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Water Uptake by Mountain Big Sagebrush (*Artemisia tridentata* subsp. *vaseyana*) and Environmental Variables Affecting Water Availability in Semiarid Rangeland Ecosystems

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Abstract: The sagebrush steppe ecosystem plays a critical role in water cycling in arid and semiarid landscapes of the western United States; yet, there is limited information regarding individual sagebrush plant water uptake. We used the stem heat balance (SHB) method to measure transpiration in mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana*) plants in a semiarid rangeland ecosystem in central Oregon, Pacific Northwest Region, USA. We evaluated the relationship between sagebrush transpiration and environmental factors from July 2022 to May 2023 for two individual plants representative of the average sagebrush stand height and crown width at the study site; transpiration rates varied by plant and by season. This study encompassed one below-average (2022; 278 mm) and one above-average (2023; 414 mm) precipitation years. Study results showed that the average water use during the entire period of study was 2.1 L d^{-1} for Plant 1 and 5.0 L d^{-1} for Plant 2. During the dry year, maximum transpiration was observed during the summer (Plant 1 = 4.8 L d^{-1}; Plant 2 = 11.1 L d^{-1}). For the wet year, both plants showed maximum transpiration levels at the end of the recording period in mid-May (Plant 1 = 9.6 L d^{-1}; Plant 2 = 8.6 L d^{-1}). The highest seasonal transpiration of both plants occurred in summer (2.87 L d^{-1}), whereas the lowest transpiration was obtained in winter (0.21 L d^{-1}). For all seasons but winter, soil moisture (*SM*), soil temperature (*ST*), and vapor pressure deficit (*VPD*) variables generally showed positive correlations with transpiration. Transpiration rates decreased in the summer of 2022 as the surface soil gradually dried. The two plants' most significant water uptake differences were obtained during the dry year. It is possible that the larger stem diameter of plant 2 may have contributed to its higher transpiration rates during times of limited water availability. The study results add to the understanding of water use by sagebrush and its potential impact on the water balance of cool-climate rangeland ecosystems. The findings also highlight the sensitivity of sagebrush to variations in seasonal soil moisture availability, soil temperature, and vapor pressure deficit. Future research should involve studying the combined effects of water use by various dominant vegetation species and its effects on the water budget at the watershed scale.

Keywords: semiarid rangelands; mountain big sagebrush; transpiration; soil moisture; soil temperature; vapor pressure deficit

1. Introduction

The sagebrush steppe ecosystem covers approximately 43 million ha in the arid and semiarid western United States [1]. It provides essential ecosystem services, including wildlife habitat, forage provisioning for wildlife and livestock [2–4], water provisioning [5,6], carbon sequestration [7,8], and a favorable environment for a diverse set of herbaceous plant species [9]. Sagebrush plants are known for their ability to survive in water-limited conditions by physiological adaptation [10]. Sagebrush carries out hydraulic redistribution, the movement of water upwards [11,12], upwards and downwards [10],

and in both directions as well as laterally [13] through its roots. Redistributing water from deeper soil layers to shallower ones increases water availability for the sagebrush and may also positively affect nearby plants [14].

The sagebrush steppe is among the most threatened landscapes in North America [15]. The loss of sagebrush ecosystems is a significant concern, posing existential threats to biodiversity and land management in the western United States [16]. Over the past century, large areas of sagebrush have been removed, modified, or fragmented [16,17] due to multiple factors, including conversion of these native ecosystems to agriculture [18], energy extraction activities [19], and expansion of woody vegetation species [20]. Various studies have shown that reducing woody vegetation stands such as juniper (various species) can positively influence the recovery of impaired sagebrush-dominated landscapes. Studies conducted in rangeland ecosystems in Oregon, USA, show that juniper stand reduction significantly increased grass and sagebrush cover [21,22]. Compared to untreated sites, higher surface and subsurface water levels were obtained in landscapes where sagebrush became the dominant overstory species after juniper removal [23].

Water is a critical resource for plant growth in arid and semiarid environments [24]. Various environmental factors influence the amount of water available for plants to use. Vapor pressure deficit (*VPD*), indicative of atmospheric water demand, has been identified as a significant driver of vegetation water use in semiarid sagebrush ecosystems [25,26]. Other factors, such as antecedent soil moisture and precipitation timing and intensity, can affect the capacity of the system to capture and redistribute water throughout the landscape [23].

Due to the typical dry environment where sagebrush plants grow, evapotranspiration losses can be substantially high, accounting for most or all of the moisture available. A study conducted by Missik et al. [27], conducted on an upland sagebrush ecosystem in central Washington, USA, showed that total annual evapotranspiration (250 mm) exceeded precipitation (224 mm). Durfee and Ochoa [6] estimated evapotranspiration to range between 210 and 260 mm yr^{-1} (mean of 242 mm yr^{-1}), accounting for the most significant portion (83%) of the annual water budget in a sagebrush-dominated watershed in central Oregon, USA. However, these studies did not account for the portioning of plant water use (transpiration) and direct evaporation losses.

Different sagebrush subspecies can exhibit substantial differences in water uptake. A study by Sharma et al. [5] showed that *Artemisia tridentata* subsp. *vaseyana* transpired nearly four times more water than *Artemisia tridentata* subsp. *wyomingensis*. Mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana*) is the most widespread sagebrush subspecies in Oregon and the surrounding region [28], and it is the subspecies present at our study site.
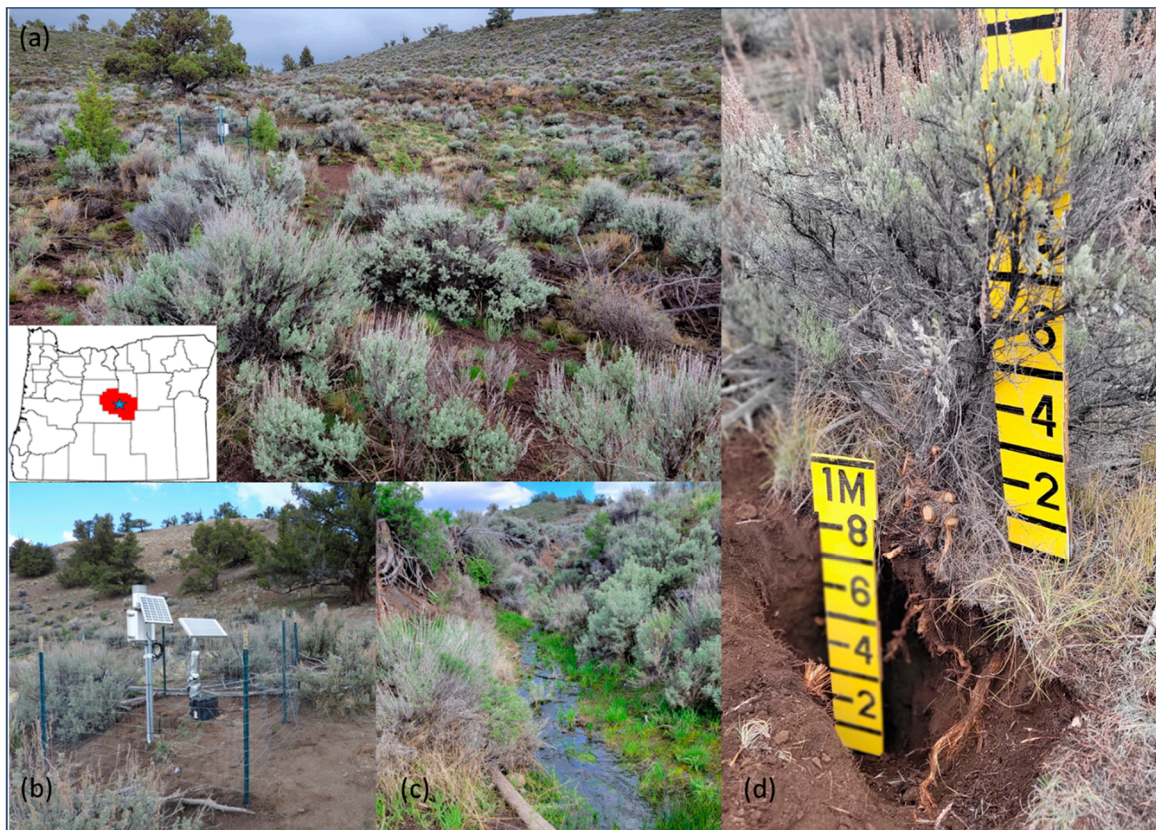
Despite the importance of sagebrush plant communities in regulating water cycling and consequently on the ecological function of water-limited regions, the body of literature on water use by sagebrush plants is limited. Moreover, studies considering the interactions between the environment and individual sagebrush plant water uptake throughout the year are practically non-existent. This study evaluated the seasonal dynamics of sagebrush plant transpiration and various environmental factors of interest in a cool-climate rangeland ecosystem in central Oregon, USA. The study objectives were to (1) determine the amount of water uptake by mountain big sagebrush and (2) assess the relationship among mountain big sagebrush transpiration, soil moisture, soil temperature, and vapor pressure deficit.

2. Materials and Methods

2.1. Study Site

This study was conducted at the Camp Creek Paired Watershed Study (CCPWS) site (43.96° lat.; −120.34° W long.) established in 1994 to evaluate vegetation and hydrology changes following the cutting of western juniper [23]. The CCPWS is located in the semiarid rangelands of central Oregon, USA, and comprises an area of approximately 500 ha, including a 116 ha watershed where mountain big sagebrush is now the dominant

overstory vegetation following the removal of approximately 90% of juniper trees in 2005 (Figure 1). Herbaceous vegetation is dominated by Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and Sandberg bluegrass (*Poa secunda*). Based on data collected in 2014 [22] from 143 ten-meter transects (*n* = 1430) distributed throughout the treated watershed, sagebrush canopy covered 9.9% of the total area. Sagebrush cover was much lower (3.4%; *n* = 1450) in the adjacent 96 ha, juniper-dominated watershed used as the control. The elevation at CCPWS ranges from 1370 m to 1524 m. The mean annual precipitation based on onsite data collected from 2005 to 2023 is 312 mm. Most precipitation in the study site occurs as a mix of rain and snow during fall and winter, with few rainfall events in spring and summer.

Figure 1. The location of the study site in Crook County, central Oregon, is indicated in the outline map (not to scale) of the state of Oregon, USA. Images taken in 2023 show the distribution of sagebrush throughout the study site. In (**a**), sagebrush now occupies the landscape where juniper trees were removed in 2005. The study site's monitoring station for soil moisture, temperature, precipitation, and plant transpiration variables is shown in (**b**). The presence of sagebrush plants next to the stream near the monitoring station is illustrated in (**c**). The depth of the root zone for a 1.2 m tall sagebrush plant at the study site is shown in (**d**).

Seasonal streamflow and augmented springflow levels in response to snowmelt runoff are observed in the spring season in years where enough snowpack accumulation (>15 cm) allows for soil saturation and percolation past the root zone that ends in lateral flow into the streams (Figure 1). Following the snowmelt runoff season, the stream network is considered ephemeral for the rest of the year, responding to infrequent convective storms occurring primarily in the summer. Soil texture determined from samples collected during soil moisture sensor installation was classified as sandy loam for all sampling depths [29]. Previous work by Abdallah et al. [8] shows that topsoil (0.25 m) soil carbon content at the study site is about 2%.

2.2. Sap Flow Measurements and Estimation of Transpiration

The stem heat balance (SHB) method was used in collecting sap flow data to determine transpiration values from two sagebrush plants between July 2022 and May 2023. The two plants were selected based on an average representation of mature sagebrush plants found at the study site. The plants are located in a hillslope near the outlet of the watershed and at 23 m distance, 10 m higher, from the nearest stream.

One branch in the two sagebrush plants was equipped with an SHB gauge (models SGB19 and SGB25, Dynamax Inc., Houston, TX, USA) to monitor sap flow. Sap flow measurements were recorded every 15 min using SapIP dataloggers (Dynamax Inc., Houston, TX, USA). These sap flow data were computed to obtain daily transpiration values (L d^{-1}) for each equipped branch.

The ratio of sap flow to branch diameter was calculated. To calculate the transpiration of the whole plant, we used the branch daily estimates and the diameter of all branches coming out of the main stem close to the soil surface. For plant 1, the mean diameter for 18 measured branches was 21 mm, ranging from 10 to 33 mm. For plant 2, the mean diameter for 15 measured branches was 28 mm, ranging from 18 to 41 mm. Other morphological features such as plant height, crown width, and branch length were measured for each equipped plant (Plant 1 and Plant 2). The two equipped plants were harvested at the end of the experiment in the fall of 2023. All leaves were removed, oven-dried at 40 °C for 24 h, and weighed. Leaf area cover was calculated using a 2500 mm^2 grid. This process was replicated ten times to get average leaf area and dry weight estimates used to estimate sagebrush leaf biomass (g m^{-2}). The obtained mean leaf biomass value and the total weight of the dried leaves for each branch were used to calculate the leaf area for each equipped branch (Table 1).

Table 1. Sensor information and characteristics of sagebrush plants.

	Plant 1	Plant 2
SHB sensor model	SGB19	SGB25
Plant height (m)	1.37	1.38
Crown area (m^2)	1.80	1.70
Equipped branch length (m)	1.26	1.25
Equipped branch diameter (mm)	23.0	32.0
Equipped branch leaf area (m^2)	0.26	0.16

2.3. Environmental Variables

Environmental data used in this experiment were obtained from onsite instrumentation (Campbell Scientific, Inc., Logan, UT, USA), including a weather station and a soil moisture (*SM*) and soil temperature (*ST*) station. The weather station is 77 m to the west and slightly south of the *SM* and *ST* station, which is installed next to the monitored sagebrush plants. An additional rain gauge (Model RG3, Onset Computer, Corp., Bourne, MA, USA) was installed next to the *SM* and *ST* station. Precipitation (*Pr*) was obtained from the RG3 rain gauge. Relative humidity (*RH*), air temperature (*AT*), and solar radiation (*SR*) data were obtained from the nearby weather station. The *SM* and *ST* data were collected using sensors (Model CS655, Campbell Scientific, Inc., Logan, UT, USA) installed at 0.2, 0.5, and 0.8 m depths. The values of *SM* and *ST* across soil depths (0.2, 0.5, and 0.8 m) were used to obtain an average *SM* and *ST* (SM_{tot} and ST_{tot}) for each monitoring station's 0 to 0.8 m soil profile. All data were collected hourly and then used to obtain daily average values. We calculated vapor pressure deficit (*VPD*) based on daily averaged values of *AT* and *RH*, as described in Ochoa and Abdallah [26].
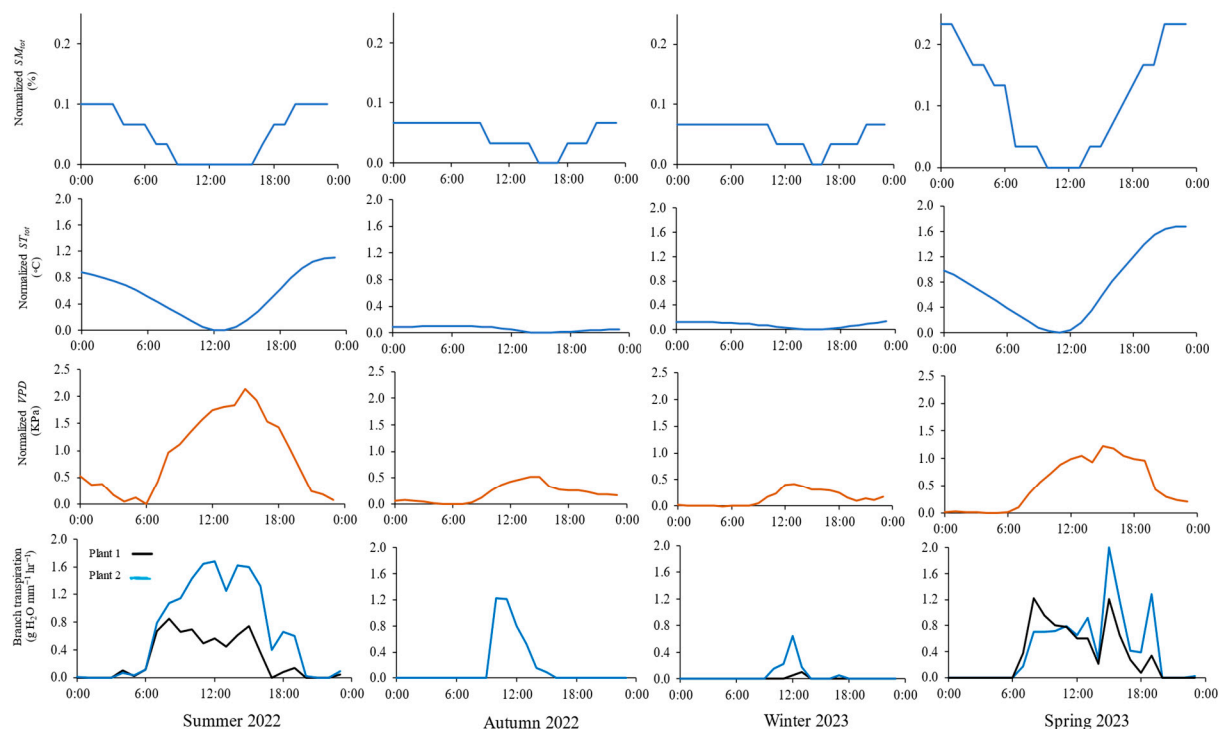
2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed to assess *SM* and *ST* variability by soil depth. The ANOVA test was also used to compare mean transpiration by sagebrush plant (Plant 1 vs. Plant 2) and by seasonal period (summer, autumn, winter, and

spring). A Spearman rank order correlation test was conducted to evaluate the relationships between sagebrush transpiration and the environmental variables. All statistical analyses were performed using SigmaPlot® version 15.0 (Systat Software, Inc., San Jose, CA, USA).

3. Results

3.1. Diurnal Courses of Environmental Variables and Transpiration

Figure 2 shows the diurnal variation in normalized SM_{tot}, ST_{tot}, VPD, and branch-level transpiration on four days (19 August, 24 November, 19 February, and 11 May), representative of environmental conditions in summer 2022, autumn 2022, winter 2023, and spring 2023, respectively. Generally, SM_{tot} and ST_{tot} peaked in the morning and tapered off throughout the day. Compared to the average environmental conditions of autumn 2022 and winter 2023, greater diurnal normalized SM_{tot} and ST_{tot} variations occurred in summer 2022 and spring 2023, indicating relatively higher transpiration rates in those seasons. The VPD increased rapidly in the early morning (between 6:00 and 8:00), peaked at noon (13:00 for winter 2023 and 15:00 for summer 2022, autumn 2022, and spring 2023), then dropped until midnight. Dynamics of transpiration reflected VPD values, but they were not necessarily synchronized. Transpiration increased rapidly in the early morning, reaching peak values (1.7, 1.2, 0.6, and 2.0 g mm^{-1} h^{-1}) between 10:00 and 15:00 for summer 2022, autumn 2022, winter 2023, and spring 2023 average environmental conditions, respectively. Then, it declined significantly, reaching minimum values of <0.1 g mm^{-1} h^{-1} at night. The relatively lowest transpiration rates recorded for autumn 2022 and winter 2023 were attributed to the low atmospheric evaporative demand represented by lower normalized ST_{tot} and VPD.
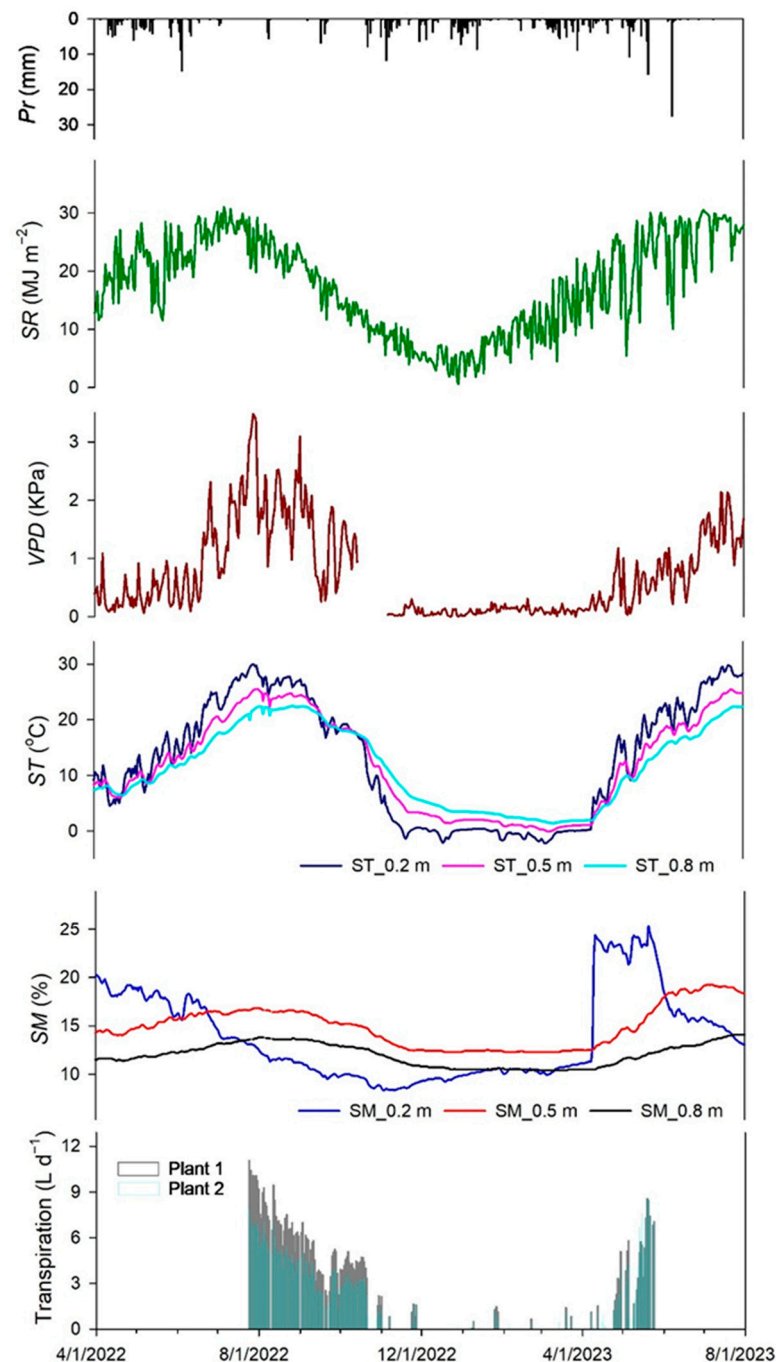

Figure 2. Diurnal courses of normalized soil moisture and soil temperature averaged over the upper 0.8 m soil profile (SM_{tot} and ST_{tot}, respectively), vapor pressure deficit (VPD), and branch-level transpiration (from sap flux) for sagebrush plants for the average environmental condition of summer 2022, autumn 2022, winter 2023, and spring 2023.

3.2. Daily Fluctuation of Sagebrush Transpiration and Environmental Variables

Figure 3 illustrates the daily averaged fluctuations of Pr, SR, VPD, SM, and ST levels between 1 April 2022 and 31 August 2023. Also, it shows the transpiration data collected

from 24 July 2022 to 23 May 2023. Total annual precipitation for the two years (2022 and 2023) encompassing this study was highly variable. Below-average precipitation records (278 mm) were obtained in 2022, following five other years of severe drought in the region.

Figure 3. Daily fluctuation of several environmental variables and sagebrush transpiration rates measured for 2022 and 2023. Environmental variables are precipitation (*Pr*), solar radiation (*SR*), vapor pressure deficit (*VPD*), and soil moisture (*SM*) and soil temperature (*ST*) at different soil depths (0.2, 0.5, and 0.8 m).

Conversely, 2023 was an above-average precipitation (414 mm) year characterized by a winter mix of rain and snow that provided early spring moisture.

Overall, mean transpiration values for the evaluation period were higher for plant 2 (5.0 L d^{-1}) than for plant 1 (2.1 L d^{-1}). During the dry year, the maximum transpiration

values were obtained at the beginning of this study in July (11.1 L d^{-1} for plant 2 and 4.8 L d^{-1} for plant 1). For the wet year, both plants showed maximum transpiration levels at the end of the recording period in mid-May (Plant 1 = 9.6 L d^{-1}; Plant 2 = 8.6 L d^{-1}). A transpiration sensor malfunction prevented data recording through the rest of the summer. Transpiration largely followed the seasonal soil and air moisture availability. The highest transpiration rates corresponded to the highest *VPD* values observed in the summer of 2022.

Similarly, the higher winter precipitation resulting in increased *SM* levels in the spring of 2023 corresponded to the higher transpiration levels observed that year. The ANOVA results showed significant *SM* differences ($p < 0.001$) among *SM* sensor depths, with greater *SM* values at 0.5 m depth ($SM_{0.5}$) and lower *SM* values at 0.8 m depth ($SM_{0.8}$). Transpiration levels began a steady decline through late summer and autumn following the drying of the soil, particularly at *SM* at 0.2 m depth ($SM_{0.2}$), indicating the potential time at which *SM* became a limiting factor for transpiration. The *VPD* levels peaked in July with an average of 1.92 and 1.51 KPa in 2022 and 2023, respectively.

Throughout this study, *SR* and *ST* exhibited a similar trend; both were lower in the cold months and gradually rose to the maximum in the warm months. There were significant *ST* differences ($p \leq 0.05$) by sensor depth during the observation period, with *ST* at 0.2 m depth ($ST_{0.2}$), generally showing higher values during the spring and summer, followed by *ST* at 0.5 m depth ($ST_{0.5}$) and *ST* at 0.8 m depth ($ST_{0.8}$). This condition was the opposite during late fall and winter.

3.3. Seasonal Transpiration and Its Response to Environmental Variables
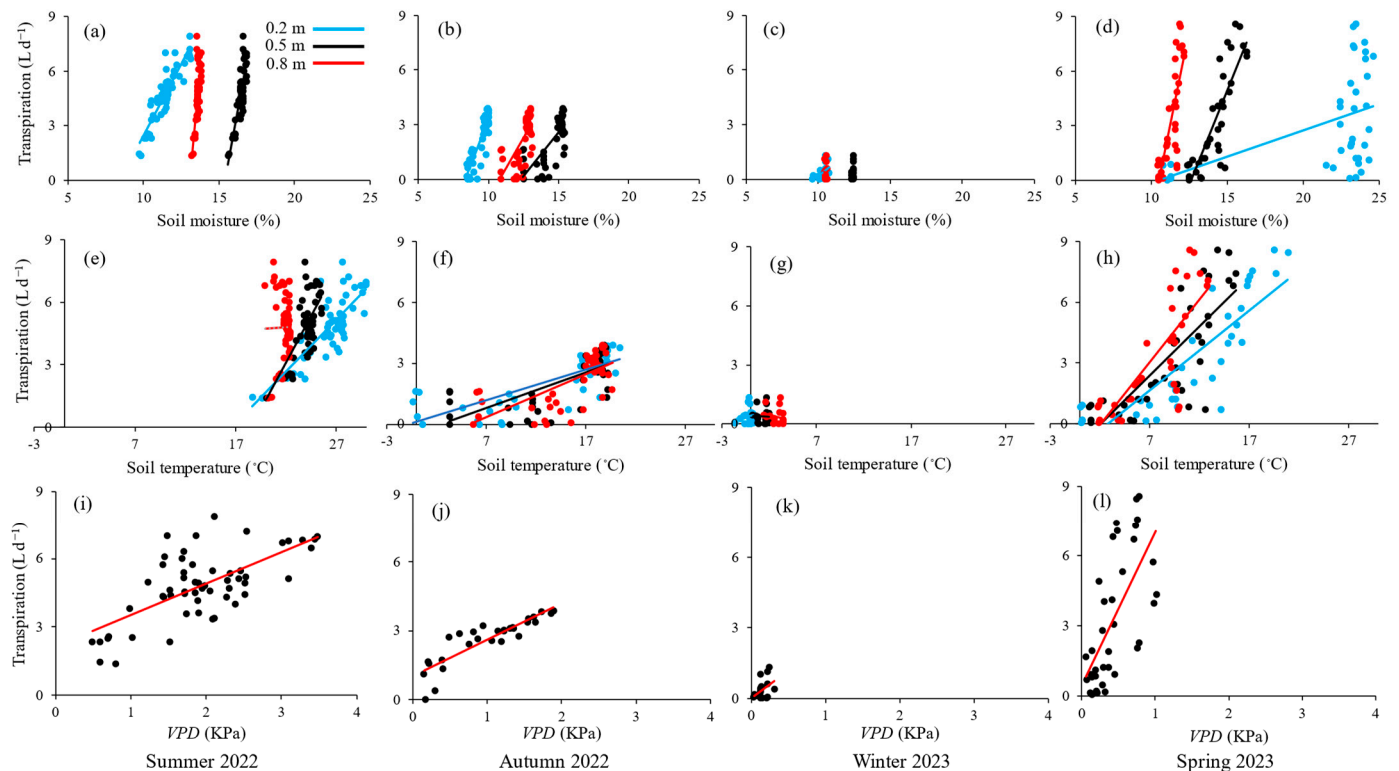
Table 2 shows seasonal transpiration estimates based on sagebrush sap flow data recorded between 24 July 2022 and 23 May 2023. The highest seasonal mean transpiration values for plants 1 (2.87 L d^{-1}) and 2 (6.71 L d^{-1}) were obtained during the summer of 2022. Transpiration rates for both plants decreased to a mean value of 2.46 L d^{-1} in autumn 2022, corresponding with the expected reduction in evaporative demand toward the end of the year. A sharp decline in transpiration rates occurred for both shrubs during winter 2023, with a mean value of 0.58 L d^{-1}. In the spring of 2023, plants became more active, and transpiration was significantly higher ($p \leq 0.05$) than during the winter and autumn seasons, with an average of 3.25 L d^{-1}. The results from the ANOVA test showed that plant 2 had a higher transpiration rate than plant 1 for all seasonal periods. Across seasonal periods, the highest transpiration values were observed in summer 2022, followed by spring 2023, autumn 2022, and winter 2023.

Table 2. Mean value $\pm$ standard error of transpiration rates of sagebrush, averaged by individual plant and by all plants for summer 2022 (24 July to September 20), autumn 2022 (21 September to 20 December), winter 2023 (21 December to 20 March), and spring 2023 (21 March to 23 May). Different lowercase letters (a, b) along rows indicate significant differences ($p \leq 0.05$) in mean transpiration rate by plant for each season. Different uppercase letters (A, B, C, D) along columns indicate mean transpiration differences ($p \leq 0.05$) by season for all plants. Numbers in parentheses in plant 1 and plant 2 represent the number of days when sap flow data were collected for each individual plant. Numbers in parentheses for both plants represent the number of averaged days using data from at least one plant.

Season, Year	Mean Transpiration Rate (L Day^{-1})		
	Plant 1	Plant 2	Both Plants
Summer 2022	2.87 $\pm$ 0.13 (56) Ab	6.71 $\pm$ 0.28 (56) Aa	4.79 $\pm$ 0.20 (56) A
Autumn 2022	1.35 $\pm$ 0.13 (41) Cb	3.56 $\pm$ 0.22 (38) Ca	2.46 $\pm$ 0.18 (45) C
Winter 2023	0.21 $\pm$ 0.06 (15) Db	0.94 $\pm$ 0.20 (7) Da	0.58 $\pm$ 0.10 (17) D
Spring 2023	2.12 $\pm$ 0.50 (26) Bb	4.37 $\pm$ 0.46 (26) Ba	3.25 $\pm$ 0.46 (36) B

Stronger relationships between sagebrush's transpiration and the environmental variables *SM*, *ST*, and *VPD* were observed in spring, summer, and autumn, whereas a more

muted response was noted in the winter (Figure 4). A positive correlation between transpiration and *SM* at all depths was noted. The greatest rate of change between *SM* and transpiration was obtained for $SM_{0.2}$ during the spring and summer. The highest variability, with $SM_{0.2}$ levels ranging from 11% to 25% and corresponding transpiration values ranging from 0.05 to 9 L d^{-1}, was observed in the spring. The relationships between transpiration and $SM_{0.2}$ was stronger than with *SM* at deeper soil layers for summer, autumn, and winter. In spring, sagebrush's transpiration was more influenced by the $SM_{0.5}$ compared to other soil depths, indicating that the transpiration process relied heavily on the moisture available at this depth.

Figure 4. Relationships of transpiration to soil moisture (**a–d**) and soil temperature (**e–h**) at various depths, and vapor pressure deficit, *VPD* (**i–l**), in summer 2022, autumn 2022, winter 2023, and spring 2023.

A positive correlation between transpiration and *ST* at all depths was also obtained. The $ST_{0.2}$ has a more significant relationship with transpiration than *ST* at deeper depths. The greatest rate of change was observed during the autumn, with $ST_{0.2}$ levels ranging from −0.4 °C to 20.5 °C and transpiration values ranging from near zero to 3.9 L d^{-1}. As expected, the greatest rate of change in the relationship between transpiration and *VPD* was obtained for the drier months in the summer, followed by autumn, spring, and winter (Figure 4).

The Spearman rank order correlation test showed that *SM* at all depths showed great explanatory power for transpiration variability for summer 2022, autumn 2022, and spring 2023 seasons, with a stronger effect recorded for SM_{tot} ($\rho = 0.93$, $p < 0.001$, $n = 36$) in spring 2023 (Table 3). Except for the relationship between transpiration and $ST_{0.8}$ in summer 2022 ($\rho = -0.10$, $p > 0.05$, $n = 56$), *ST* also had a positive correlation with transpiration at all depths, which was most significant at $ST_{0.2}$ ($\rho = 0.91$, $p < 0.001$, $n = 36$) in spring 2023. In winter 2023, the dependence of transpiration on *SM* and *ST* became either negative or not detectable, except for the positive correlation between transpiration and $SM_{0.2}$ ($\rho = 0.52$, $p \leq 0.05$, $n = 17$).

Table 3. Spearman's rank correlation coefficients between sagebrush's transpiration and *SM*, and *ST* at different soil depths, SM_{tot}, and ST_{tot}, and *VPD* for summer 2022, autumn 2022, winter 2023, and spring 2023.

Season, Year	$SM_{0.2}$	$SM_{0.5}$	$SM_{0.8}$	SM_{tot}	$ST_{0.2}$	$ST_{0.5}$	$ST_{0.8}$	ST_{tot}	*VPD*
Summer 2022	0.88 ***	0.76 ***	0.62 ***	0.73 ***	0.74 ***	0.49 ***	−0.10 ns	0.58 ***	0.54 ***
Autumn 2022	0.80 ***	0.66 ***	0.66 ***	0.72 ***	0.79 ***	0.65 ***	0.67 ***	0.72 ***	0.92 ***
Winter 2023	0.52 *	0.39 ns	−0.08 ns	0.46 ns	0.06 ns	−0.06 ns	−0.27 ns	−0.15 ns	0.31 ns
Spring 2023	0.47 **	0.85 ***	0.79 ***	0.93 ***	0.91 ***	0.84 ***	0.79 ***	0.88 ***	0.72 ***

*** = $p < 0.001$; ** = $p < 0.01$; * = $p \leq 0.05$; ns = not significant.

Transpiration and *VPD* were moderately correlated in summer 2022 (ρ = 0.54, $p < 0.001$, $n = 56$), very strongly correlated in autumn 2022 (ρ = 0.92, $p < 0.001$, $n = 29$), and strongly correlated in spring 2023 (ρ = 0.72, $p < 0.001$, $n = 36$). No significant correlation between transpiration and *VPD* was observed in winter 2023 (ρ = 0.31, $p > 0.05$, $n = 17$). The best predictor for transpiration variability was $SM_{0.2}$ in summer 2022 and winter 2023, SM_{tot} in spring 2023, and *VPD* in autumn 2022.

4. Discussion

This study quantified water uptake by mountain big sagebrush plants and evaluated its correlation with several environmental variables of interest (i.e., *SM*, *ST*, and *VPD*). Plant transpiration varied daily and seasonally, with maximum values obtained during the warm months and acute reductions during the cold months corresponding with decreasing *SM*, *ST*, *SR*, and *VPD*. Various other studies have reported similar patterns of seasonal water use in shrubs [30–32].

Even though the range of transpiration levels for the period of study was similar for both plants (0.01 to 9.6 L d⁻¹ for plant 1 and 0.1 to 11.1 L d⁻¹ for plant 2), their annual mean transpiration (2.1 vs. 5.0 L d⁻¹) and seasonal transpiration levels were different. The much greater seasonal transpiration levels for plant 2 compared to plant 1 were partly attributed to the larger total branch diameter obtained for this plant. The difference in transpiration levels between the two plants was exacerbated during the drier 2022 year, which resulted in higher air and soil moisture deficits. In the spring of the wetter 2023 year, the close peak transpiration values of 9.6 and 8.6 L d⁻¹ for plant 1 and plant 2, respectively, were attributed to the abundance of moisture available. Sagebrush plants have extensive root systems reaching depths up to 2 m [33,34]. Some studies have shown that sagebrush plants' productivity is strongly associated with shallow soil moisture [35,36]. Overall, water uptake by sagebrush plants in this study closely followed the pattern of $SM_{0.2}$ availability, with sagebrush water use declining as $SM_{0.2}$ levels depleted through the summer and increasing in response to an $SM_{0.2}$ rise during the spring snowmelt runoff season. The positive relationship between transpiration and $SM_{0.2}$ observed during winter suggested that sagebrush primarily used water from the surface soil layer in cold weather rather than penetrating deeper with its roots.

In response to cold temperatures, many plants, including shrubs, reduce their metabolic activities, including root growth and water uptake [37,38]. This is a survival strategy to conserve energy and resources during the harsh winter conditions. Therefore, in cold conditions, plants rely more on the water available in the surface soil layers, which are more easily accessible and require less energy to extract water from [39]. In the spring, when *SM* was abundant, the SM_{tot} was a strong predictor of water uptake by sagebrush. That means sagebrush could utilize water from the entire soil profile, which can contribute to their growth and survival.

The rise in *ST* in the spring, particularly near the surface ($ST_{0.2}$), stimulated increased transpiration rates by the sagebrush plants. The lower transpiration and *ST* levels observed in autumn and winter are consistent with reports by Onwuka and Mang [40], who found that low *ST* during winter can hinder plants' water uptake by reducing the transpiration

rate. Overall, results from this study are similar to other research showing that plant transpiration positively relates to *ST* [26,41,42].

Similar to *SM* and *ST*, transpiration sensitivity to the *VPD* explanatory parameter was positive in all seasons except winter. The association between *VPD* and transpiration became more evident in conditions where *SM* was low, such as in the autumn season. Under low *SM* conditions, a decrease in *VPD* likely led to a decrease in stomatal conductance, thereby reducing sagebrush transpiration. This aligns with various studies investigating vegetation water use in response to low *VPD* and water availability [43–45]. Stomatal conductance helps minimize plant water loss [46]. Under high *SM* conditions in spring, *VPD* was also an important environmental factor affecting the transpiration rate of sagebrush. Daily increases in *VPD*, co-occurring with *ST*, enhanced transpiration throughout the spring season. When *VPD* increases, it creates a more significant gradient for water to move from the plant to the atmosphere, which can increase the transpiration rate [47]. As *ST* rises, it can enhance plant roots' activity and cell membrane permeability, promoting water absorption [48].

The limitations of this study included the fact that the transpiration data collected were from only two plants. Caution should be exercised when extrapolating plant scale findings to the larger landscape scale. Also, some transpiration data were lost during early summer due to sensor malfunctioning. We may have missed the peak transpiration values during the warmest month in June in both years. Even though the data comprised nearly one year, and the data followed the expected distribution of seasonal weather: the first part (summer and fall) of the data was collected during a below-average precipitation year (2022; 278 mm), whereas the other part (most winter and spring) was collected in an above-average precipitation year (2023; 414 mm). This can lead to a less-accurate interpretation of seasonal transpiration and environmental relationships during average conditions. Other environmental factors not considered in this study may influence the sagebrush plant water dynamics observed. For example, studies indicate that reductions in leaf stomatal conductance under rising atmospheric carbon dioxide concentration (CO_2) may promote water use efficiency (WUE) to benefit plant growth, especially in water-limited ecosystems [49–51].

Results from this study provide essential information regarding mountain big sagebrush water use and its relations with various environmental drivers critical for the sustainability of arid and semiarid ecosystems. The project outcomes contribute to an enhanced understanding of soil–plant–water interactions in cool-climate rangeland ecosystems where restoration practices such as juniper stand reduction have been implemented. Similar efforts to control woody vegetation expansion and invasive grass species can be found in many other landscapes in the Pacific Northwest region, USA, and arid and semiarid landscapes worldwide. Future research involves studying the combined effects of water use by various dominant vegetation species, such as sagebrush and juniper, and the effects of vegetation water uptake on the water budget at the watershed scale.

Conflicts of Interest: The authors declare no conflicts of interest.

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