

1 **Aspect Differences in Vegetation Type Drive Higher Evapotranspiration on a Pole-facing**
2 **Slope in a California Oak Savanna**

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13 **Keywords:** evapotranspiration, aspect, soil moisture, remote sensing, oak savanna

14

15 **Key Points:**

16 • Higher evapotranspiration on cooler pole-facing slope than warmer equator-facing slope
17 within an oak savanna in a Mediterranean climate.

18 • Aspect-differences in plant functional groups and phenology drive observed
19 evapotranspiration variability.

20 • Higher evapotranspiration contributes to a drier subsurface on pole-facing slopes.

21

22 **Abstract**

23 Quantifying evapotranspiration is critical to accurately predict vegetation health, groundwater
24 recharge, and streamflow generation. Hillslope aspect, the direction a hillslope faces, results in
25 variable incoming solar radiation and subsequent vegetation water use that influence the timing
26 and magnitude of evapotranspiration. Previous work in forested landscapes has shown that
27 equator-facing slopes have higher evapotranspiration due to more direct solar radiation and
28 higher evaporative demand. However, it remains unclear how differences in vegetation type (i.e.,
29 grasses and trees) influence evapotranspiration and water partitioning between hillslopes with
30 opposing aspects. Here, we quantified evapotranspiration and subsurface water storage deficits
31 between a pole- and equator-facing hillslope with contrasting vegetation types within central
32 coastal California. Our results suggest that cooler pole-facing slopes with oak trees have higher
33 evapotranspiration than warmer equator-facing slopes with grasses, which is counter to previous
34 work in landscapes with singular vegetation types. Our water storage deficit calculations indicate
35 that the pole-facing slope has a higher subsurface storage deficit and a larger seasonal dry down
36 than the equator-facing slope. This aspect difference in subsurface water storage deficits may
37 influence subsequent deep groundwater recharge and streamflow generation. In addition, larger
38 root-zone storage deficits on pole-facing slopes may reduce their ability to serve as hydrologic
39 refugia for oaks during periods of extended drought. This research provides a novel integration
40 of field-based and remotely-sensed estimates of evapotranspiration required to properly quantify
41 hillslope-scale water balances. These findings emphasize the importance of resolving hillslope-
42 scale vegetation structure within Earth system models, especially in landscapes with diverse
43 vegetation types.

44 **Plain Language Summary**

45 Understanding how much water leaves hillslopes as evapotranspiration (i.e. evaporation and
46 plant water use) is important for predicting water storage and movement within hillslopes. Small
47 differences in solar radiation between adjacent hillslopes that face opposite directions can
48 produce contrasting plant water use and hillslope water storage patterns. However, previous
49 studies have focused on landscapes with trees on either hillslope. It remains unclear how the
50 combination of differences of solar radiation and plant type (i.e. grasses and trees) influence
51 evapotranspiration and water storage within hillslopes that face opposite directions. Here, we
52 combined on-site measurements and remote-sensing data to show that in central coastal
53 California, a hillslope with oak trees that received less direct sunlight had higher
54 evapotranspiration than a hillslope with grasses that received more direct sunlight. Importantly,
55 we suggest that the cooler hillslope with oak trees may be drier and have lower groundwater
56 recharge than the warmer hillslope with grasses, which is opposite the findings of studies with
57 trees on both hillslopes. Our findings highlight the critical need for forest managers and modelers
58 to consider hillslope-scale vegetation types to more accurately predict groundwater recharge,
59 streamflow generation, and vegetation health within oak savannas.

60 **1 Introduction**

61 Differences in hillslope aspect, or the direction a hillslope faces, produce subcatchment-
62 scale variability in the delivery of solar radiation to the land surface, which is one of the
63 strongest controls on vegetation distribution and water partitioning within terrestrial landscapes
64 (Chorover et al., 2011; Ying et al., 2019). Equator-facing slopes (EFS; south-facing in the

65 northern hemisphere) with more direct solar radiation have higher air temperature, aridity, and
66 evaporative demand compared to pole-facing slopes (PFS, north-facing in the northern
67 hemisphere; Smith & Bookhagen, 2021). Current conceptual frameworks depict warmer EFS
68 with higher potential evapotranspiration and subsequently lower infiltration, groundwater
69 recharge, and runoff (García-Gamero et al., 2021; Pelletier et al., 2018; Regmi et al., 2019; Webb
70 et al., 2023). In contrast, cooler PFS are considered to have lower potential evapotranspiration
71 and higher infiltration, groundwater recharge, and runoff (García-Gamero et al., 2021; Pelletier
72 et al., 2018; Regmi et al., 2019; Webb et al., 2023). While this current conceptual model may
73 provide insight into how differences in energy inputs drive hydrologic partitioning, it is unclear
74 if the expected patterns are universal across diverse environments and vegetation types (Brooks
75 et al., 2015; Ying et al., 2019; Zapata-Rios et al., 2016).

76 Understanding the compounding role of variable solar radiation and plant functional
77 groups (e.g., grass, tree, shrub) is important for determining the transferability of current
78 expectations of hydrologic partitioning between hillslopes with opposing aspects (Kumari et al.,
79 2020). The current conceptual model of hydrologic partitioning within aspect-regulated
80 landscapes is largely based on environments where potential differences in actual
81 evapotranspiration (ET) due to variability in plant functional groups are not incorporated
82 (Pelletier et al., 2018; Regmi et al., 2019). Studies in watersheds with similar plant functional
83 groups (e.g., trees) have shown higher transpiration rates on EFS compared to PFS (Bilir et al.,
84 2021; Burns et al., 2023; Holst et al., 2010). However, there is also documented diversity in the
85 responses of different plant functional groups and species between aspects, which create
86 complex patterns of vegetation water uptake (e.g. due to differences in rooting depth) and have
87 lesser known consequences on subsurface water cycling (Armesto & Martínez, 1978; Gutiérrez-
88 Jurado et al., 2013; Hassler et al., 2018). Given the importance of vegetation water uptake in
89 driving subsurface hydrologic partitioning, understanding the role of vegetation type is required
90 to accurately forecast water cycling patterns within Earth system models (Kumari et al., 2020;
91 Marston et al., 2022; Ying et al., 2019).

92 Here, we address these knowledge gaps by quantifying hourly to monthly ET and shallow
93 subsurface water storage between a grass-dominated EFS and an oak tree-dominated PFS in
94 central California. We combined field-based measurements of soil moisture, oak and grass
95 transpiration, tree survey-based scaling, and remotely-sensed normalized difference vegetation
96 index (NDVI) and ET to determine how hydrologic partitioning differs between hillslopes with
97 opposing aspects and different plant community types.

98 **2 Methods**

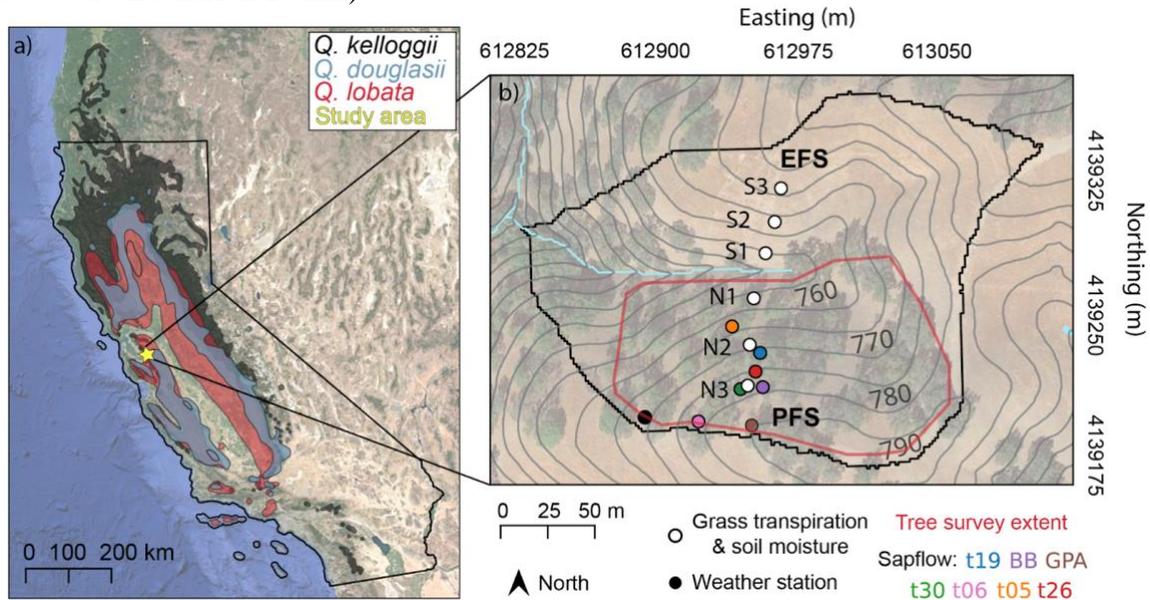
99 **2.1 Site Description and Instrumentation**

100 The study site (Arbor Creek Experimental Catchment; 37.393, -121.723) ranges from
101 720 - 790 m above sea level and is located within the University of California Blue Oak Ranch
102 Reserve (Figure 1). This reserve is located within the Mt. Diablo Range, ~24 km northeast of San
103 Jose, California, USA. The local climate is classified as Mediterranean, with hot, dry summers
104 and cool, wet winters and an average 600 mm of precipitation mostly falling as rain between
105 October - April (Donaldson et al., 2023). Soils are loamy and thin (~50 cm) and the dominant
106 rock types are sandstone and shale consistent with the Yolla Bolly Unit and the Great Valley
107 Sequence (Donaldson et al., 2023).

108 We installed a weather station (ClimaVUE50, Campbell Scientific; Logan, Utah) at the
109 ridge of the PFS to record precipitation at 10-min intervals from October 1, 2020 - September 30,

110 2021 (2021 water year). We excavated soil pits at each landscape position (e.g. toeslope, mid-
 111 slope, and shoulder) on the PFS and EFS (Figure 1). We monitored soil moisture (ECHO/EC-5,
 112 Decagon, Devices Inc. Washington, USA) every 10-min at 10 cm and 50 cm depths from winter
 113 2020 through September 2021 (start date varied due to sensor installation).

114 The study site is characterized as a mixed-deciduous oak savanna composed of blue oak
 115 (*Quercus douglasii* Hook., Fagaceae), black oak (*Quercus kelloggii*, Newb.), and valley oak
 116 (*Quercus lobata*, Nee), with evidence of some extent of hybridization between species (Nixon,
 117 2002). While oaks are largely on the PFS, grasses are across the study site and include species
 118 from both native and non-native genera, including *Avena*, *Bromus*, and *Elymus* (Pers. Comm.
 119 land steward Zachariah Tuthill).



120 Figure 1. (a) Location of study area (yellow star) and approximate natural range of *Q. kelloggii*
 121 (*Q. kelloggii* (black shaded region), *Q. lobata* (red shaded region), *Q. douglasii* (blue shaded region) (United
 122 States. Forest Service, 1971). Background is a Google Earth Imagery shaded relief of
 123 topography. (b) Study site with instrumentation nests of grass transpiration and soil moisture
 124 measurements (white), weather station (black), study trees with sap flow sensors (colors) and
 125 tree survey extent (red line). Stream channels are delineated in light blue; contour interval is 5 m
 126 and numbers refer to elevation in m above sea level.
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129 2.2 Field-based transpiration measurements

130 We measured plot-scale, surface ET with an open-path, infrared gas analyzer (model LI-
 131 7500, LICOR, Lincoln, Nebraska) within a chamber (0.5 m x 0.5 m x 0.5 m) constructed of a
 132 PVC pipe frame, covered by Tefzel film with a fan placed inside for chamber mixing
 133 (Supplementary Figure 1; Huxman et al., 2004). This measurement included both evaporation
 134 from the ground surface and grass transpiration, however, we assume that the evaporative flux is
 135 negligible, thus we refer to this measurement as “grass transpiration” throughout the manuscript
 136 (Arnone & Obrist, 2003; Schlesinger & Jasechko, 2014). We collected measurements weekly at
 137 each instrument nest starting when the grass became active after the first rainfall (December 10,
 138 2020) to when the grass senescence (June 10, 2021), which represented a full grass growing
 139 season. We averaged grass transpiration across landscape positions on the PFS and EFS to
 140 determine hillslope-averaged grass transpiration for each measurement period. To determine a

141 weekly hillslope-averaged grass transpiration, we assumed each measurement to be
142 representative of the week and multiplied by 7 (number of days in the week). To calculate total
143 grass growing season transpiration (December - June), we summed each hillslope-averaged grass
144 transpiration value.

145 To quantify oak water use, we installed heat pulse velocity sap flow probes (Edaphic
146 Scientific; Forster, 2019, 2020) within seven mature oak trees at 1.4 m height above ground
147 surface (e.g., breast height) along the PFS of Arbor Creek Experimental Catchment. We chose
148 the instrumented oak trees to include a wide range of landscape positions and sizes
149 (Supplementary Table 1). We measured sap flux during the oak tree growing season at 10 mm
150 (outer position) and 20 mm (inner position) within the xylem every 15-min from May -
151 December 2021. To correct for probe misalignment during installation, we assumed zero flow
152 after leaf off (late December 2021) and used a wound correction diameter of 0.2 mm (Burgess et
153 al., 2001). To measure sapwood thickness, we extracted tree cores using an increment borer in
154 August 2021 and identified a shift from translucence to opaqueness, which represented the
155 sapwood to heartwood transition (Quiñonez-Piñón & Valeo, 2018). With these cores, we
156 quantified wood water content and density, which we used to convert heat pulse velocity to sap
157 flux (Burgess et al., 2001). We quantified the radial profile of sap flux in two ways and for the
158 final calculations we assume a constant sap flux across the sapwood (see Supplementary Section
159 1.2 for details;(Percy Link, Kevin Simonin, Holly Maness, Jasper Oshun, Todd Dawson, Inez
160 Fung, 2014)). To calculate sap flow volumetrically, we multiplied the sap flux by the
161 corresponding sapwood area of the tree.

162 To scale oak tree sap flow measurements to hillslope-scale transpiration, we performed
163 cruising surveys of every oak on the pole-facing hillslope (red outline in Figure 1b). A total of
164 113 trees were surveyed within the 12,550 m² survey area, which were used to estimate total
165 hillslope-scale oak transpiration. We recorded the species and diameter at breast height (DBH)
166 for each tree (Supplementary Table 2). Trees that forked below breast height were recorded as
167 two individual trees. We estimated the growing season total sap flow for the surveyed trees using
168 a power law function relating tree diameter to the growing season total sap flow for the
169 instrumented trees. We summed the total sap flow for all trees and divided it by the survey area
170 to quantify a hillslope-scale transpiration magnitude [mm].

171 172 **2.3 Remotely-sensed NDVI and ET**

173 To explore temporal variability in vegetation greenness, we used Google Earth Engine to
174 extract weekly NDVI values from the mid-slope position on the PFS and EFS using images
175 collected from January 2017 to December 2021 on the Copernicus Sentinel-2 mission (10-m
176 spatial resolution). NDVI compares the intensity of reflectance in the visible red and near-
177 infrared spectrum to quantify vegetation greenness (Acker et al., 2014).

178 We quantified ET at the mid-slope position of our study hillslopes, with remotely-sensed
179 ET products using Python application programming interface to access models from OpenET
180 (Melton et al., 2022). OpenET uses Landsat imagery to estimate monthly ET at 30 m resolution
181 with a variety of approaches, including surface energy balance, Priestley-Taylor, and
182 psychrometry (FAO, 2023)(see Supplementary 1.3 for details). A multi-model Ensemble ET
183 estimate was calculated by OpenET based on the arithmetic average after removing outliers
184 using the Median Absolute Deviation method (Leys et al., 2013; Volk et al., 2024). While we
185 included the ET results from all models in the Supplementary information (Supplementary
186 Figure 3), we used the Ensemble model for analyses in this study.

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189 **2.4 Subsurface water storage deficit calculations**

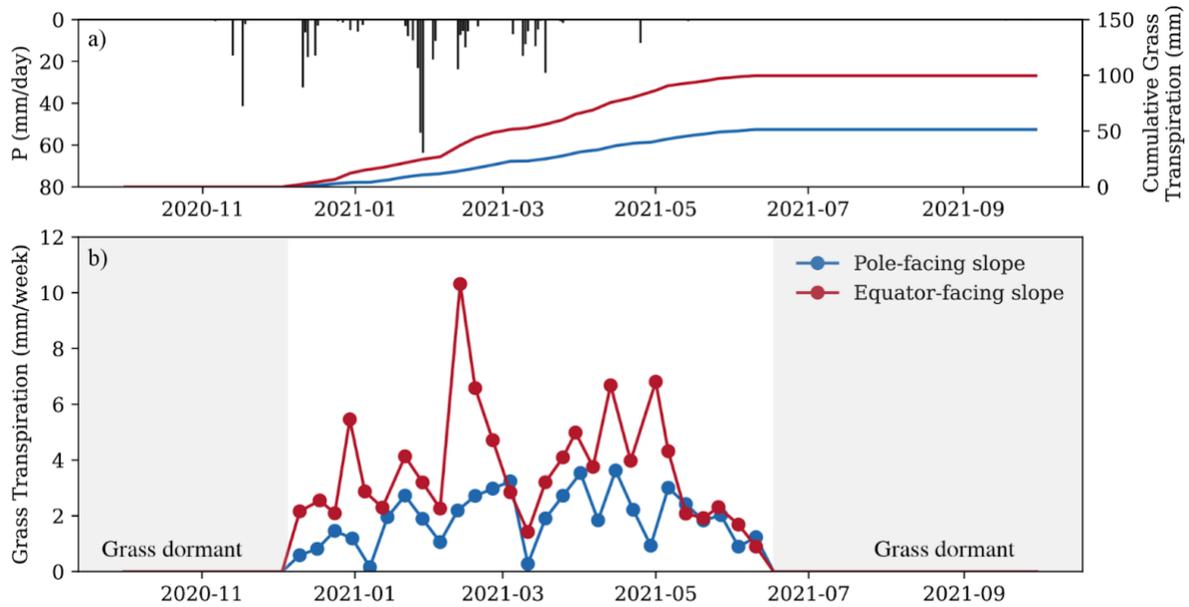
190 We calculated the hillslope-average soil water storage [mm] by integrating soil water
191 content from the surface to the 50 cm depth. We calculated the soil water storage deficit by
192 subtracting the volumetric water content at each timestep from the maximum recorded
193 volumetric water content, assuming the maximum represents a maximum unsaturated water
194 content at field capacity. In addition, we compare this to an estimated subsurface water storage
195 deficit calculated by the total field-based ET measurements on the EFS and the PFS.

196 Previous studies have shown that oak tree roots can extend beneath the soil, into the
197 weathered bedrock, to extract deeper water storage referred to as rock moisture (Hahm et al.,
198 2020, 2022; McCormick et al., 2021). To estimate this deeper storage we calculated the total
199 subsurface water storage deficit (i.e. soil and rock moisture) across multiple water years, we
200 calculated the root-zone storage deficit from October 2017 to September 2021 using statistically
201 interpolated precipitation data (Oregon State's PRISM daily precipitation) and remotely-sensed
202 ET (Ensemble model from OpenET; described above) following the method by (Wang-
203 Erlandsson et al., 2016) and adapted by (Dralle et al., 2021). The method used a mass-balance
204 approach to estimate a root-zone storage deficit as a running, integrated difference between
205 fluxes entering and exiting the root zone, assumed to be precipitation and ET, respectively. Here,
206 we estimated the root-zone storage deficit over subsequent water years (2017-2021), where the
207 running deficit represents a lower-bound on the amount of ET supplied from the root zone that
208 has not been replenished by precipitation. Therefore, the root-zone storage deficit represents the
209 minimum amount of vegetation water uptake that is not accounted for by precipitation (refer to
210 Wang-Erlandsson et al., 2016; Dralle et al., 2021; and McCormick et al., 2021 for details).

211 **3 Results**

212 **3.1 Field-based estimates of grass and oak transpiration**

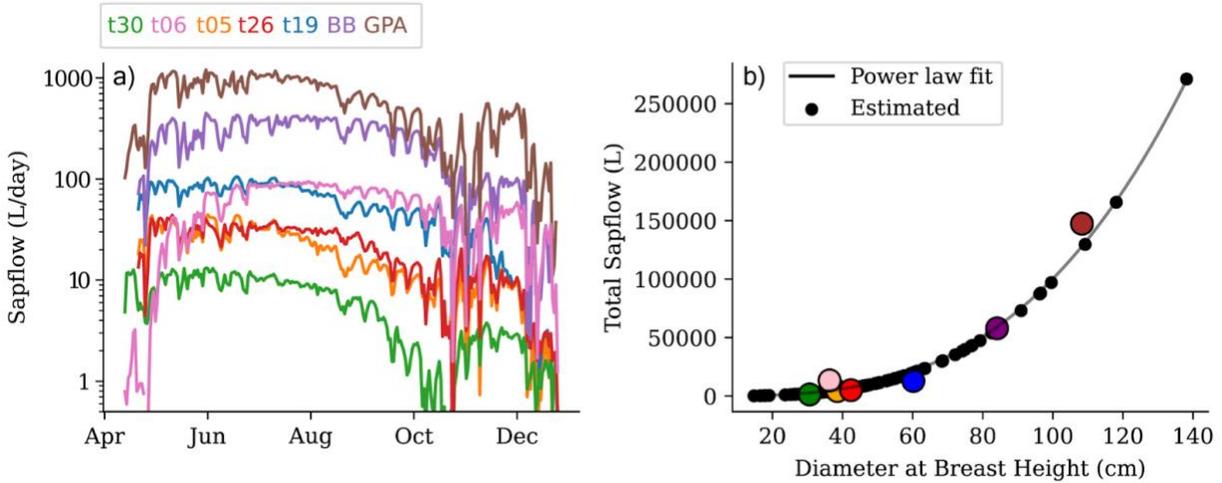
213 The EFS consistently had higher weekly grass transpiration than the PFS (Figure 2). The
214 average grass transpiration on the EFS was 3.7 mm/week, while the average on the PFS was 1.9
215 mm/week. The total growing season grass transpiration was 99 mm and 50 mm, on the EFS and
216 PFS, respectively. Anecdotally, we observed higher grass density on the EFS compared to the
217 PFS (Supplementary Figure 2).



218
 219 Figure 2. a) Daily precipitation (black) and cumulative grass transpiration for PFS (blue) and
 220 EFS (red) slopes, b) Slope-averaged weekly grass transpiration measurements for the PFS (blue)
 221 and EFS (red) slopes. Shaded regions are time periods with no measurements because grasses
 222 were dormant.
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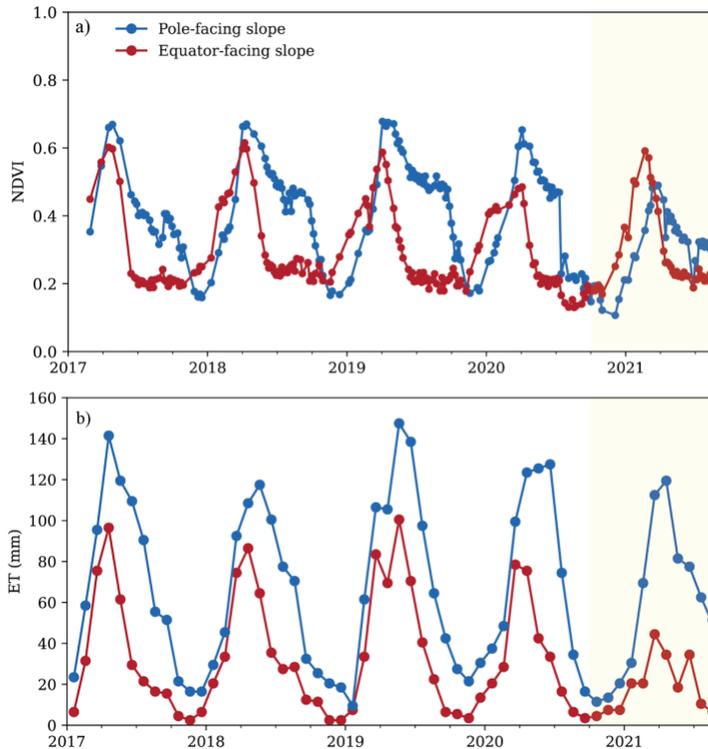
224 Oak tree transpiration varied across the growing season (Figure 3a). Oak tree leaf
 225 development began in April (not entirely recorded due to sensor installation) and transpiration
 226 was generally low until a rapid increase in May. Transpiration reached a maximum in June and
 227 remained relatively constant until late August/September, when there was a decline. In October,
 228 there was an increase in transpiration that coincided with the first precipitation event of the fall,
 229 which lasted until December when the oak trees went dormant (Figure 3a).

230 Average volumetric oak tree transpiration (L/day) was positively correlated with DBH
 231 (Figure 3). For example, during oak tree peak water use (June), transpiration varied by DBH
 232 from approximately 12 L/day (T30; DBH: 30.6 cm) to 1100 L/day (GPA; DBH: 108.3; Figure
 233 3a). Consequently, total oak tree growing season transpiration generally varied with DBH
 234 (Figure 3b). From the smallest tree to the largest tree, the total growing season transpiration
 235 magnitude increased from 1427 L, 13433 L, 4373 L, 5078 L, 12988 L, 57962 L, and 147387 L
 236 (Figure 3b). The total hillslope-scale oak tree transpiration for the entire sap flow measurement
 237 period (May - December 2021) was 172 mm and 148 mm for the 2021 water year (May -
 238 September 2021).



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Figure 3. (a) Daily sap flow (L/day) on log-scale, (b) total sap flow (L) by DBH (cm) for each instrumented tree (colors) and surveyed trees fitted with a power-law function (black line).



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Figure 4. (a) Weekly NDVI on PFS (blue) and EFS (red) from January 2017 - September 2021. (b) Ensemble monthly ET on the PFS (blue) and EFS (red) for the same period. Timeframe of the field-based ET and soil moisture measurements are shaded in yellow.

3.2 Remotely-sensed NDVI and ET

There were annually consistent seasonal differences in NDVI values between the PFS and EFS (Figure 4a). During the winter season with only grasses actively transpiring (November - April), the EFS NDVI was on average 0.37, while the PFS NDVI was on average 0.32. During the oak tree growing season (April - October), the PFS had higher NDVI than the EFS with 0.39

253 and 0.28, respectively. During the 2021 water year, which coincided with our field-based
 254 measurement time period, the average NDVI values on the PFS and EFS were 0.33 and 0.28,
 255 respectively.

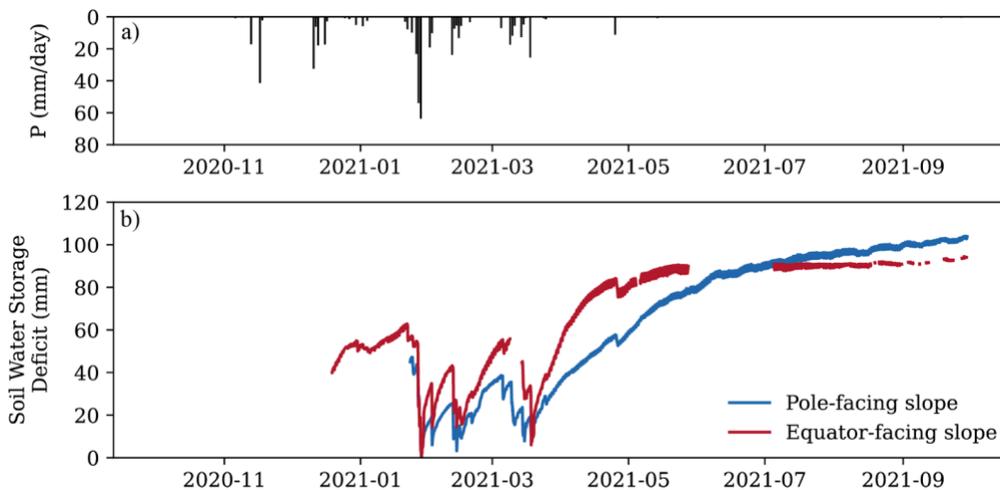
256 The remotely-sensed monthly ET was always higher on the PFS than the EFS (Figure
 257 4b). During the winter, the average ET on the PFS was 41 mm/month, while the average ET on
 258 the EFS was 21 mm/month. During the oak tree growing season, the average ET on the PFS was
 259 64 mm/month, while the average ET on the EFS was 29 mm/month. During the 2021 water year,
 260 the total ET on the PFS and EFS were 649 mm and 195 mm, respectively.

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262 3.3 Subsurface water storage deficit

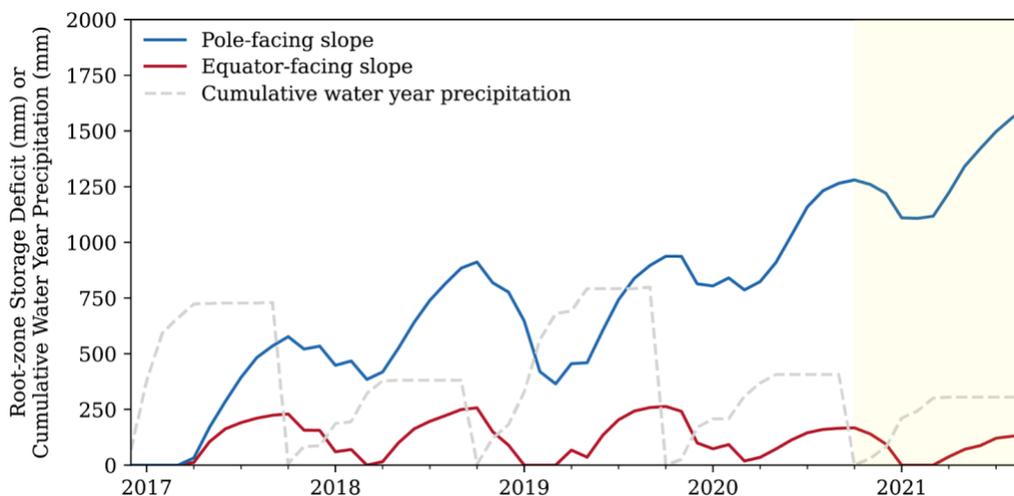
263 During the 2021 water year, the timing and magnitude of field-calculated soil water
 264 storage depletion varied by season between hillslopes with opposing aspects (Figure 5b). There
 265 was higher subsurface water storage depletion on the EFS during the winter season, when
 266 grasses were active (January - April, Figure 2). In contrast, during the summer, the EFS had
 267 negligible soil water depletion, while there was considerable soil water storage depletion on the
 268 PFS with active oak trees (Figure 5b). At the end of the summer (September), there was a
 269 slightly lower cumulative soil water storage deficit on the EFS (94 mm) than the PFS (104 mm).
 270 In comparison, field-based ET measurements for the 2021 water year (October 2020 - September
 271 2021) were used to calculate a subsurface storage deficit of 99 mm on the EFS (i.e. total grass
 272 transpiration) and 198 mm on the PFS (i.e. total grass and oak tree transpiration).

273 Across the 2017 - 2021 water years, the remotely-sensed root-zone storage deficits
 274 between the PFS and EFS showed contrasting behavior. Despite variability in precipitation
 275 magnitude, the root-zone storage deficit on the EFS (average 110 mm; standard deviation = 84
 276 mm) was replenished each year (i.e. returned to zero; Figure 6). In contrast, on the PFS, the root-
 277 zone storage deficit was not annually replenished and increased from 534 mm at the end of water
 278 year 2017 to 1608 mm at the end of water year 2021.
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281 Figure 5. (a) Daily precipitation, (b) Field observations of slope-averaged soil water storage
 282 deficit within the top 50 cm from January - September 2021 on the PFS (blue) and EFS (red).
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285 Figure 6. Monthly root-zone storage deficit for PFS (blue) and EFS (red) and cumulative water
286 year precipitation (dashed gray) at the study site from remotely-sensed observations. The period
287 of field-based ET and soil moisture measurements are shaded in yellow.

288 4 Discussion

289 4.1 Oak and grass transpiration in rain-dominated mediterranean climates

290 During water year 2021 (October 1 - September 30) the average ET within Arbor Creek
291 Experimental Catchment ranged between 124 mm (field-based measurements) and 422 mm
292 (remotely-sensed measurements). We interpret this range to represent a possible lower and upper
293 bound on ET (see Section 4.3), which encompasses other reported ET values in California oak
294 woodlands (Baldocchi et al., 2021; Lewis et al., 2000; Ma et al., 2020). Regardless of method,
295 the majority of ET contributions were from the oak tree dominated PFS.

296 Extensive research quantifying and partitioning ET between oak and grass water use has
297 been done within the Sierra Nevada, CA foothills dominated by blue oaks. For example, (Lewis
298 et al., 2000) estimated an annual average ET of 364 mm over a 17 year period using a water
299 balance approach. Over a similar time period, Baldocchi et al. (2021) used eddy flux towers to
300 show that evaporative fluxes were higher within an oak savanna (420 ± 58.2 mm), compared to a
301 nearby annual grassland (315 ± 37.7 mm). Building on this work, (Ma et al., 2020) combined
302 nested eddy flux towers and partitioning models to determine that within the oak savanna, oak
303 and grass transpiration contributed approximately 281 mm and 67 mm, respectively. These
304 studies demonstrate the range of ET in oak savannas and highlight the need for more research
305 across different environmental conditions to identify the mechanistic controls on oak water use.

306 Outside of the Sierra foothills, there has been limited research quantifying oak woodland
307 ET and the role of ET on subsurface water storage deficits. A notable exception includes work
308 by (Hahm et al., 2022) that investigated blue oak transpiration and vadose zone storage dynamics
309 within northern California. They reported that the mean annual ET at this site was 332 mm
310 between 2001 and 2018 (Breathing Earth System Simulator; Ryu et al., 2011). By combining
311 sapflow sensors and borehole hydrologic monitoring, they demonstrated that oak water use
312 during the dry growing season was sustained by rock moisture below the soil (Hahm et al.,
313 2022). However, while the authors describe the landscape as “aspect-regulated with negligible
314 woody-vegetation on EFS,” the authors do not include information about the differences in oak
315 and grass water uptake that drive subsurface water storage depletion.

316 In alignment with this study, our field-based and remotely-sensed estimates of ET
317 suggest that soil water storage is insufficient to sustain oak tree transpiration during the summer.
318 In addition, previous studies within Arbor Creek Experimental Catchment have shown that
319 groundwater during the summer is depleted below 5 m (Donaldson et al., 2023), suggesting that
320 oak transpiration is likely reliant on rock moisture on the PFS. Therefore, our research
321 contributes to a growing body of literature that demonstrates the ecohydrologic importance of
322 rock moisture for oak tree health.

323

324 **4.2 Ecohydrologic implications for higher ET on PFS**

325 The magnitude and timing of vegetation water uptake exerts a strong control on
326 subsurface water storage and movement (Li et al., 2018; Sadayappan et al., 2023). In both the
327 field-based estimates and remotely-sensed estimates of subsurface storage deficits, we observed
328 higher subsurface water storage deficits on PFS compared to EFS. It is likely oak tree water
329 uptake from rock moisture may limit groundwater recharge and streamflow generation on PFS
330 (Dralle et al., 2023). Under these conditions, we hypothesize that groundwater recharge and
331 streamflow contributions may be higher on EFS, which is contrary to existing conceptual models
332 of water partitioning between hillslopes with opposing aspects (Pelletier et al., 2018; Regmi et
333 al., 2019; Webb et al., 2023). Future field work utilizing deeper measurement tools, such as a
334 neutron probe or other geophysical tools, will be used to validate the derived estimates of
335 subsurface water storage and test this hypothesis.

336 In water-limited and rain-dominated landscapes, variability in root-zone storage deficit is
337 a strong control on the spatial distribution of ecosystem resilience to disturbances, such as
338 drought (Callahan et al., 2022). Our results suggest that multiple consecutive years of low
339 precipitation inputs may exacerbate root-zone water storage deficits on PFS. During multi-year
340 droughts, consistently high root-zone storage deficits on PFS may cause oak trees to be more
341 susceptible to mortality (Ackerly et al., 2020; Brown et al., 2018; Kueppers et al., 2005). In
342 comparison, even in relatively low precipitation years, subsurface water storage is replenished on
343 the EFS. This finding highlights an important question: *why aren't there oaks on the EFS with a*
344 *lower subsurface water storage deficit?* We hypothesize that the absence of oak trees on EFS
345 may be driven by higher air temperature, higher vapor pressure deficits, and lower shallow soil
346 moisture that may limit oak seedling survival, despite potentially higher water availability below
347 the soil (Nudurupati et al., 2023; Swiecki & Bernhardt, 1998). These findings highlight the
348 importance of adequately representing plant functional group distributions and water uptake
349 patterns through time to accurately refine water balances within aspect-regulated landscapes
350 (Istanbulluoglu & Bras, 2005; Nudurupati et al., 2023; Ying et al., 2019; Zhou et al., 2013).

351

352 **4.3 Multi-tool approaches to quantify oak savanna ET**

353 An accurate quantification of hillslope-scale ET is essential for sustainable water
354 resource management in the face of a changing climate, but it remains one of the biggest
355 challenges within the ecohydrologic sciences (Brooks et al., 2015.; Marston et al., 2022; Ying et
356 al., 2019). Through the advancement of field-based techniques and remote-sensing technology,
357 the ecohydrology community is entering an exciting frontier where we can combine approaches
358 and provide water resource managers with more accurate ET estimates (Volk et al., 2024).
359 However, each method to quantify plant water uptake includes a suite of benefits and limitations
360 that must be considered.

361 Field-based measurements using sap flow sensors can directly characterize biologically
362 mediated plant-water uptake across diverse environmental conditions (Poyatos et al., 2021). In
363 addition, sap flow sensors can provide high temporal resolution (e.g., minutes) data, which
364 allows for a more robust characterization of transpiration patterns compared to remote sensing,
365 which typically reports ET on daily to monthly time intervals (Melton et al., 2022; Link et al.,
366 2014). However, sap flow measurements often produce a conservative estimate of ET and can be
367 time consuming, expensive, limited in scope, and require substantial field expertise (Köstner et
368 al., 1998). For example, re-installations early in the growing season due to probe misalignment
369 hindered our ability to quantify transpiration in April 2021, which suggests our hillslope-scale
370 transpiration values are underestimates. In addition, the relationship between DBH and sap flow
371 may vary across stand structure (e.g. density, species, age) and the relationship between sapwood
372 area and DBH may vary across the oak genus (Forrester et al., 2022; Schoppach et al., 2021,
373 2023). This highlights the importance of well-thought-out field-based studies to identify how
374 stand structure influences sap flow to better constrain oak transpiration from the individual tree
375 to hillslope-scale.

376 Remotely-sensed estimates of ET come with their own unique set of benefits and
377 limitations (FAO, 2023). On the one hand, remotely-sensed ET data provides information at
378 large spatial-scales, takes minimal time for a user to acquire, and is readily comparable between
379 diverse landscapes and different ET models (Melton et al., 2022). On the other hand, individual
380 ET models have known, difficult-to-resolve biases that inhibit their use within upland landscapes
381 (Wang et al., 2022; Zhao & Li, 2015). For example, most remotely-sensed models within the
382 OpenET ensemble do not include a correction for complex terrain (e.g., slope, aspect). The ET
383 models' inability to correct for aspect-driven differences in solar radiation may contribute to the
384 unexpected higher ET during the winter on the PFS despite higher field-based ET on the EFS
385 (<https://openetdata.org/known-issues/>; last accessed Jan 9, 2023). Therefore, we interpreted the
386 ensemble ET to represent an upper bound of ET and highlight the need for more remotely-sensed
387 ET models to incorporate corrections for variable terrain indices (e.g., slope, aspect) and
388 vegetation phenology. Given that each approach has its limitations and produces a range of ET
389 values, a more holistic and accurate approach to quantifying ET dynamics should include
390 multiple methods in tandem.

391 **5 Conclusions**

392 A commonly used conceptual model of ET, hydrologic partitioning, and landscape evolution
393 between hillslopes with opposing aspects is based on landscapes with similar plant functional
394 groups (e.g., trees)(Pelletier et al., 2018; Riebe et al., 2017). This conceptual model assumes that
395 a larger energy input on EFS will induce a higher evaporative demand, increase transpiration
396 rates, and drive higher annual ET on EFS compared to PFS (Pelletier et al., 2018). However,
397 these studies do not account for the potential confounding influence of distinct vegetation
398 communities on hillslopes with opposing aspects. In the Arbor Creek Experimental Catchment,
399 we observed that our PFS had higher annual ET due to oak tree water uptake, compared to the
400 equator-facing hillslope with only grasses. Higher ET on PFS contributed to higher subsurface
401 water storage deficits through time. Our work reveals the importance of accurately representing
402 vegetation types and phenology at the scale of individual hillslopes to better estimate ET and
403 subsurface hydrologic partitioning.

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419 **Open Research**

420 All data used in the publication are cited in the references and are hosted on the Consortium of
421 Universities for the Advancement of Hydrologic Science, Inc. web-based hydrologic information
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