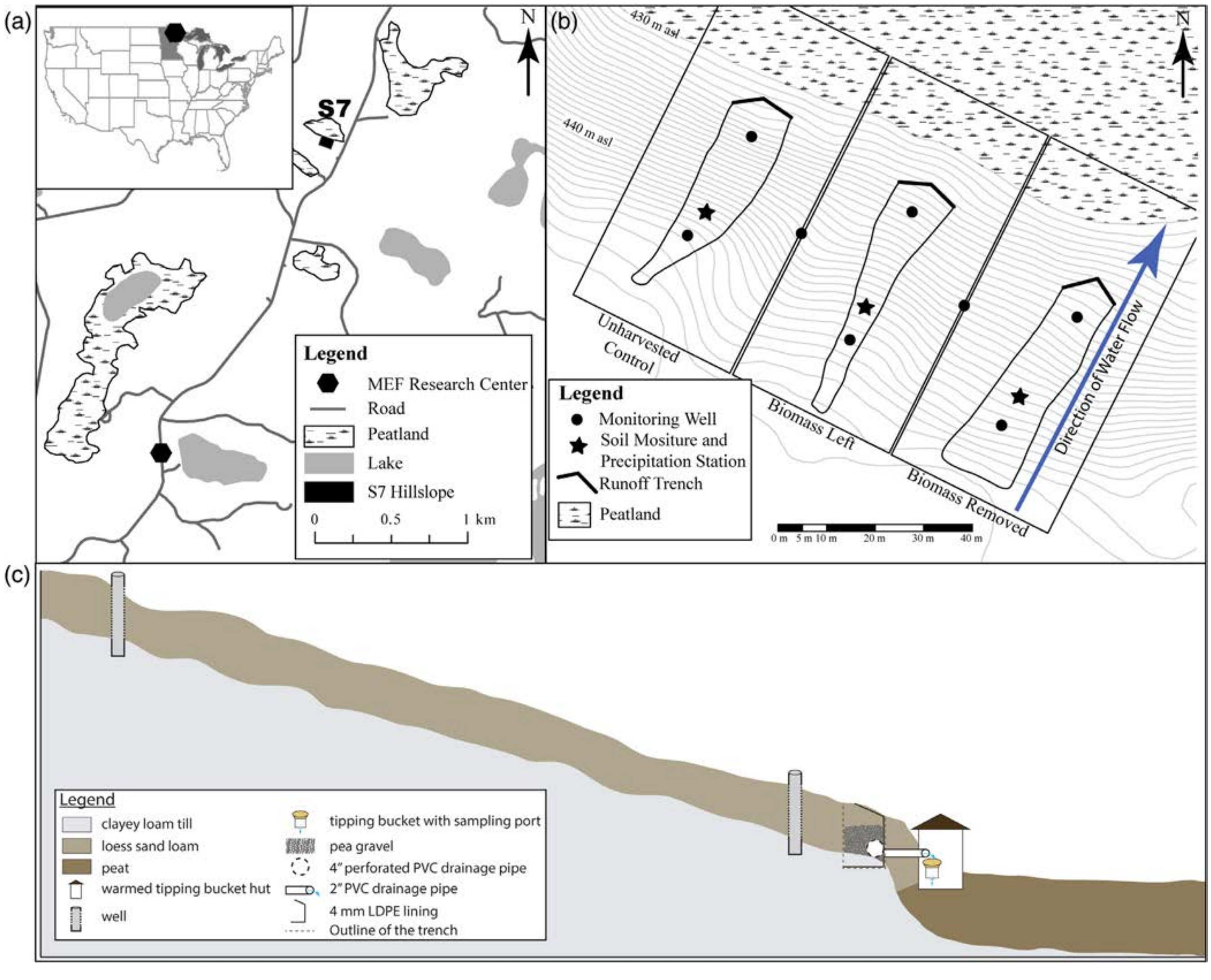

FIGURE 1 (a) Study site location; (b) map of study site and monitoring equipment; (c) a schematic of a runoff trench, monitoring wells and hillslope topography for one hillslope plot

TABLE 1 Density of fine and coarse woody debris (kT ha^{-1}) on each hillslope before and after harvesting from Mazur et al. (2014)

Debris type	Treatment period	Biomass removed	Biomass left	Unharvested control
Coarse Woody Debris (CWD)	Before	94.7	94.6	105.5
	After	105.4	220.9	105.5
Fine Woody Debris (FWD)	Before	89.8	121.8	191.6
	After	164.3	468.2	191.6

During the "Before" portion of the BACI design, relationships among hillslopes for various hydrological measurements (subsurface runoff rates, soil moisture and water table elevations) were established. In March 2012, two of the three hillslopes were mechanically clearcut over frozen soils with relatively shallow snow cover. One forested plot was maintained as the Unharvested Control hillslope. On one of the harvested hillslope areas, approximately 85% of residual biomass was removed both by machine and then additionally by hand after forest harvesting (Biomass Removed). Residual biomass was left on the forest floor at the other harvested hillslope (Biomass Left). Mazur et al. (2014) reported both the coarse (diameter > 7.6 cm) and fine (diameter < 7.6 cm) woody debris pre- and post-harvest at all hillslopes (Table 1). During the "After" period, relationships for hydrological measurements among hillslopes were again examined, specifically Biomass Removed and Biomass Left both in relation to the Unharvested Control, leading to treatment ratios between "Impacted" hillslopes and the "Control" hillslope. By examining differences in treatment ratios between Before and After periods, impacts related to forest harvesting can be isolated from, for example, inter-annual variations in climate.

2.2 | Site hydrology

Hydrological instrumentation was installed in 2009 and monitored between 2010 to 2013. No measurements were made while frozen soils persisted at the site, typically early November – April. Three throughflow collection trenches were constructed, one per hillslope, during the summer of 2009 approximately 20 m apart from one another at the toe slope position of the hillslope that transitions to a peatland (Figure 1). The three 10 m wide broad-V-shaped trenches were dug by machine to the base of the permeable loess sandy loam horizon and lined along the bottom, downslope side, and top with thick (4 mm) plastic sheeting (Figure 1). Perforated drainage pipe was laid along the bottom of the trench and connected in a Y-junction to 5 cm diameter PVC pipe, which exited the down-gradient side of the trench apex. Each trench was half back-filled with washed pea gravel, with the remainder of the trench back-filled with native soil. The V-shape was preferable for ensuring gravity-driven drainage to a single collection point at the lowest point of a trench. There were no signs of leakage around or below the trenches. A few metres downslope of a trench, a small wooden shelter housed a large tipping-bucket style flow meter, to which the PVC drainage pipe was connected. The flow meter tips at 0.1 L intervals and was digitally recorded using an event-type pendant datalogger (Pendent Event Data Logger, HOBO, Bourne, MA). During the spring and fall seasons, a propane fueled lamp in each shelter prevented nighttime freezing of the flow meter. The contributing area to each trench was calculated by assuming that the topography of the boundary between the loess sandy loam and Koochiching clay loam till determined the direction of subsurface flow. Haynes and Mitchell (2012) previously measured contributing areas to the trenches at this site through detailed and georeferenced soil depth mapping to the boundary between the loess sandy loam and Koochiching clay loam till (>100 point measurements) and overlay onto a LiDAR-derived digital elevation model. Contributing areas draining the Biomass Removed, Biomass Left, and Unharvested Control hillslopes were estimated as 437, 339 and 439 m^2, respectively.

Perched water table positions and hydraulic gradients were measured using six wells screened along their full lengths and installed to the loess sandy loam-till clay loam boundary. Two wells were installed in each plot, one upslope and one downslope at the runoff trench (Figure 1). A datalogging (15-min intervals) pressure transducer (S-BPB-CM50, HOBO, Bourne, MA) was installed in each well and corrected for changes in barometric pressure using records from a digital barometer located onsite. The elevation of the wells were surveyed annually using a laser-sighted total station verify well elevation.

Soil moisture was measured at 15-minute intervals at the midslope of each plot (Figure 1) using EC5 soil moisture sensors (Decagon Devices, Pullman, WA) installed approximately 5 cm above the Koochiching clay loam till at each hillslope and attached to Hobo data loggers. Where the soil moisture probes were installed, the depth to the Koochiching clay loam till was 32, 44 and 103 cm at the Biomass Removed, Biomass Left and Unharvested Control hillslopes, respectively.

Bulk precipitation was recorded from a nearby (~1 km) precipitation gauge without canopy cover maintained at the south MEF station (south_PCP) (Sebestyen et al., 2020). There were minimal differences between the bulk precipitation at the MEF station and post-harvest at the Biomass Removed hillslope (Figure S1). The failure of the datalogger on the Unharvested Control hillslope resulted in no precipitation or soil moisture measurements on that hillslope. This equipment failure on the Unharvested Control hillslope limited inferences on changes in precipitation interception and soil moisture due to harvesting practices.

2.3 | Hydrological parameters

The event runoff ratios (RR_e) were determined for each precipitation event outside of the snowmelt period (May – November) by,

$$RR_e = \frac{R_e}{P_e}, \tag{1}$$

where, R_e (mm) is the total event runoff for an event and P_e (mm) is the total liquid precipitation for an event. The start of a given runoff event was determined by the onset of precipitation, while the end of a given runoff event was determined when the change in runoff during the recession limb was either near or at pre-event conditions and the change in runoff was <0.1 mm day^{-1} for two consecutive days prior to a second precipitation event. Given that the hillslope does not have any baseflow, the typical event end was when runoff was near or at zero.

Effective hydraulic conductivity (K_{eff}, m day^{-1}) was assessed as,

$$K_{eff} = \frac{Q}{iA}, \tag{2}$$

where, Q is the subsurface runoff collected in each trench (m^3 day^{-1}), i is the hydraulic gradient between the upslope and downslope monitoring wells (–), and A is the area of the loess sandy loam-till clay loam trench face (m^2). Initial exploration of the high temporal resolution data (15-min averaging intervals) did not produce systematic differences from daily data, thus the daily data was used for the calculation of K_{eff}. Plotting K_{eff} versus the depth of water table at the lower slope well gives the effective hydraulic conductivity profile. Any large deviations from this profile between pre- and post-harvesting would suggest structural changes to the bulk soil hydraulics.

2.4 | Statistical analysis

To statistically assess the impact of harvesting and residual biomass removal, the hydrological measurements and parameters at the Biomass Removed and Biomass Left hillslopes were normalized to the Unharvested Control hillslope through the calculation of a treatment ratio (*TR*) (Conner, Saunders, Bouwes, & Jordan, 2016),

$$TR = \frac{y_i}{y_{UH}}, \tag{3}$$

where, y_i is a given measurement for either the Biomass Removed or Biomass Left hillslopes and y_{UH} is the temporally-paired measurement at the Unharvested Control hillslope.

The *TR* for each individual measurement or derived parameter (runoff, event runoff ratio, water table gradient, soil moisture, and K_{eff}) was then used as the dependent variable in mixed effect models to assess statistical differences among experimental manipulations. Due to the equipment failure at the Unharvested Control hillslope, the treatment ratio of soil moisture could not be determined and the daily average soil moisture from both treatment hillslopes were used as the dependent variable. To assess the overall treatment effect, the data was grouped by treatment period, either pre- or post-harvest,

$$y_{TR} = per * tre + (1|Date), \tag{4}$$

where, $y_{TR}$is the treatment ratio (or average daily soil moisture) of a given measurement or derived parameter, *per* is the treatment period (pre- or post-harvest), *tre* is the treatment hillslope (either Biomass Removed or Biomass Left) and *Date* is the date of measurement. To elucidate the seasonal effects, a third interaction term was added to Equation (4),

$$y_{TR} = per * tre * sea + (1|Date), \tag{5}$$

where, *sea* is the season of measurement (spring, summer and fall). To ensure the residuals of each mixed effect model were normally distributed, the natural log of the *TR* was assessed. To account for temporal correlation between measurements, the date of measurement was used as the random effect in all models. All models were generated in R Statistical Software (R Development Core Team, 2018) using the *lmer* function in the *lme4* package (D. Bates, Maechler, Bolker, & Walker, 2015; Pinheiro, Bates, DebRoy,, & Team RDC, 2018). The resultant least-squares means were then compared using the post-hoc Tukey test (Lenth, 2016) to determine the statistical differences among treatment sites (Biomass Removed hillslope and Biomass Left hillslope), treatment periods (pre- and post-harvest), and seasons (spring, summer, and fall).

3 | RESULTS

3.1 | Hydrological parameters pre- and post-harvest

Though the impact of forest harvesting is best discerned from the treatment ratios, an examination of hydrological values from a more simplified Before-After standpoint can help in comparing with other studies. The annual liquid rainfall varied from 475 to 686 mm during the study period (Table 2), with 2013 having the lowest liquid rainfall (475 mm) and 2010 the most (686 mm) (Figure 2). All runoff reported here is subsurface runoff and no surface runoff was observed during the study. Among the hillslopes, the annual study period subsurface runoff varied substantially (52–149 mm) and did not follow the trends in precipitation (Table 2). Average runoff increased (Table 2) by 140% (Biomass Left) and 151% (Biomass Removed) following harvesting and residual biomass removal, respectively. Peak runoff during precipitation events also increased at both hillslopes post-harvest with the Biomass Left hillslope having greater peak runoff than Biomass Removed (Figure 2). There was large inter-annual variability in annual runoff ratios, with 2013 having the highest runoff ratios (0.16–0.26) and 2010 the lowest (0.07–0.10) (Table 2). This inter-annual variability masked the treatment effects when a simple comparison among hillslopes was used (Figure 2 and Table 2). The annual average event runoff ratios were variable on all hillslopes, with no discernable trends due to harvesting (Table 2).

TABLE 2 Annual total or average (± one *SD*) hydrological parameters for each site

Site	Year	Precipitation [mm]	Runoff [mm]	Annual runoff ratio [–]	Event runoff ratio [–]	Upslope water table [m asl]	Downslope water table [m asl]	Number of days with no water table [days]	K_{eff} [m day^{-1}]
Biomass removed	2010	686	52	0.07	0.06 (0.05)	440.94 (0.13)	433.01 (0.14)	236 (0.98)	0.6 (0.09)
	2011	633	83	0.13	0.09 (0.13)	440.88 (0.08)	432.89 (0.20)	128 (0.98)	0.8 (0.16)
	2012	618	96	0.13	0.06 (0.06)	440.98 (0.16)	432.83 (0.23)	135 (1.23)	0.14 (0.21)
	2013	475	108	0.23	0.06 (0.04)	440.92 (0.11)	432.82 (0.19)	142 (1.75)	0.11 (0.14)
Biomass left	2010	686	62	0.09	0.06 (0.06)	439.59 (0.16)	431.18 (0.09)	150 (0.63)	0.6 (0.12)
	2011	633	133	0.21	0.05 (0.09)	439.50 (0.13)	431.16 (0.07)	71 (0.55)	0.16 (0.82)
	2012	618	149	0.20	0.09 (0.09)	439.49 (0.10)	431.21 (0.12)	119 (1.08)	0.66 (2.03)
	2013	475	124	0.26	0.11 (0.09)	439.54 (0.15)	431.18 (0.09)	82 (1.01)	0.19 (0.45)
Unharvested control	2010	686	70	0.10	0.08 (0.05)	438.25 (0.15)	429.59 (0.16)	240 (–)	0.08 (0.11)
	2011	633	128	0.20	0.08 (0.09)	438.14 (0.11)	429.44 (0.19)	130 (–)	0.07 (0.09)
	2012	618	109	0.13	0.07 (0.07)	438.18 (0.16)	429.47 (0.27)	110 (–)	0.06 (0.09)
	2013	475	78	0.16	0.04 (0.04)	438.12 (0.07)	429.36 (0.15)	81 (–)	0.11 (0.11)

Note: Pre-harvest: 2010 and 2011, Post-harvest: 2012 and 2013. For the "Number of days with no water table" the value in brackets indicates the treatment ratio (i.e., the number of days observed divided by the number of days observed at the Unharvested hillslope).

The average of and variation in the annual upslope and downslope water tables were similar across both hillslopes (Table 2). Similar to the annual values, both water tables had comparable temporal variability at all hillslopes pre-harvest (Figure 3). Post-harvest, maximum event water table elevations at both the upslope and downslope positions increased relative to pre-harvest (Figure 3). There was a large increase in the number of days the water table was absent from the hillslope at both treatment hillslopes when comparing treatment ratios (Table 2). Lower total annual precipitation during 2013 compared to 2010–12 resulted in a greater number of normalized days of the water table being absent from the hillslope for the Biomass Removed treatment but this trend was not apparent at the Biomass Left hillslope (Table 2). Post-harvest, there was less response in hydraulic gradients to precipitation events at both treatment hillslopes, while the response at the Unharvested Control hillslope remained similar to the pre-harvest period (Figure 3). The average annual K_{eff} noticeably and systematically increased due to harvest (Table 2 and Figure 4).

The response to harvesting on the soil structure can be determined through analysis of the K_{eff} profiles and soil moisture. Forest harvesting did not influence the spread or shape of the K_{eff} profile (Figure 5), rather it changed the timing and magnitude of the K_{eff} response, increasing peak K_{eff}, similar to runoff (Figure 4). At all hillslopes there were clear deviations from the exponential decline in K_{eff} at deep water tables and/or low K_{eff} (Figure 5).

Forest harvesting had a differential response on soil moisture approximately 5 cm above the Koochiching clay loam till, depending on residual biomass removal (Figures 6 and S2). Compared to pre-harvest, soil moisture in the Biomass Removed hillslope significantly increased ($p < 0.0001$) over the snow-free seasons, whereas in the Biomass Left hillslope, soil moisture became more temporally variable and overall significantly drier ($p < .0001$) (Figure 6 and Table S1). However, the failure of the soil probes at the Unharvested Control hillslope throughout the study and Biomass Left hillslope in 2010 prevented more rigorous statistical testing and only general comparisons are presented here.

3.2 | Before-after-control-impact analysis

The examination of the treatment ratios allows for a clearer understanding of how different harvesting practices affect hillslope runoff generating processes. When treatment ratios are calculated for hydrological parameters observed at the harvested hillslopes as a time-matched ratio to observations at the Unharvested Control hillslope, it becomes more apparent that forest harvesting, regardless of residual biomass removal, impacted the hydrology of the hillslopes. The magnitude of runoff increased with forest harvesting. Average runoff treatment ratios significantly increased at both harvested hillslopes (Figure 7a, Tables S2 and S3). However, the relative increase in runoff on the Biomass Removed hillslope was less than observed on the Biomass Left hillslope (Figure 7a, Tables S2 and S3). When the residual biomass was removed, the overall increase in runoff treatment ratio was due to a significant increase in runoff during the fall, whereas on the Biomass Left hillslope, there were significant increases in runoff during both the summer and fall (Figure 8a, Tables S4 and S5). In both cases there was no significant difference in the spring runoff treatment ratios (Figure 8a, Tables S4 and S5). When event-scale runoff ratios were examined as treatment ratios, increases were apparent post-harvest at both harvested hillslopes (Figure 7d, Tables S2 and S3). Event scale runoff ratios significantly increased during the fall at both harvested hillslope and at the Biomass Left hillslope in the summer (Figure 8d, Tables S4 and S5). There was no significant change in treatment ratios during the summer at the Biomass Removed hillslope, nor the spring on either harvested hillslope (Figure 8d, Tables S4 and S5).

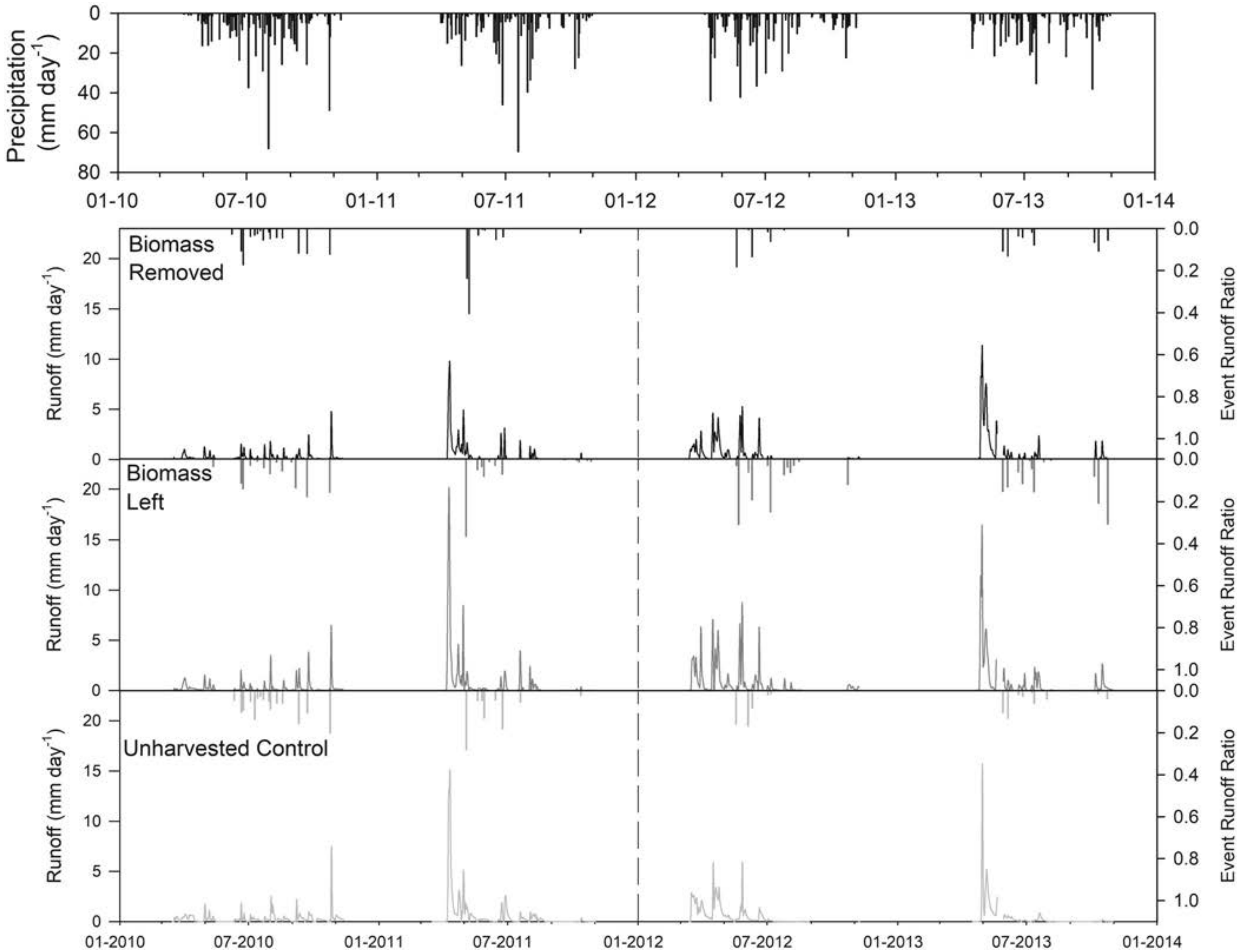

FIGURE 2 Timeseries of runoff and event runoff ratios at the Biomass Removed, Biomass Left, and Unharvested Control hillslopes, as well as precipitation from April 2010 until November 2013. Left of the dashed line indicates pre-harvest, while right of the dashed line indicates post-harvest

The treatment ratios of the hydraulic gradients significantly, but differentially, changed with harvesting practice (Figure 7c, Tables S2 and S3). At both treatment hillslopes, the overall magnitude of the hydraulic gradient treatment ratio response to precipitation events decreased post-harvest. At the Biomass Removed hillslope, there was an increase in the hydraulic gradient treatment ratios, whereas on the Biomass Left hillslope the hydraulic gradient treatment ratios decreased (Figure 7, Tables S2 and S3). The changes in these ratios were driven by a differential response in water tables at the different slope positions. At the Biomass Removed hillslope, the upslope water table typically increased, while there was not a proportional change in the downslope water table (Figure 3). The changes or lack thereof in water table elevations drove the observed increase in hydraulic gradient treatment ratio (Figures 7c and 8c). At the Biomass Left hillslope, there was an increase in the downslope water table but no proportional change in the upslope table (Figure 3), leading to the decrease in hydraulic gradient treatment ratio (Figures 7c and 8c). These trends were broadly observed over the course of treatment periods, but some seasonal differences were also apparent between treatments. At the Biomass Left hillslope, only the hydraulic gradient treatment ratios during the summer were significantly lower, while in the fall the hydraulic gradient treatment ratios were lower but not significantly (Figure 8c, Tables S4 and S5). No change was observed during the spring at the Biomass Left treatment (Figure 8c, Tables S4 and S5). At the Biomass Removed hillslope, there was significantly higher hydraulic gradient treatment ratios during all seasons post-harvesting (Figure 8c, Tables S4 and S5).

The K_{eff} treatment ratios did not increase on the Biomass Removed hillslope, whereas on the Biomass Left hillslope, the K_{eff} treatment ratios significantly increased post-harvest (Figure 7b, Tables S2 and S3). The increase in K_{eff} treatment ratios on the Biomass Left hillslope was due to a large increase in the summer runoff and associated higher water tables (Figure 8b, Tables S4 and S5). There were slight decreases in K_{eff} treatment ratios during the spring and fall on the Biomass Left hillslope (Figure 8b, Tables S4 and S5). Although there was no statistical difference in K_{eff} treatment ratios on

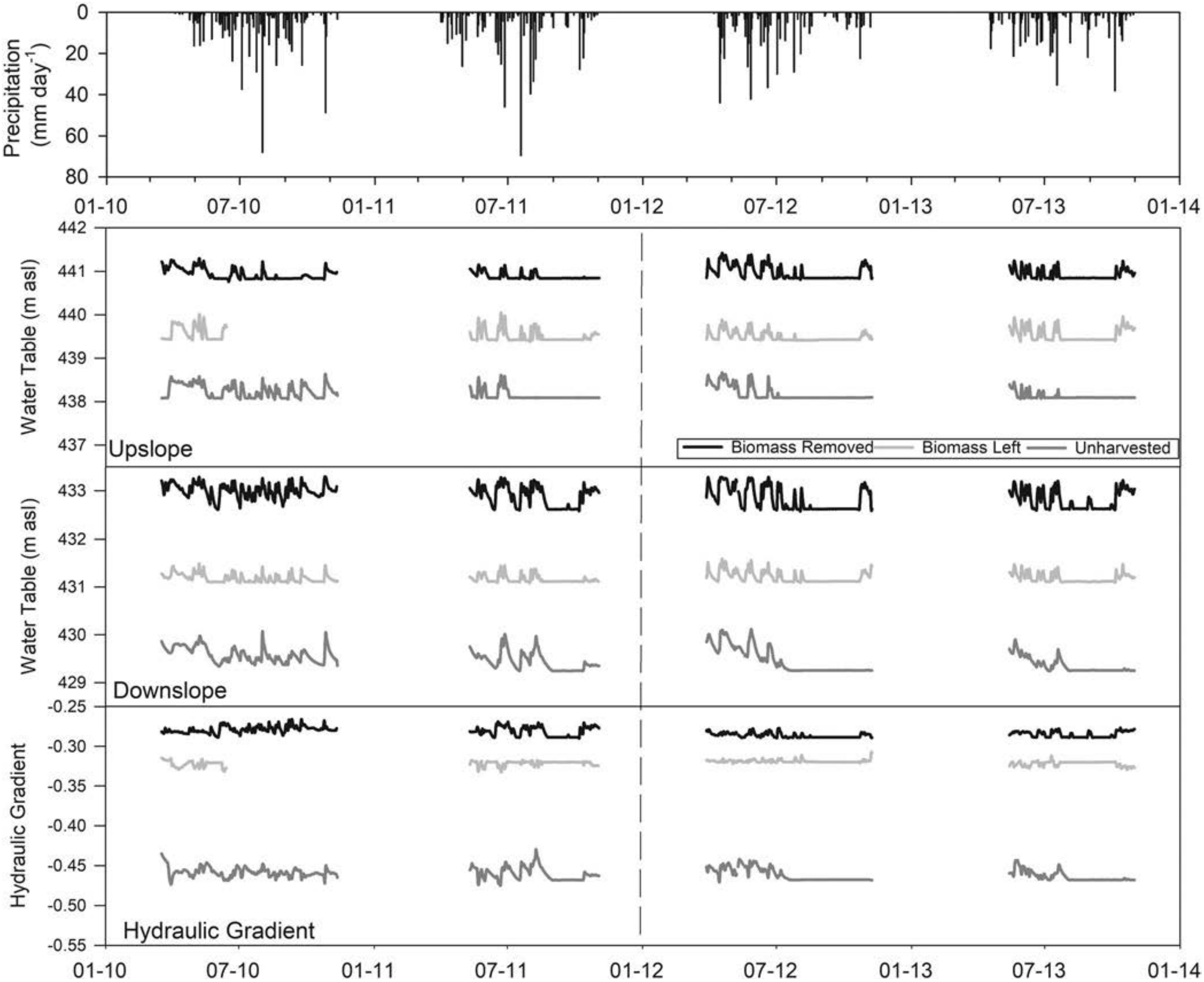

FIGURE 3 Timeseries of the upslope and downslope water tables (m asl), and hillslope hydraulic gradients at the Biomass Removed, Biomass Left, and Unharvested Control hillslopes, as well as precipitation from April 2010 until November 2013. Left of the dashed line indicates pre-harvest, while right of the dashed line indicates post-harvest. Note, at Biomass Left hillslope after July 2010 to May 2011 data are missing due to equipment failure

the Biomass Removed hillslope, an inverse pattern to Biomass Left hillslope was apparent (Figure 8b, Tables S4 and S5); increasing during the spring and decreasing in the summer and fall (Figure 8b, Tables S4 and S5).

4 | DISCUSSION

Regardless of the experimental treatment in this study, subsurface runoff significantly increased post-harvesting. The increase in subsurface runoff was driven both by increases in the total time the hillslopes generated runoff and by greater runoff amounts during precipitation events (i.e., larger event runoff ratios). Event runoff ratios significantly increased post-harvest during the summer and fall for the Biomass Left hillslope, while only during the fall at the Biomass Removed hillslope. There were not significant differences at either hillslope during the spring. The apparent but not necessarily significant increase in event runoff ratio in all seasons for the Biomass Removed hillslope agrees with the muted runoff response relative to when residual biomass remained on the hillslope following harvest. The increase in event runoff ratio due to harvesting indicates that less water was partitioned to evapotranspiration or interception and more runoff water was transmitted downslope during precipitation events. The increase in event runoff ratio at both harvested hillslopes, regardless of the muted response for Biomass Removed treatment, suggests that the decrease of canopy interception capacity and evapotranspiration losses (Breña Naranjo, Weiler, & Stahl, 2011; Dung et al., 2012; Moore & Wondzell, 2005) resulting from either harvesting practice were the dominant controls on runoff processes.

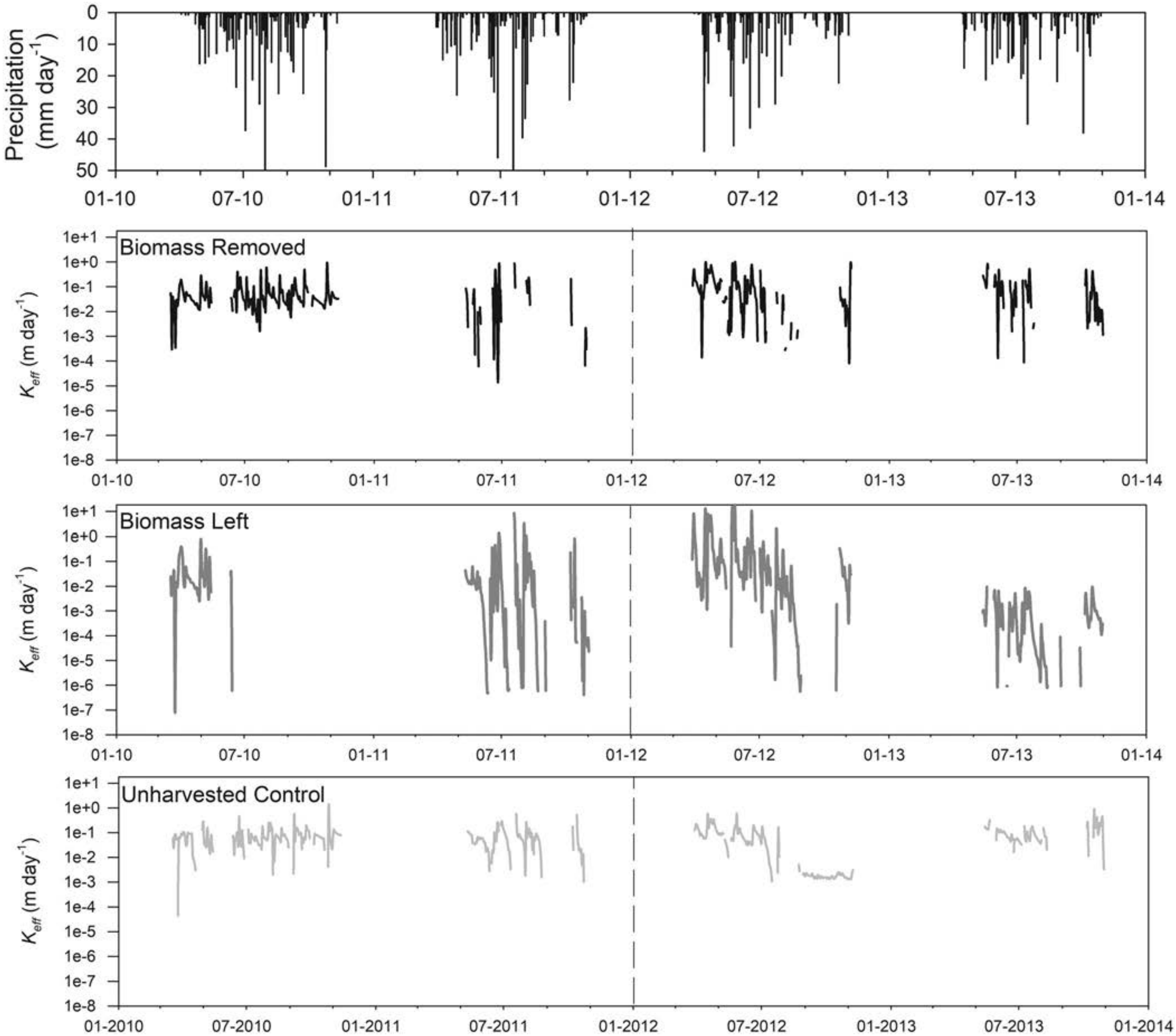

FIGURE 4 Timeseries of K_{eff} at the Biomass Removed, Biomass Left, and Unharvested Control hillslopes, as well as precipitation from April 2010 until November 2013. Left of the dashed line indicates pre-harvest, while right of the dashed line indicates post-harvest

At all hillslopes, there was a clear deviation from the expected exponential decline in K_{eff} at low water table depths, indicating potential periods of preferential flow that are associated with hillslope runoff processes, as previously discussed by Seibert, Bishop, Rodhe, and McDonnell (2003) and Weiler and McDonnell (2007). Based on the steepness of the K_{eff} profiles between hillslopes, the near vertical profile (i.e., K_{eff} remains relatively constant over large water table changes) for the Biomass Removed hillslope would suggest a greater water table response for a given runoff event. That is, a proportionately greater rise in water table would be required to activate the higher hydraulic conductivity upper layers than a steep K_{eff} profile. Alternatively, the steeper profile at the Biomass Left hillslope, coupled with shallower soils at the trench would saturate the higher conductivity near-surface soil layers with a proportionally smaller water table rise. Although this trend was generally observed on all hillslopes it was not consistently observed. This inconsistent response suggests preferential flow through macropores in addition to higher conductivity near-surface soil layers.

Though we lack soil moisture data for the Unharvested Control, correlations between moisture content and both water table elevation and K_{eff} at the treatment hillslopes were insignificant. Binning soil moisture at the sites into quartiles did not improve our interpretation significantly, though a lower and upper quartile-biased upward trend between soil moisture and both water table elevation and K_{eff} at the Biomass Left hillslope was observed. Finally, we also considered antecedent precipitation index as a driver but only found, at best, weak relationships with other parameters (e.g., $R^2 < 0.26$), with significant scatter and a small number of larger values leveraging the

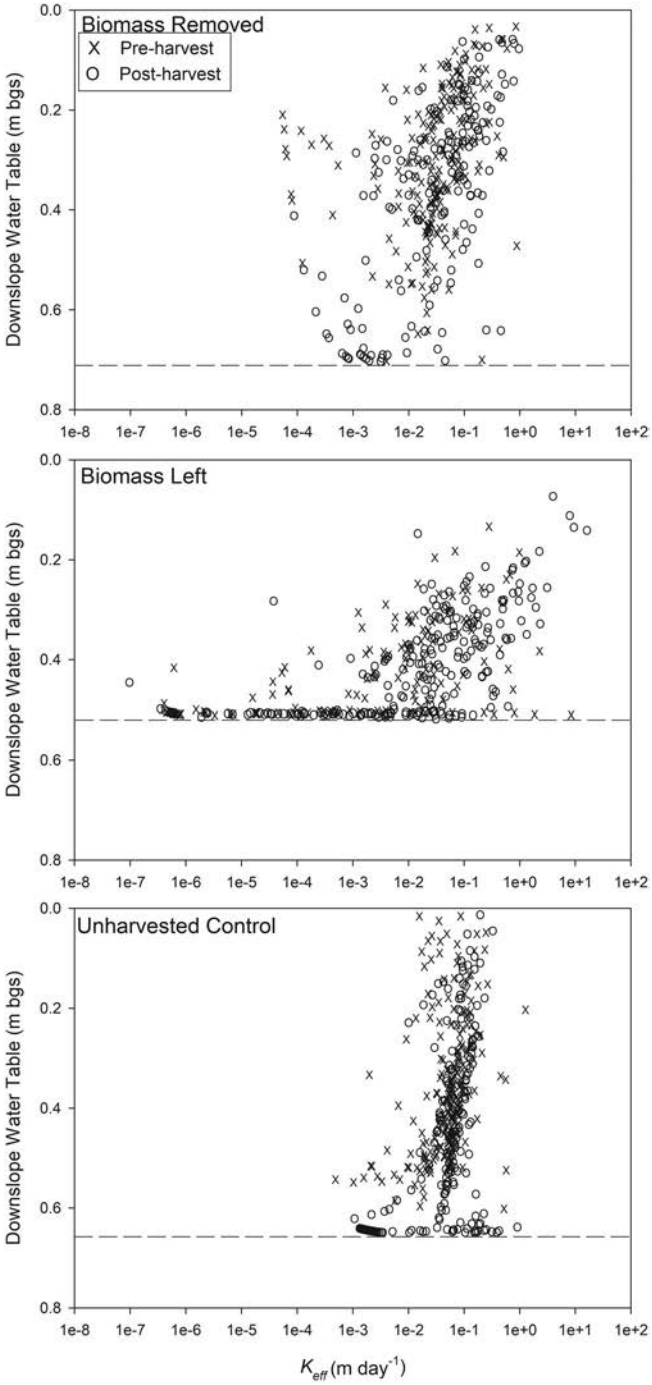

FIGURE 5 The K_{eff} profiles for the Biomass Removed, Biomass Left, and Unharvested Control hillslopes. Note, the log-scale for K_{eff} and the overlap between before and after harvest measurements

relationships. Though it is more difficult to discern from these measurements what may have been occurring at a finer scale, these weak relationships further support a hypothesis that some of the flow is occurring as preferential flow through macropores.

Changes to hydrophysical soil properties following forest harvesting can manifest in large-scale changes in hydrology, primarily due to the development of surface water flow paths along skidder tracks, where permeability is greatly reduced (Ampoorter et al., 2012; Buttle et al., 2019; Dung et al., 2012; Ebeling et al., 2016; Labelle & Jaeger, 2011). The lack of an apparent difference in the K_{eff} profile between pre- and post-harvest periods at any hillslope suggests that compaction effects were not an issue in our study. Holub et al. (2013) found that the removal of residual biomass changed the soil structure due to increased heavy machinery traffic. However, in this study, the timber and residual biomass harvest occurred during the winter on frozen soils, which likely limited soil compaction and decreased the prevalence of rutting on the hillslopes (Kolka et al., 2012). If the residual biomass had been removed when there was no snowpack and the soils were not frozen, the changes to the soil structure would have been apparent in the K_{eff} profile, and had a greater impact on the overall hydrology. Although K_{eff} profiles did not change at either of the Biomass Removed or Biomass Left hillslopes post-harvest, there was a clear increase in average K_{eff} at both harvested hillslopes. Given the lack of observable change to the bulk soil hydraulics, changes in K_{eff} were more a function of changes in the absolute water table height, the hydraulic gradients, the duration of elevated water tables, and runoff events.

The water table dynamics of the Biomass Removed hillslope was more similar to the Unharvested Control hillslope than that of the Biomass Left hillslope. However, there were key seasonal changes to the hillslope water table dynamics that drove the runoff response. The loss of overall spring water table recharge was likely due to increased soil frost (Verry, 1991) and decreased permeability post-harvest (Buttle et al., 2001; Monteith et al., 2006; Moore & Wondzell, 2005). An increase in soil frost and accompanying reduction in near-surface permeability would preferentially generate greater shallow water flow (Verry et al., 2011), resulting in the observed greater spring runoff; notwithstanding the lack of statistical differences in spring runoff at the Biomass Removed hillslope. The likely development of deeper soil frost increased hydraulic gradients and runoff, which resulted in decreased overall water storage during this period. This generated lower water tables, particularly at the downslope position. During the summertime, the decrease in water tables post-harvest were exacerbated by increased hydraulic gradients and changes to the partitioning of water between evaporation and transpiration. During the summer months in 2012, decreased transpiration after harvesting was likely offset by increased soil evaporation (Araki, 2005; Buttle & Murray, 2011), driven by increased energy reaching the soil surface (Mazur et al., 2014), a change in atmospheric mixing at the soil-atmosphere boundary (Carrera-Hernández, Mendoza, Devito, Petrone, & Smerdon, 2011) and the shallow depth of soil where the sensor was installed. This manifested in wetter soils above the confining layer and similar water tables comparted to pre-harvest. By 2013, vegetation regrowth at the Biomass Removed treatment was greater (average 112 g dry-weight m^{-2}) than the Biomass Left treatment (average 67 g dry-weight m^{-2}) (unpublished data), potentially resulting in greater transpiration, thus further limiting runoff at the Biomass Removed hillslope. The increase in water tables during the fall, and subsequent increase in runoff due to decreased evaporation, was not enough to offset the losses during the spring and summer, resulting in an overall muted treatment response. On these particular hillslopes

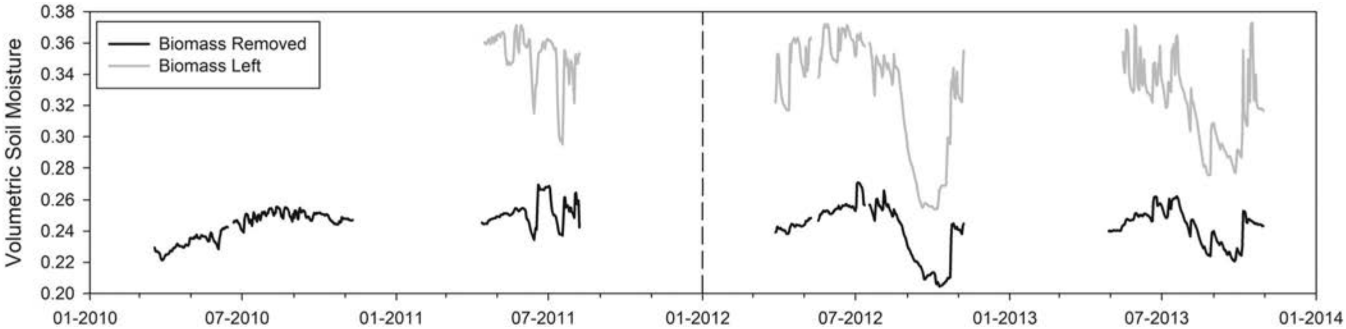

FIGURE 6 Timeseries of the volumetric soil moisture at the Biomass Removed and Biomass Left hillslopes. Left of the dashed line indicates pre-harvest, while right of the dashed line indicates post-harvest

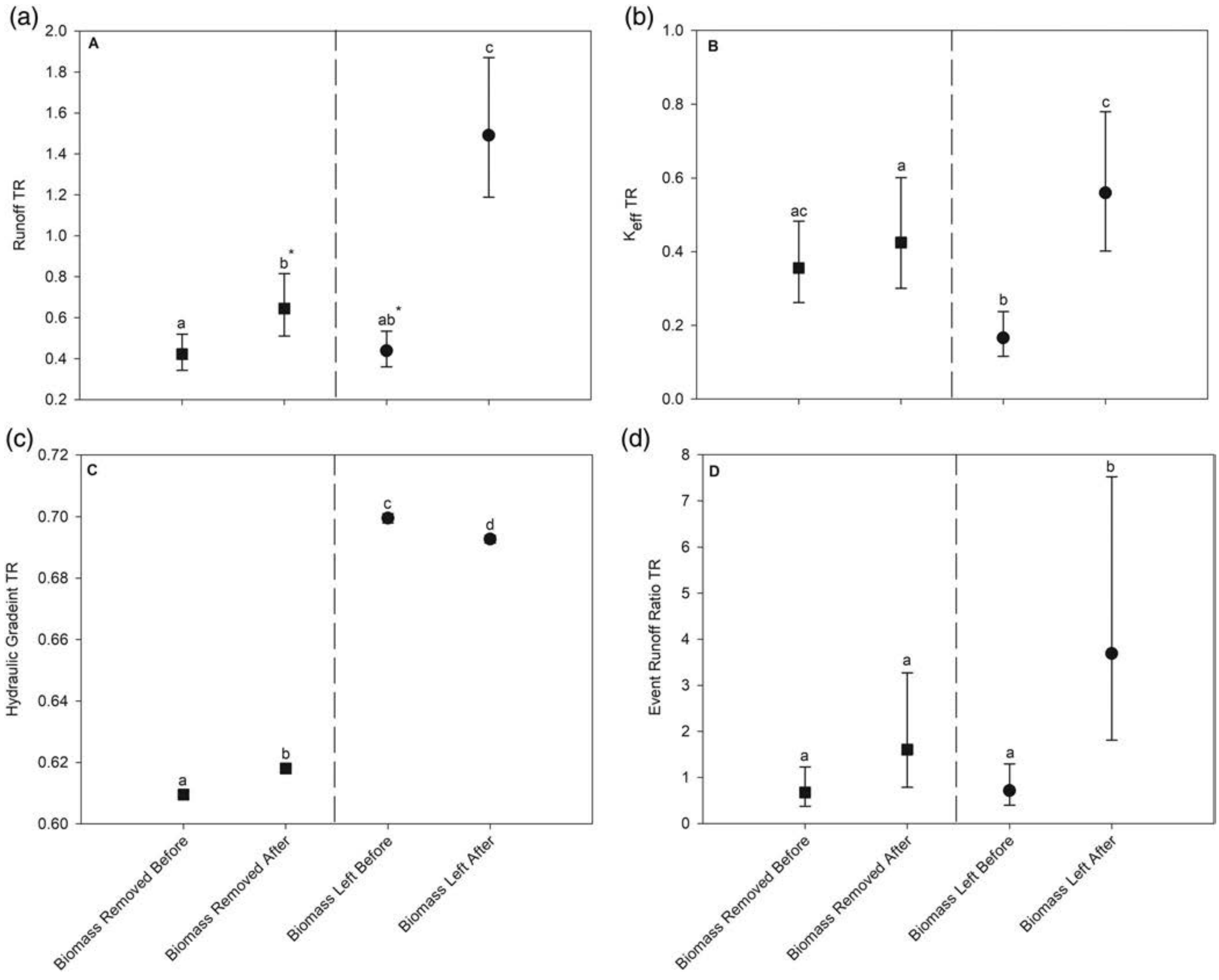

FIGURE 7 The resultant least-square means for pre- and post-harvest treatment ratios (TR) at the Biomass Removed and Biomass Left hilllslopes for (a) Runoff, (b) K_{eff}, (c) hydraulic gradients, and (d) event runoff ratio. The different letters represent significant differences at $p < .05$, while * indicates $p < .10$

the removal of biomass represents a moisture regime similar to pre-harvest, resulting in a depressed runoff response relative to the Biomass Left hillslope.

In contrast to the Biomass Removed hillslope, the Biomass Left treatment had a much larger impact on the overall hydrology. On the Biomass Left hillslope, water tables increased at the downslope position, decreasing the overall hydraulic gradients of the hillslope. The additional groundcover provided by the residual biomass likely increased the snowpack by providing structure to entrain and retain snow (Buttle et al., 2005), which ultimately resulted in more stable spring water tables and greater groundwater recharge. Relative to the Biomass Removed hillslope, more water was stored within the hillslope at the onset of summer and significant increases in the downslope water tables were observed, which propagated through the summer. In addition to the higher water tables observed in the spring, the residual biomass likely decreased evapotranspiration through shading and decreased insolation (Araki, 2005; Mazur et al., 2014), changes to soil-atmosphere mixing processes (Buttle & Murray, 2011; Sun et al., 2001) and decreased herbaceous ground cover (unpublished data), altering the water budget to allow for more water to enter short-term storage or runoff rather than leaving the hillslope as evapotranspiration during the summer (e.g., the Biomass Removed hillslope). Resulting from the higher water tables in the summer, there was a larger water table response in the fall and thus the hydraulic gradient did not significantly change relative to pre-harvest conditions. The hydrological response on the Biomass Left hillslope resulted in greater hydrological efficiency (i.e., higher event runoff ratios) at the Biomass Left hillslope than the Biomass Removed hillslope. The increase in the water table across the Biomass Left hillslope did not propagate to the soil moisture, where decreased soil moisture and increased variability approximately 5 cm above the Koochiching clay loam till was observed on the Biomass Left hillslope. This suggests that there was continual evaporation from the soil surface, leading to greater soil moisture variability and lower average soil moisture. Whereas, on the Biomass Removed hillslope, evaporation from the soil surface was likely limited by drier soil conditions at the soil-atmosphere interface and the shallower soil depth where the moisture probe was installed (Araki, 2005; Breña Naranjo et al., 2011; Mazur et al., 2014). It is evident that changes to the interplay between winter processes, such as snow accumulation, and summer evapotranspiration were a strong control on runoff processes from harvested hillslopes, but the directionality and magnitude of response differed due to harvesting practice. Leaving residual biomass may increase the potential for downgradient hydrological impacts.

Many hillslope forest harvesting studies have focused on systems where the hillslope water table was present throughout the year and generally observed that water table elevations increased post-harvest (Choi, Dewey, Hatten, Ezell, & Fan, 2012; Dung et al., 2012; Johnson, Edwards, & Erhardt, 2007; Thompson et al., 2018; Whitson, Chanasyk, & Prepas, 2005). The perched and more ephemeral water table that was present at these hillslopes led to a different hydrological response than has been observed in the broader literature. Over a larger range of permeable soil depth, Grip (2015) found that water table elevations significantly increased across a boreal hillslope in Sweden in response to harvesting. At that particular hillslope, the soils were various podzols ranging from <1 to >3 m overlying an impermeable layer. When the permeable soil layer was shallow, significant lateral runoff occurred along the interface with the impermeable layer (Grip, 2015), similar to this study. Yet, where soils were deeper, more available soil storage limited runoff (Grip, 2015). Similarly, Thompson et al. (2018) described a comparable process occurring after harvesting of aspen stands in the Western Boreal Plains, Canada. In the Western Boreal Plains, Thompson et al. (2018) predicted that water tables would increase up to 3 m post-harvest due to decreased transpiration demand but there was limited impact on streamflow due to the large hydrological buffering capacity of downgradient peatland systems. The lack of streamflow response was attributed to deep soils above the impermeable layer, resulting in a large water storage capacity, as well as the general atmospheric condition wherein potential evapotranspiration was greater than precipitation (Thompson et al., 2018). The interplay between permeable soil depth and atmospheric condition can offset the water table response on harvested hillslope by years (Carrera-Hernández et al., 2011), resulting in potential long-term effects that are not traditionally captured by shorter-term studies. However, changes in runoff, and other hydrological processes, on harvested hillslopes are chiefly attributed to changes in evapotranspiration and interception (Buttle et al., 2009; Harr, 1986; Moore & Wondzell, 2005). The study presented here adds to a small body of literature (Grip, 2015; Harr, 1977, 1986; Sartz & Knighton, 1976; Sartz & Knighton, 1978) suggesting an important link between runoff and permeable soil depth that needs to be accounted for when predicting potential hydrological impacts due to forest harvesting. Hillslopes with deeper permeable soil layers may dampen and delay the runoff response, while shallow permeable soils layers, such as in this study, will have much more immediate, and likely larger magnitude, runoff responses. These differences in permeable soil thickness can alter catchment scale runoff responses (Dung et al., 2012, 2015), partly explaining the widely reported differences among streamflow responses in literature.

5 | CONCLUSIONS

The overall short-term (i.e., 2 years) hydrological impacts of forest harvesting on the relatively subdued topographic setting of this study were governed by the interplay between seasonal water storage and runoff processes. Seasonal changes to the recharge of the perched system, even if not statistically significant, induced large hydrological impacts in later seasons. Forest harvesting practices where residual biomass was largely left behind (i.e., Biomass Left treatment in this study) increase the subsurface runoff relative to practices where residual biomass was harvested (i.e., Biomass Removed treatment in this study). The hydrological conditions on the Biomass Removed hillslope were similar to those observed prior to forest harvest. Although soil moisture and some water tables at the Biomass Removed hillslope were similar to the Unharvested Control hillslope after harvesting, there was still an overall increase in runoff and runoff efficiency (i.e., event runoff ratios) from the hillslope. Leaving the residual biomass on the hillslope resulted in higher water tables and increased hydrological connectivity on this segment of the hillslope, generating

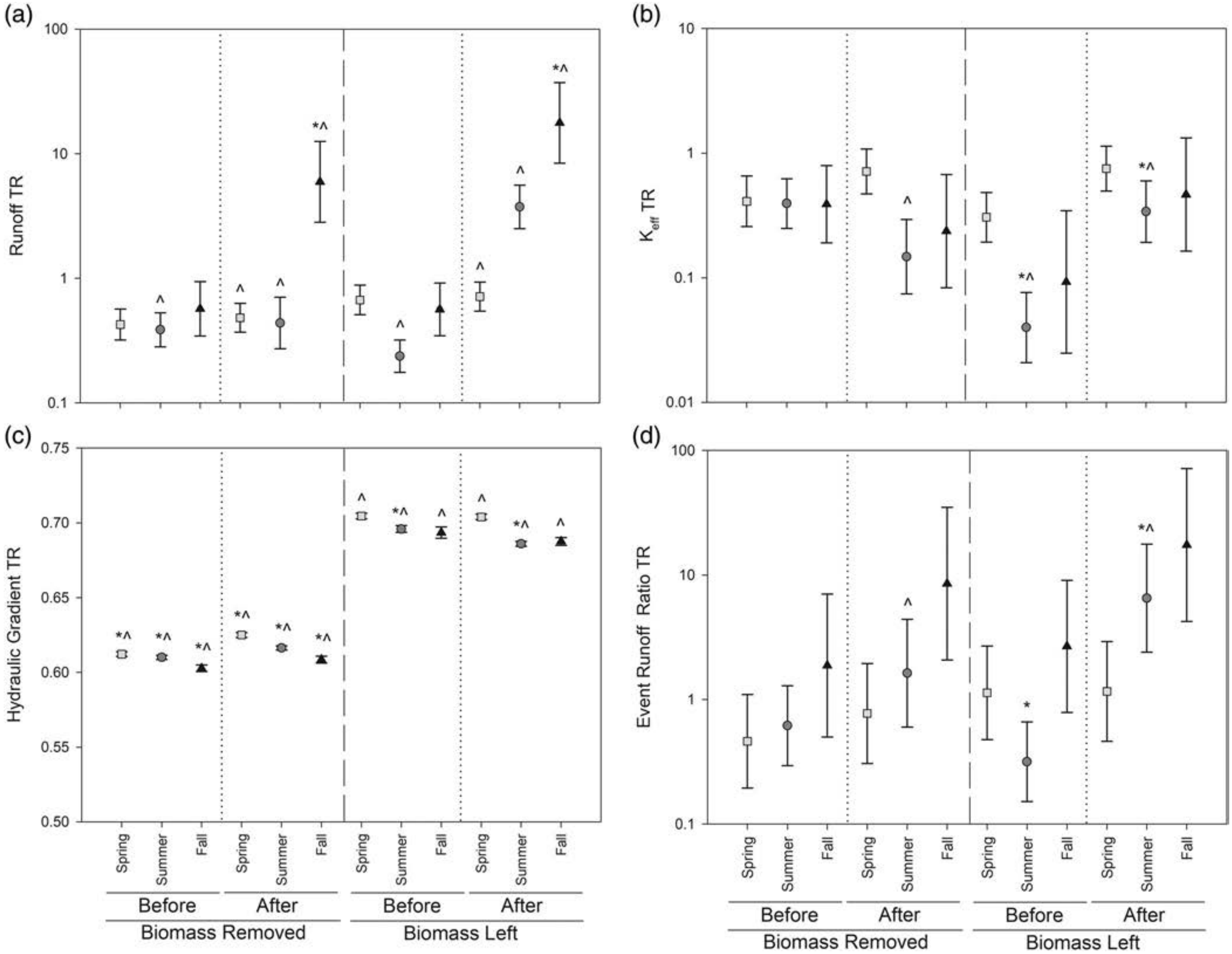

FIGURE 8 The resultant seasonal least-square means for pre- and post-harvest treatment ratios (TR) at the Biomass Removed and Biomass Left hillslopes for (a) Runoff, (b) K_{eff}, (c) hydraulic gradient, and (d) event runoff ratio. * indicates significant differences ($p < .05$) between pre- and post-harvest for a given site and season. ^ indicates significant differences ($p < .05$) between sites for a given treatment period and season

proportionally more runoff than when the residual biomass was removed. The observed hydrological changes were most likely due to differences in the partitioning of water between evapotranspiration and runoff, while the differences between harvested hillslopes were partially driven by differences in vegetation or woody debris cover rather than structural changes to the soil due to increased heavy machinery traffic associated with residual biomass harvesting. The lack of soil structural changes highlights the relatively well-known benefit of harvesting on snow-covered frozen ground. In practice, however, harvesting on frozen ground is not always economically possible and thus a gap in our understanding remains as to how residual biomass harvesting may respond under more soil compacting conditions. This study highlights the complex interplay between soil structure, vegetation, and climatic conditions on the hydrological response to differing forestry practices on an intermittently perched hillslope wherein storage is largely confined to relatively shallow soils.

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DATA AVAILABILITY STATEMENT

All data used in this publication is available at https://doi.org/10.2737/RDS-2020-0049.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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