Effectiveness Study Interim-Report

Name of Grantee: Washington State University **Date: 10/2/2020**

Agreement Number: 93-097801 **Year grant was awarded:** 2019

Name of Project Contact: Dr. A. Jayakaran **Email:** anand.jayakaran@wsu.edu

Project Name: The effectiveness of trees in mitigating stormwater runoff in Western Washington

Percent Completed: 54%

Is the project on target for successful completion by agreement end date? Yes

List work/activities accomplished to date:

1. Sites located, and study trees identified.
2. Final QAPP reviewed approved and marked complete
3. Instrumentation for Sap flow at all sites completed.
4. Instrumentation for throughfall completed at all sites.
5. Soil moisture sensors installed at all sites.
6. Sensor maintenance and sensor downloads are occurring on a weekly basis
7. Initial efforts have been undertaken to determine best data curating and analysis methods. A website available to project researchers has been set up to visualize the data: https://lidlab.shinyapps.io/utsDataViewer
8. Data collection is ongoing with data downloaded once every two weeks.
9. Maintenance of interception troughs, rain gages, and soil moisture sensors, are also ongoing.

10. Some replacement parts were purchased and installed – several cables and sensors associated with the sap flux sensors had gone bad. Purchasing was done with help from Abby Barnes.
11. Initial steps on how best to analyze the data have been taken.
12. Data summary is presented below

Have you experienced any challenges or issues that could delay or otherwise affect the project?

As of this reporting period, a couple of power outages, sensor disconnections, cable issues, and rain gage cloggings have impacted some data streams, but most have been rectified and are functioning as expected.

Adjustments to the proposal must be approved by DNR. Do you anticipate any adjustments to the original proposal?

As of this reporting period, not new adjustments have been identified.

Any other comments? No

<u>Reimbursement requests must include an agency invoice with original signature and include documentation for all eligible costs.</u>

Email completed report to:

Abby Barnes, Aquatic Resources Division
Abby.barnes@dnr.wa.gov

Data Summary Report

Ben Leonard, Ani Jayakaran

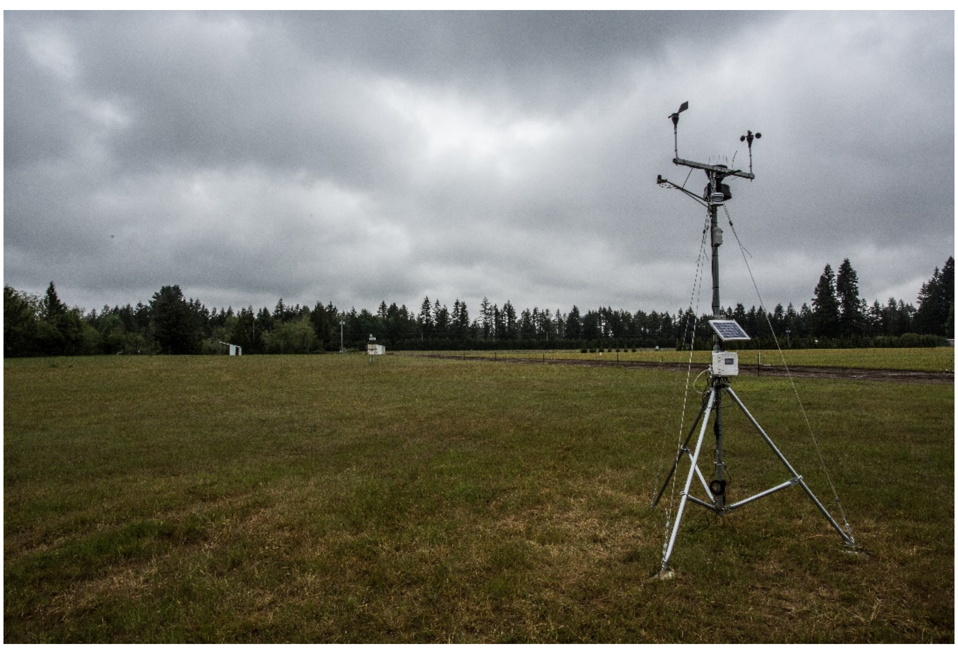
October 2, 2020

1. Introduction

This data summary report outlines data collected as part of the SAM funded project *The effectiveness of trees in mitigating stormwater runoff in Western Washington* through September 2020. For this project, a variety of environmental sensors were deployed to measure how trees manage water. The following data summary report is divided into sections detailing preliminary results from several groups of sensors. Data analyses performed are not final and are subject to change in future revisions.

1.1. Sensor Deployments

Data collection began in spring 2019 with the deployment of weather stations in fields near our two field sites *The Evergreen State College* (Evergreen) and *Webster Forest Nursery* (Webster). *Table 1* illustrates the timeline of sensor deployments ending with soil moisture sensors installed at individual plots. *Tables 2 and 3* further detail the deployment of sensors for weather stations and sap flux stations respectively.



Weather station deployed at Webster Forest Nursery in May 2019.

Table 1. List of Equipment Deployments

	Date of First Deployment		# of Sensors
	Evergreen	Webster	
Weather Station	Apr 26, 2019	Apr 30, 2019	9 per site[a]
Sap Flux Station	Jun 16, 2019	May 17, 2019	4 per site[b]
Canopy VPD	Aug 01, 2019	Jul 17, 2019	5 total[c]
Plot Soil Moisture	Aug 26, 2019	Sep 09, 2019	5 per plot[d]
Throughfall Troughs	Sep 01, 2019	Sep 01, 2019	32 total[e]

[a]13 variables from 9 sensors. See Table 2 for list of weather station variables.
[b]8 trees per site and 1 to 2 sensors per site. See Table 3 for list of trees.
[c]2 at Evergreen and 3 at Webster due shared canopy at plots 1+2, 3+4, and 7+8.
[d]Not deployed at Evergreen parking lot until fall 2019 due to digging concerns around underground cable.
[e]Two sets of rain gauges at 0', 5', and 10' used for two trees at Evergreen parking lot rather than troughs.

Table 2. List of Weather Station Variables

Variable	Range of Values
Air Temperature °C	-7.6 to 37.5
Dew Point °C[a]	-10.5 to 20.7
Gust Speed m/s[b*]	0 to 8.8
Leaf Wetness %[*]	0 to 100
PAR µE[*]	1 to 2377
Pressure mbar[*]	989.5 to 1031.9
Rain mm	0 to 5.6
RH %	15.8 to 100
Soil Moisture m3/m3[*]	0 to 0.3
Soil Temperature °C[*]	0.9 to 28.1
Solar Radiation W/m2[*]	1 to 1204.7
Wind Direction °	0 to 358
Wind Speed m/s	0 to 5.7

[a]Calculated from air temperature and relative humidity (RH).
[b]Calculated from wind speed.
[*]Selected important environmental variables included in Tables 4a,b and Figure 1.

Table 3. List of Sap Flux Trees

Site	Location	Plot #	Tree Species			
			Douglas-fir	western red cedar	bigleaf maple	red alder
			Pseudotsuga menziesii	*Thuja plicata*	*Acer macrophyllum*	*Alnus rubra*
Evergreen	Organic Farm	1	2(1)	0	0	6(5)
		2	2(1)	0	6(5)	0
	Parking Lot	3	0	6(1*)	2	0
		4	6(1*)	0	1	1
Webster	North Field	5	2(2)	0	0	6(3)
		6	5(5)	0	1(1)	2
	South Field	7	1(1)	5(4)	2(1)	0
		8	3(3)	0	3(2)	2(1)
Total	-	-	21(14)	11(5)	15(9)	17(9)

Numbers in parentheses show the number of canopies used for interception.
*Six rain gauges were placed under a single canopy (*Table 1*[e]).

2. Environmental Data

General environmental data were collected to help elucidate tree water use across all study sites. For example, precipitation data are needed to calculate interception and delineate storm events. Other environmental data collected will be used to explain direct measurements of transpiration – intensity of sunlight needed for photosynthesis, soil water availability in the root zone, and the direct evaporation of water from a leaf's surface are all important co-parameters. Relevant environmental parameters measured for this study are photosynthetically active radiation (PAR), soil moisture, and vapor pressure deficit (VPD). VPD is calculated from measurements of temperature, relative humidity, and atmospheric pressure. Other parameters such as leaf wetness, wind speed, and soil temperature may be interpreted more qualitatively to better understand the general micro-environments each site operates within.

Weather stations were set up in fields at least 300 feet from any obstructing objects (trees, buildings, etc) and stabilized with guy-wires and ground anchors. Soil moisture probes were installed 5 per plot (evenly distributed around one center probe at the data logger) at a depth of approximately 18 inches. Canopy VPD sensors measured RH and air temperature (atmospheric pressure measured by weather stations) and were hung at approximately half canopy height for 5 canopies covering the 8 plots. Rain gauges not associated with weather stations were used to measure throughfall.

All weather stations, soil moisture, VPD, and rain gauge sensors recorded measurements every minute. All equipment was purchased from OnSet in spring 2019. Data were uploaded to the *Hobolink* cloud using a *RX-3000* data logger every hour. Weekly data summaries were downloaded and post-processed to average measurements every 15-minutes.

Tables 4a, b and *5a, b* provide monthly summary values for important environmental data variables. In *Tables 4a, b* E = Evergreen and W = Webster. Precipitation totals in *Tables 5a, b* and *Figure 1* show that a) Webster precipitation totals are greater than Evergreen for most months recorded, b) January 2020 is the wettest month so far recorded with 452.6 mm. For spring and summer months recorded in both 2019 and 2020 (May, Jun, Jul, Aug) 2019 was considerably drier in late spring early summer months (May = 25.7 and 20.1 mm, Jun = 9.9 and 8.6 mm for Evergreen and Webster respectively) compared to 2020 (May = 74.2 and 65.5 mm; Jun = 56.1 and 63.2 mm). Late summer months on the other hand were wetter in 2019 (Jul = 25.9 and 35.8 mm, Aug = 21.3 and 16.5 mm) compared to 2020 (Jul = 2.5 and 3.8 mm, Aug = 8.1 and 10.7). This makes July 2020 the driest month recorded averaging only 3.2 mm of precipitation between sites.

A timeseries of important environmental data and are illustrated in *Figure 2*. Additionally, vapor pressure deficit (VPD) and soil moisture data are also shown in *Figure 2* - those data are absent from weather tables (*Tables 4a, b and 5a, b*) because those parameters were measured at individual plot locations, and not at the two weather stations (*Table 1*).

Table 4a. 2019 Weather Station Summary Statistics

		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
		E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
Air Temperature °C	mean	13.9	13.8	15.6	15.4	17.9	17.6	18.5	18.2	15.1	14.7	8.3	7.8	5.9	5.5	5.8	5.5
	sd	4.9	5.5	4.9	5.5	4.2	4.9	4.5	5.4	4.1	4.6	4.3	5.3	3.8	4.7	2.4	2.8
	min	3.5	1.6	5.5	3.4	9.0	5.8	9.9	6.8	2.7	-1.1	-2.7	-4.8	-4.4	-7.6	-0.3	-1.4
	median	12.7	12.5	14.8	14.7	17.4	17.3	17.7	17.7	14.9	14.6	9.0	8.8	6.8	6.2	6.0	5.8
	max	30.6	30.8	33.0	34.6	31.5	31.7	33.3	33.3	26.7	27.6	17.2	18.3	13.5	15.2	11.6	11.6
Leaf Wetness %	mean	36.2	34.1	24.8	29.2	31.1	37.7	33.8	41.2	56.8	56.9	67.7	66.0	77.2	66.8	87.0	81.8
	sd	42.6	41.9	37.3	41.4	41.9	45.0	43.2	46.0	45.8	45.8	43.0	42.2	37.4	40.9	29.7	33.4
	min	0.0	0.0	1.1	0.6	1.8	1.2	1.8	1.6	2.9	2.4	2.9	1.8	4.1	2.9	5.9	4.1
	median	3.3	3.3	2.9	2.4	3.5	3.5	3.7	4.1	95.9	95.3	100.0	100.0	100.0	100.0	100.0	100.0
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
PAR µE	mean	395.5	447.9	427.8	516.0	408.9	472.7	354.4	405.5	220.8	258.5	108.1	186.9	49.1	96.6	34.7	44.5
	sd	517.8	565.8	517.2	598.5	511.4	564.4	469.0	519.9	336.4	383.9	198.7	303.2	82.2	180.4	62.0	87.2
	min	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	median	102.5	157.8	140.7	254.3	129.0	221.7	76.0	119.1	13.4	16.3	1.0	1.0	1.0	1.0	1.0	1.0
	max	1,837.0	2,039.7	2,008.9	2,377.0	1,862.3	2,211.0	1,708.0	1,965.5	1,515.6	1,738.9	1,140.8	1,285.7	441.5	936.3	363.9	769.2
Pressure mbar	mean	1,007.8	1,007.2	1,012.9	1,012.4	1,011.6	1,011.1	1,010.4	1,009.8	1,009.7	1,009.2	1,015.2	1,014.5	1,013.8	1,013.1	1,010.3	1,009.7
	sd	4.7	4.6	4.3	4.3	2.4	2.4	3.0	3.0	4.5	4.5	7.6	7.5	6.7	6.8	5.9	5.9
	min	994.3	993.6	1,003.0	1,002.6	1,005.5	1,004.5	1,003.2	1,002.6	999.5	999.0	995.8	994.8	992.1	991.2	995.0	994.7
	median	1,008.3	1,007.7	1,013.0	1,012.4	1,011.5	1,010.9	1,009.9	1,009.3	1,010.0	1,009.4	1,015.2	1,014.9	1,015.7	1,014.9	1,010.8	1,010.1
	max	1,017.5	1,016.8	1,024.3	1,023.7	1,019.1	1,018.2	1,018.0	1,017.2	1,020.2	1,019.4	1,027.4	1,026.7	1,026.3	1,025.1	1,022.7	1,022.4
RH %	mean	76.4	76.1	72.3	72.0	75.8	76.1	78.1	77.3	88.2	87.2	88.9	87.4	94.8	92.6	99.4	98.8
	sd	19.3	20.8	16.8	19.3	17.3	19.3	16.3	19.3	12.9	14.6	14.5	17.1	11.1	13.1	2.3	3.1
	min	19.2	18.5	33.2	28.8	26.0	26.5	32.7	25.3	39.4	38.0	27.7	25.0	45.1	38.9	77.5	67.1
	median	81.3	83.0	74.4	74.9	79.6	81.3	81.9	83.4	93.6	93.3	95.1	96.1	100.0	99.4	100.0	100.0
	max	100.0	100.0	98.4	99.9	100.0	100.0	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 4b. 2020 Weather Station Summary Statistics

		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug	
		E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
Air Temperature °C	mean	6.0	6.2	4.9	4.8	5.5	5.3	9.9	9.5	13.5	13.4	15.2	15.1	17.7	17.4	18.2	17.8
	sd	3.2	3.3	3.4	3.9	3.9	4.4	5.0	5.6	4.8	5.3	4.3	4.8	5.3	6.0	5.3	6.0
	min	-1.5	-2.5	-2.6	-4.9	-2.4	-4.3	-1.1	-3.1	2.6	0.7	6.6	4.6	8.8	6.2	7.0	4.3
	median	6.3	6.4	5.1	4.9	5.3	5.2	9.7	9.5	12.6	12.6	14.6	14.4	16.7	16.5	17.6	17.5
	max	13.2	13.9	15.0	17.2	17.7	18.7	23.4	23.4	30.1	30.5	29.5	29.7	35.5	36.3	37.5	37.5
Leaf Wetness %	mean	88.3	83.1	68.2	68.3	56.5	56.8	35.6	42.2	36.5	40.9	33.5	38.6	30.9	37.4	35.7	40.5
	sd	27.7	32.4	40.8	40.5	44.5	43.6	43.0	45.0	43.3	45.0	42.5	44.0	37.7	44.3	42.1	46.1
	min	7.1	4.7	5.1	4.0	3.5	2.9	2.9	1.8	2.9	2.4	2.9	2.4	3.5	1.8	2.9	1.2
	median	100.0	100.0	100.0	100.0	77.9	73.7	5.5	5.4	5.3	5.1	5.3	5.1	8.2	4.1	7.0	3.4
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
PAR µE	mean	38.1	52.5	85.8	145.5	188.7	235.2	342.4	352.5	377.9	410.5	404.0	447.9	454.0	525.3	430.2	485.0
	sd	69.3	103.9	151.1	251.9	297.7	355.0	462.3	464.9	492.5	522.0	511.4	551.2	553.1	605.5	539.2	593.3
	min	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	median	1.0	1.0	1.0	1.0	2.8	3.3	53.9	67.1	93.9	149.8	132.9	191.6	135.6	264.3	70.5	133.4
	max	416.4	713.1	1,025.7	1,141.1	1,555.8	1,515.7	1,670.8	1,822.6	1,887.5	2,037.5	1,893.0	2,226.0	1,913.5	2,231.4	1,808.8	2,074.8
Pressure mbar	mean	1,009.0	1,008.6	1,018.4	1,017.8	1,012.2	1,011.4	1,013.9	1,013.1	1,010.7	1,009.9	1,011.4	1,010.6	1,011.6	1,010.8	1,011.3	1,010.6
	sd	6.5	6.5	6.4	6.2	5.8	5.8	5.6	5.6	6.0	6.0	4.1	4.1	3.2	3.2	3.5	3.5
	min	989.8	989.5	1,002.9	1,002.9	996.7	996.4	996.6	995.6	998.8	998.1	1,000.1	999.4	1,003.4	1,002.8	1,002.7	1,001.8
	median	1,009.0	1,008.7	1,018.2	1,017.5	1,012.0	1,011.4	1,014.5	1,013.8	1,011.2	1,010.4	1,010.9	1,010.2	1,012.0	1,011.3	1,011.4	1,010.7
	max	1,023.1	1,022.8	1,031.9	1,031.2	1,024.7	1,024.0	1,024.5	1,023.3	1,027.1	1,026.2	1,019.9	1,019.0	1,017.6	1,016.5	1,019.9	1,018.6
RH %	mean	98.2	97.3	92.3	92.2	85.4	85.3	74.8	76.1	77.7	77.2	79.6	79.0	74.4	75.0	73.9	74.0
	sd	4.2	4.8	10.6	12.5	15.9	17.1	19.6	21.2	18.4	20.5	15.0	17.1	16.9	19.9	18.4	20.7
	min	73.7	59.5	49.0	36.1	34.6	32.1	18.8	16.5	22.9	21.8	36.9	30.4	31.0	25.1	32.7	28.2
	median	100.0	99.7	96.7	98.1	92.1	92.8	79.4	82.4	81.8	83.6	83.0	84.3	77.5	80.0	76.2	78.7
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	97.9	99.8	100.0	100.0

Table 5a. 2019 Monthly Total Precipitation (mm)

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evergreen	25.7	9.9	25.9	21.3	64.0	108.0	38.9	216.2
Webster	20.1	8.6	35.8	16.5	108.7	147.6	54.1	269.5

Table 5b. 2020 Monthly Total Precipitation (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Evergreen	351.3	83.1	94.5	30.5	74.2	56.1	2.5	8.1
Webster	452.6	120.4	95.8	38.1	65.5	63.2	3.8	10.7

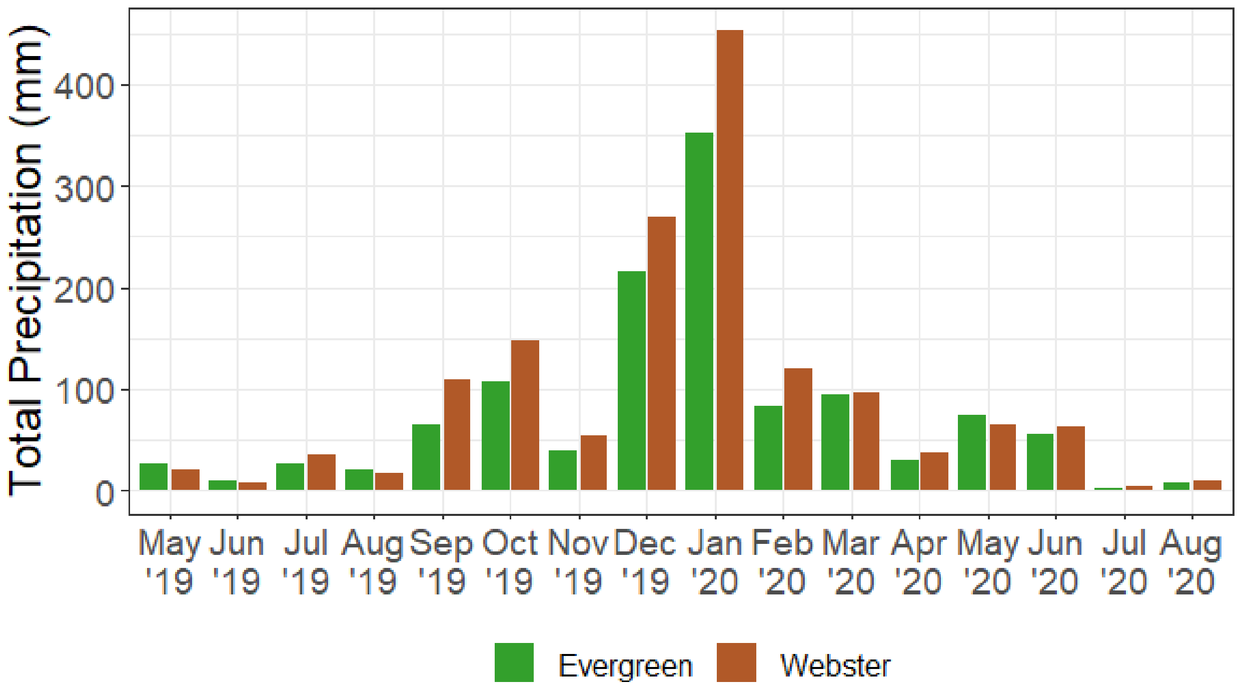


Figure 1. Monthly Total Precipitation

Figure 2. Environmental Data Time Series

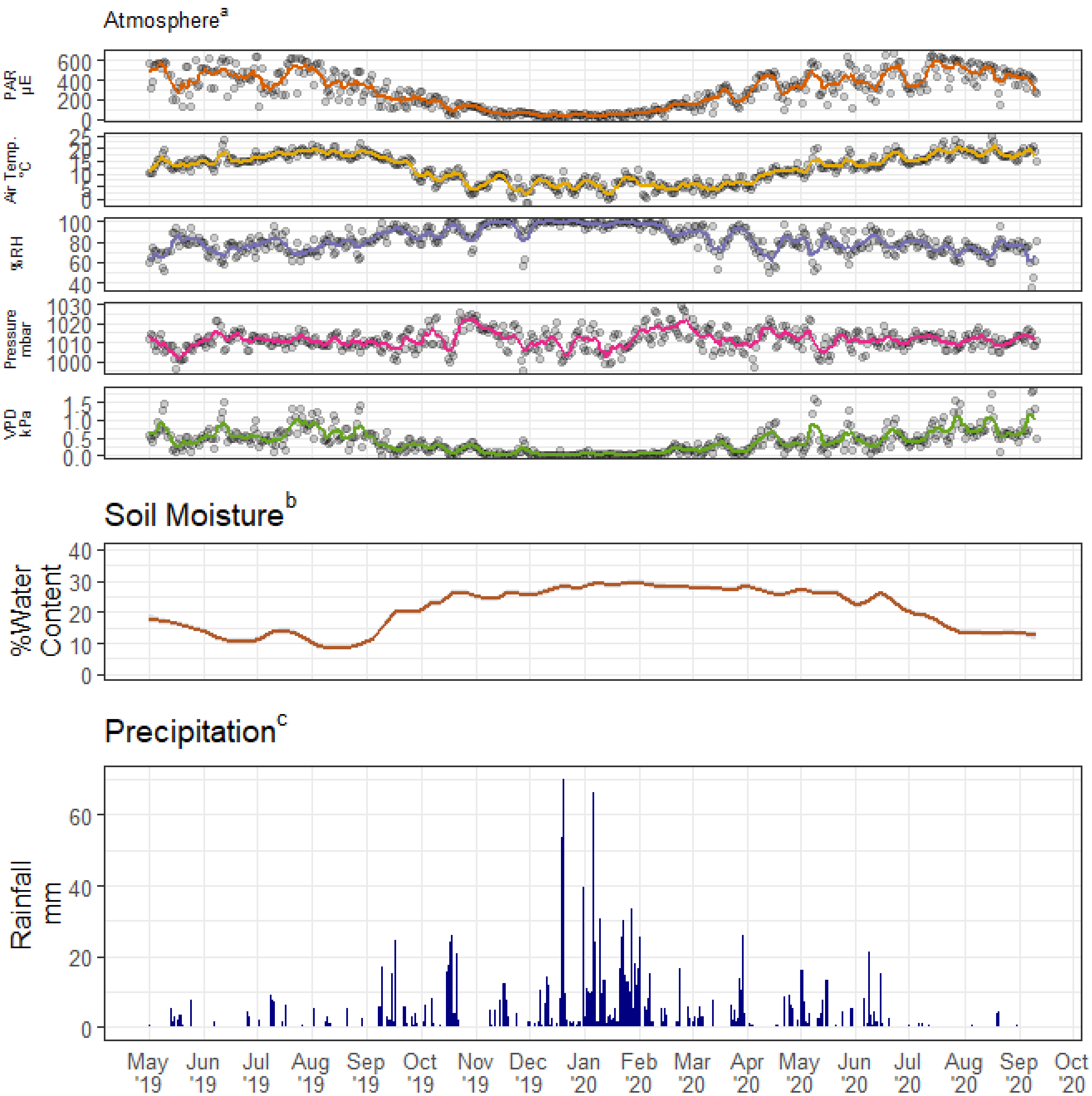


Figure 2: PAR = photosynthetically active radiation; Temp. = temperature; RH = relative humidity; VPD = vapor pressure deficit. (a) Data points show average daily means and lines represent 7-day centered rolling means. (b) Average daily means calculated using data from both weather stations and individual plots and smoothed using loess for illustrative purposes. (c) Daily totals averaged between weather stations.

3. Sap Flux Data

Transpiration, a critical component of individual tree water use, is typically calculated using direct measurements of sap flux. The thermal dissipation probe (TDP) technique for sap flux involves measuring the temperature difference between heated top and unheated bottom probes inserted into the tree's xylem. As sap moves upwards during transpiration the heated probe is cooled and the temperature difference between probes is diminished (*Figure 3*). This signal is normalized by assuming a daily maximum temperature difference each day in the early morning hours before transpiration has begun. A formula developed by Granier transforms the normalized heat differences into sap velocity measurements. This value is often expressed as the volume of water per unit sapwood area per unit time ($cm^3_{water} \times cm^{-2}_{sapwood} \times hour^{-1}$). To calculate individual tree water use volume per unit time it is necessary to accurately measure the tree's sapwood depth. Due to the variability of sapwood conductivity TDP measurements at multiple depths provide a more accurate assessment of water use.

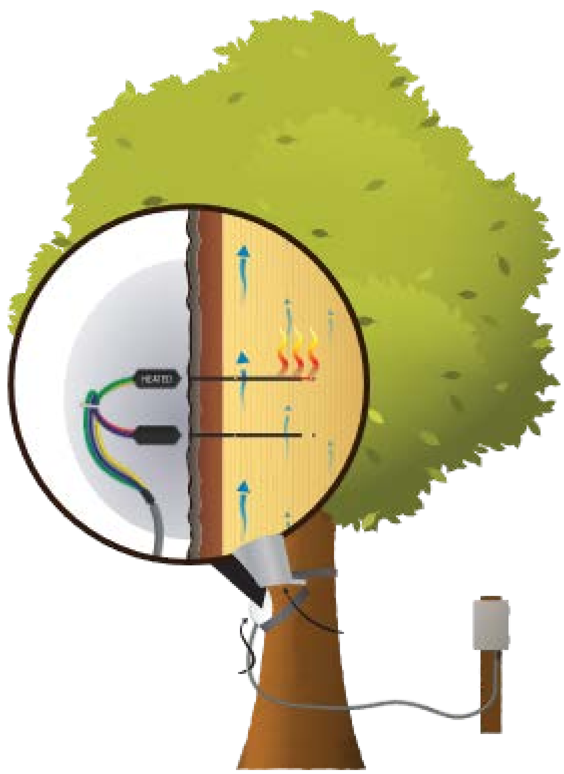


Figure 3: Upper sap flux probe that is heated and measures temperature dissipation, while lower probe measures ambient sap temperature. The temperature difference between the two probes is dependent on the rate of sap transported up the xylem.

We measured sap flux every minute and averaged measurements every 15-minutes. Eight sap flux stations were supplied by *DynaMax Inc.* in spring 2019. Data were recorded on *Campbell Scientific CR-1000X* data loggers. Several types of TDP probes were used to measure sap flux at a variety of depths (15, 25, 50, 70, and 90 mm). All 64 trees in this study were measured at more than one depth using a combination of probes.

Tables 6a, b shows monthly median sap flux density in addition to 25th and 75th percentiles. The use of non-parameteric summary statistics was chosen due to the lack of normality in average daily sap flux measurements within tree species. *Figure 3* shows individual daily medians for each species in addition to 7-day rolling means to smooth the time series.

Coniferous evergreen tree species (Douglas-fir and western red cedar) showed lower average daily sap flux compared to deciduous trees (bigleaf maple and red alder). The highest sap flux rates occurred between May and September 2019 during leaf-on for deciduous trees. The highest monthly median sap flux rate occurred in bigleaf maples during July 2020, and was measured at 7.88 $cm_{water}^{3} \times cm_{sapwood}^{-2} \times hour^{-1}$.

Table 6a. 2019 Monthly Median Sap Flux Density

	Percentile	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Douglas-fir	25%	1.94	1.61	0.55	0.24	0.26	0.33	0.16	0.09
	50%	2.50	2.34	0.75	0.32	0.36	0.49	0.25	0.12
	75%	2.66	2.70	1.00	0.48	0.76	0.78	0.40	0.16
western red cedar	25%	1.99	2.21	1.44	0.38	0.27	0.42	0.16	0.06
	50%	2.31	2.46	1.60	0.67	0.46	0.75	0.23	0.11
	75%	2.60	2.69	2.17	0.97	1.08	1.01	0.34	0.14
bigleaf maple	25%	5.44	7.16	6.12	4.21	1.61	0.47	0.21	0.12
	50%	6.74	7.71	7.28	4.77	2.62	0.74	0.35	0.15
	75%	6.96	9.00	7.96	5.62	3.69	1.56	0.39	0.22
red alder	25%	2.94	3.83	2.63	1.73	0.51	0.33	0.19	0.11
	50%	4.28	4.54	3.47	2.13	0.84	0.45	0.24	0.13
	75%	5.08	5.76	3.93	2.87	1.43	0.49	0.29	0.17

Table 6b. 2020 Monthly Average Sap Flux Density

	Percentile	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Douglas-fir	25%	0.13	0.30	0.48	1.64	1.49	2.04	1.59	0.47
	50%	0.19	0.48	0.95	1.92	2.05	2.63	1.96	0.55
	75%	0.29	0.87	1.53	2.19	2.41	3.46	2.51	0.78
western red cedar	25%	0.12	0.15	0.23	1.91	1.82	2.10	2.41	0.58
	50%	0.17	0.21	0.63	2.57	2.47	2.65	2.83	0.99
	75%	0.26	0.34	1.26	2.99	2.97	3.01	3.08	1.33
bigleaf maple	25%	0.19	0.24	0.22	0.56	3.21	5.91	6.78	5.55
	50%	0.29	0.33	0.37	0.65	4.40	6.79	7.88	6.32
	75%	0.41	0.50	0.52	1.18	6.03	8.65	8.83	6.86
red alder	25%	0.15	0.22	0.24	0.60	1.52	2.56	3.85	2.61
	50%	0.22	0.31	0.35	0.71	2.10	3.28	4.49	3.26
	75%	0.34	0.42	0.62	1.04	2.97	4.63	4.88	3.68

Units in $cm^3_{water} \times cm^{-2}_{sapwood} \times hour^{-1}$.

Figure 3. Sap Flux Data Time Series

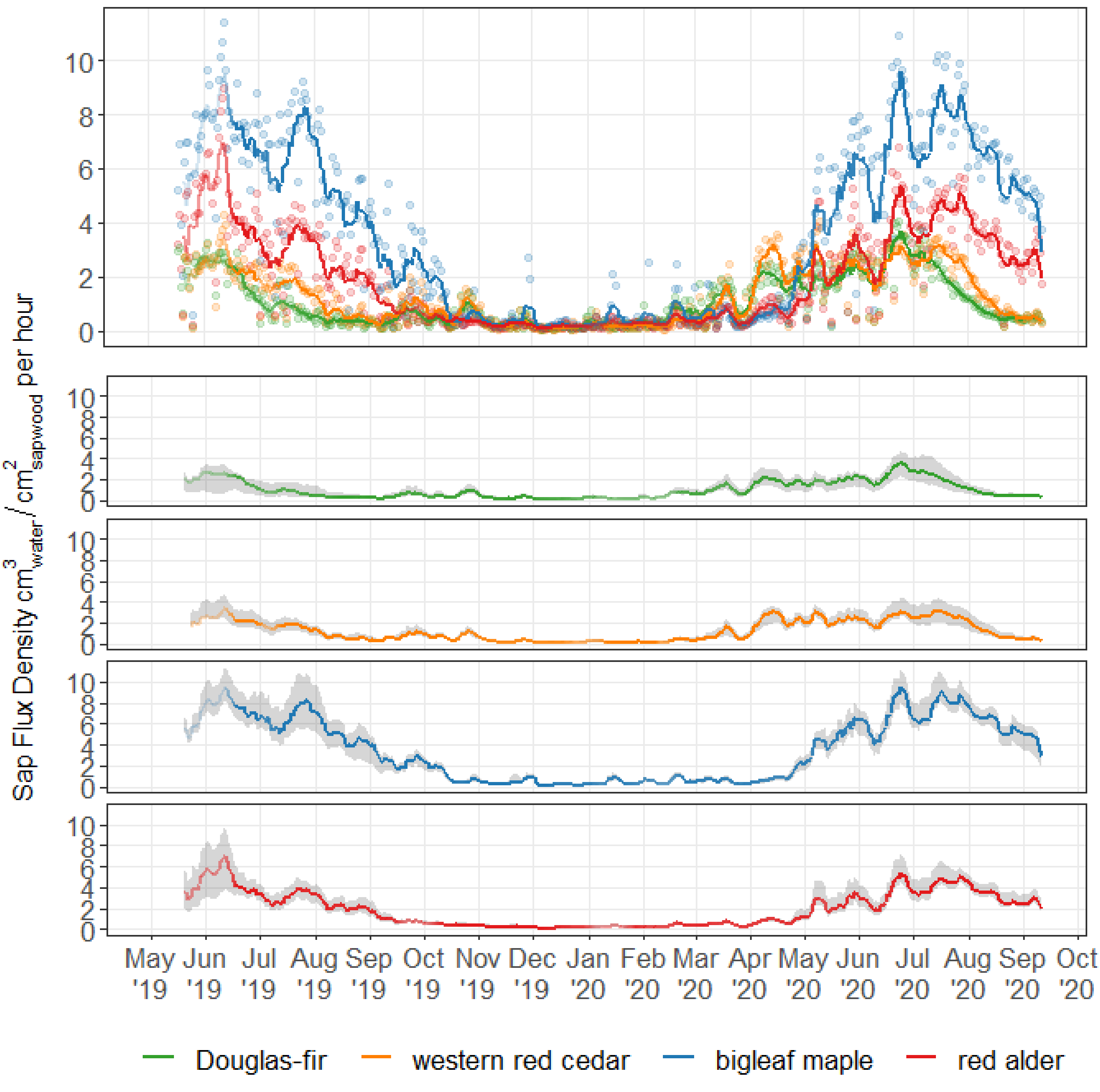


Figure 4: Data points show average daily medians and lines represent 7-day centered rolling means. Shaded areas shown on plots for individual tree species represent the interquartile range (IQR) bounded by the 25th and 75th percentiles. Line transparency controlled by percentage of active trees

4. Interception

4.1. Throughfall Troughs

Throughfall troughs were made of two slotted 4" PVC pipe transects extending from the tree bole to the drip line underneath the canopy. The total area of the openings in these troughs that collect rainfall making its way through the tree canopy, is approximately $300^2\ in.$. A rain gauge with a diameter of 6.5 $in.$ was installed at the point of intersection of the two pipes so that water collected by the troughs pour into this rain gage. Measurements collected by the rain gage were then used to calculate the volume of throughfall and then corrected for the area of the openings in the interception troughs. Interception was then calculated by subtracting these corrected throughfall measurements from the total rainfall measured by the weather stations.

Figure 6 shows the 30-storm average interception as measured with throughfall troughs. Sizable well-separated storm events for each month of the study were chosen (except for July 2020 due to lack of precipitation).

Figure 5: Red alder canopy at the Evergreen State College Organic Farm plot during leaf-off in fall of 2019.

Figure 3. 30 Storm Median Interception by Species

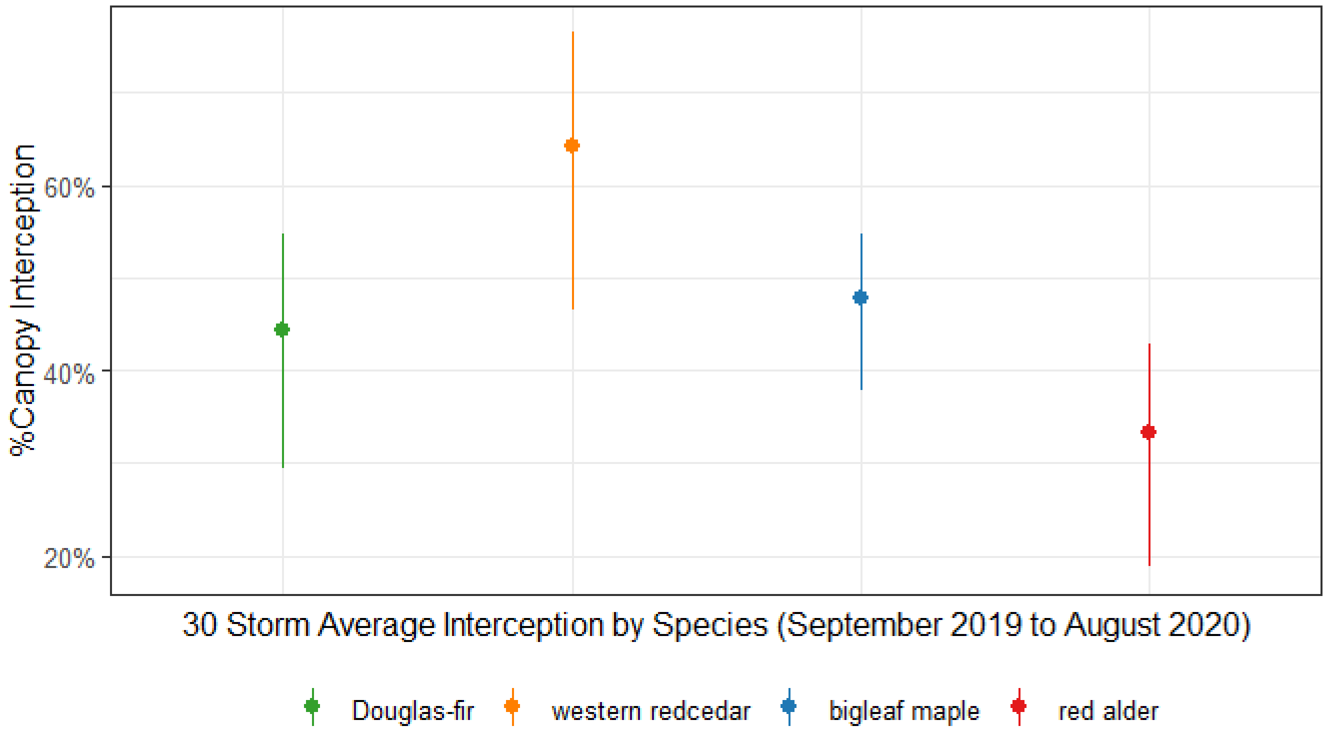


Figure 6: Data points show medians and lines represent the IQR. Measurements from 30 storms that occurered between Sep 08, 2019 and Aug 21, 2020 were used to develop this information

4.2. Stem Flow

Stem flow was measured by affixing collars to 12 trees at each site (24 trees total). A tube was installed to transfer water collected by the collars to a four-gallon bucket placed at the base of each tree. The contents of the buckets were routinely emptied and the volumes of water decanted from them recorded. These stemflow measurements will be used to offset canopy interception since the volume of water measured by these collars is essentially rainfall not being intercepted by the tree's canopy.

Table 7 shows measured stemflow volumes for 13 events in 2020 at each of the 24 trees across the four study species (*DF = Douglas-fir; WC = western red cedar; BM = bigleaf maple; RA = red alder*). Of the storms that contributed to stemflow measurements shown here, rainfall depths ranged from 3.5 mm to 75.7 mm. Storm event duration, defined as the time between collections, ranged from 3 to 30 days. Longer durations between collection events were often associated with larger stemflow volumes.

Stemflow data normalized by tree diameter and total precipitation between collections is shown in *Figure 8*. We chose to depict stemflow data in terms of the stem funneling ratio. The stem funneling ratio is the volume of water collected divided by the total volume of water generated by precipitation between collections given the area of the tree's stem. Values greater than 100% suggest that rainfall is being funneled by the tree's canopy to its stem. Tree canopy area will eventually be incorporated into the funneling ratio.

Figure 7: Stem flow buckets placed beneath stem flow collars on a Douglas-fir (left) and bigleaf maple (right).

Table 7. Volume of Stem Flow Water Collected for 13 Events in 2020

	Volume of Stem Flow Water Collected (mL)												
	02-11	02-24	03-27	03-31	04-24	04-27	05-04	05-07	05-15	05-18	05-27	06-01	06-16
1-4-RA	8980	1112	1660	7210	265	1285	2622	164	1200	1870	72	36	3590
1-6-RA	5950	1350	1610	6350	153	800	2458	119	854	1858	128	78	3185
2-4-BM	1530	130	20	1508	0	93	154	25	12	42	0	0	90
2-5-BM	13850	170	61	395	0	24	64	3	35	54	0	0	100
2-6-DF	15000	949	494	6928	170	344	242	89	187	192	32	10	1095
2-7-DF	8240	523	45	2885	0	54	88	69	0	0	0	0	10
3-4-WC	7335	230	128	2941	0	48	69	3	22	108	0	0	0
3-5-WC	15000	560	158	10840	5	93	210	31	206	148	18	4	260
3-8-WC	15000	1180	249	15000	0	102	660	0	689	172	2	0	1660
4-1-RA	7223	1490	2070	8531	1130	2640	2400	318	2560	2457	346	150	7555
4-6-BM	2000	1140	520	3584	185	711	1072	82	808	678	49	42	1930
4-8-DF	7580	865	184	3859	30	178	269	28	178	160	6	14	445
5-6-RA	14217	105	3	15	0	0	1149	3	0	540	3	0	3310
5-7-DF	9985	90	94	310	3	0	24	0	0	59	0	0	0
6-8-DF	15000	45	43	445	0	18	28	0	0	0	0	0	0
7-5-WC	13695	0	0	250	0	0	20	0	3	36	0	0	40
7-6-WC	2805	0	0	1060	0	2	53	3	0	0	0	0	210
7-7-WC	15000	47	67	1810	0	130	62	0	0	30	0	0	390
8-1-BM	5645	0	174	310	2	64	102	2	19	80	0	0	320
8-2-BM	11420	35	45	1420	3	82	124	3	60	95	0	0	220
8-3-BM	15000	0	0	865	0	0	104	3	0	32	0	0	0
8-5-DF	15000	1460	164	15000	162	1758	282	8	162	246	16	20	5354
8-7-RA	15000	1248	2000	15000	1374	5218	3050	7	681	2126	5	34	8948
8-8-RA	15000	10	330	10010	618	2560	2030	11	389	1015	15	48	5848

Figure 5. Stem Flow Expressed as Stem Funneling Ratio

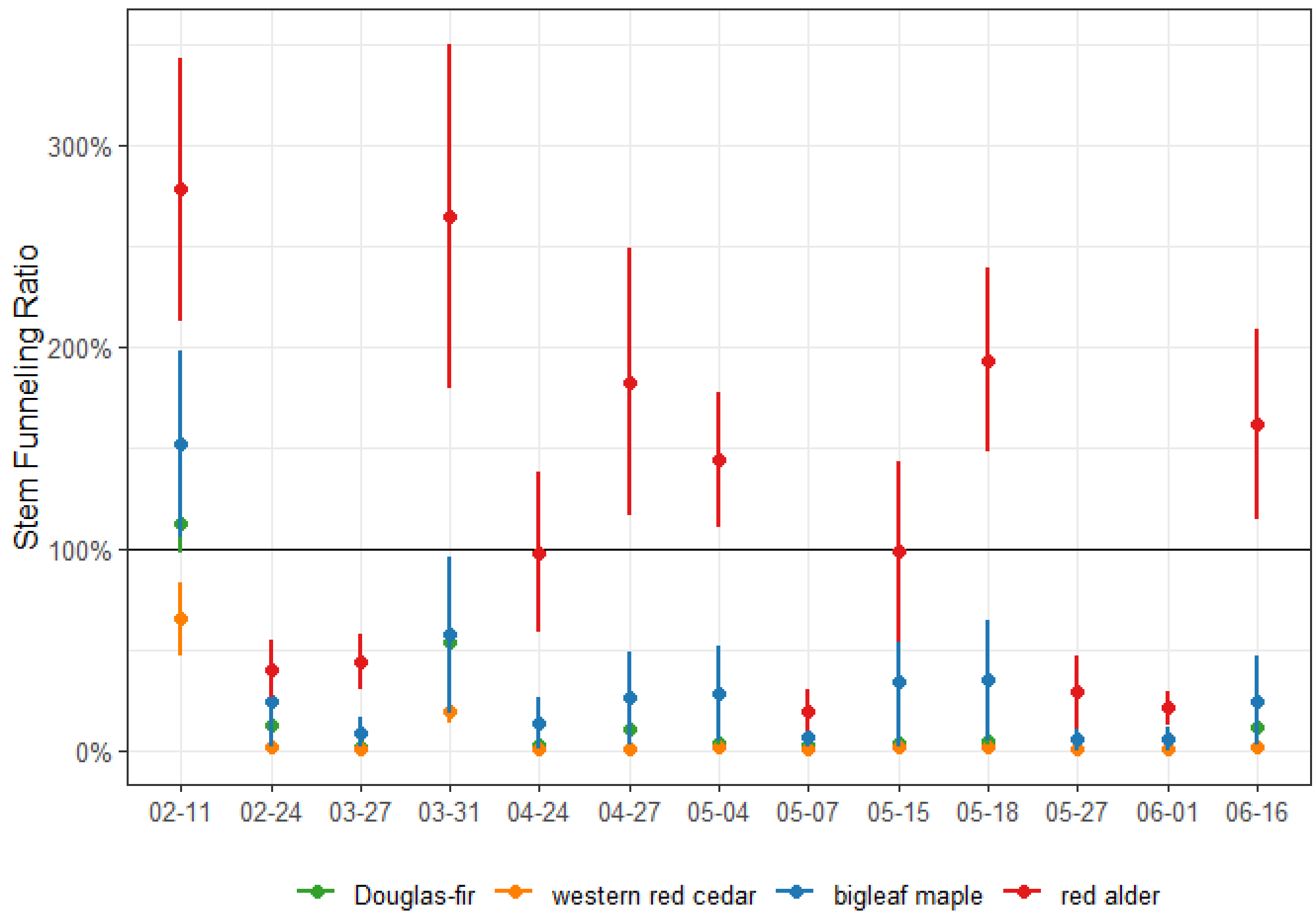


Figure 8: Data points show means; error bars show standard error

4.3. Putting it All Together

Ultimately, this study will deliver individual tree water use (ITWU) budgets as a range for each tree species by season. ITWU in terms of transpiration and interception will be estimated separately because the former is measured on a continuous basis, while the latter collected around storm events. These values may be combined for seasonal or annual estimates.

Transpiration $ITWU_t$ can only be calculated after assuming a sapwood depth and an attenuation profile for sap flux measurements. The following formula and example shows this calculation.

$$ITWU_t = Average\ Sap\ Flux\ Density \times Sapwood\ Area$$

Where,

ITWU is calculated in $Lday^{-1}$,

average sap flux density is expressed in $L_{water}cm_{sapwood}^{-2}day^{-1}$ and is adjusted for attenuation,

sapwood area in cm^2 is calculated from sapwood depth given diameter at breast height ($Sapwood\ Area = Basal\ Area\ (\pi r_{tree}^2) - Heartwood\ Area\ (\pi r_{heartwood}^2)$).

As an example, the highest median sap flux values in the study so far were observed in July 2020 for a bigleaf maple at 7.88 $cm_{water}^3 cm_{sapwood}^{-2} hour^{-1}$. This value expressed in terms of a daily timeframe is 0.19 $L_{water}cm_{sapwood}^{-2}day^{-1}$. The median diameter at breast height for the 15 bigleaf maples in this study is 41.66 cm which gives us a basal area of 1363.10 cm^2. If a sapwood depth of 10 cm ($heartwoodarea = 368.34\ cm^2$) was assumed (approximately 50% of the tree's radius) without attenuation then the transpirative ITWU is:

$$ITWU_t = 0.19\ Lcm^{-2}day^{-1} \times (1363.10\ cm^2 - 368.34\ cm^2) = 189\ Lday^{-1}$$

However, with better and more accurate sapwood depth estimates, and attenuation curves, this value will be refined. The assumptions made above are crude and the calculated $ITWU_t$ is likely overestimated.

Interception $ITWU_i$ can only be calculated for a storm event after measuring canopy area for every individual study tree. While we have not done this yet, the following formula and example show this calculation with an assumed canopy area:

$$ITWU_i = Average\ \%Interception \times Precipitation \times CanopyArea - Average\ Stem\ Flow\ Volume$$

Where,

ITWU is calculated in $Lstorm^{-1}$,

precipitation is the total depth of rainfall for a storm event in cm,

canopy area is in cm^2,

and average stem flow volume is in cm^3.

Values are divided by 1000 to convert from mL (cm^3) to L.

As an example, assume the average interception for Douglas-fir is 40%, and the crown radius of that tree's canopy is $300cm$ ($Canopy\ Area = 282{,}743.30\ cm^2$); then a 1 cm storm event with a stem flow volume of $500cm^3$ will give an $ITWU_i$ calculation of:

$$ITWU_i = (0.40 \times 1\ cm \times 282{,}743.30\ cm^2 - 500cm^3)/1000 = 112.60\ Lstorm^{-1}$$

While the measurements and calculations shown above are mostly to illustrate how the data might be used to yield ITWU estimates, the assumptions made are very general and are will be refined considerably. Ultimately, we will be calculating these estimates by tree species, by season, and over the two years of planned data collection.