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A multi-scale assessment of forest treatment impacts on evapotranspiration and water yield in the Sierra Nevada

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Abstract

The future of the Western United States is threatened by both an increase in wildfire frequency and a decrease in water availability. By reducing fuel loads, wildfire mitigation measures (forest treatments) can offer reduced fire severity and increased annual total runoff (water yield) via reduction in evapotranspiration (ET). While the benefits of forest treatments for fire management are well studied, their impact on ET and water yield remains largely unknown, and existing literature shows conflicting results. Here, we aim to resolve this ambiguity by quantifying the impact of forest treatments on ET and water yield, at spatially localized scales. Using daily average flow rates from sub-basin and basin scale gauges, 100-m LiDAR data, 800-m PRISM precipitation data and 30-m SSEBop ET_a data, we analysed the impact of forest treatments on ET_a and water yield in the Sagehen Experimental Watershed. Within treated areas of Sagehen, there is a linear relationship between loss of canopy cover and ET_a reductions at the 100-m pixel scale when canopy cover loss exceeds 10%. The impact of treatment was highly localized, and across the entire watershed (30 km^2), treated areas with reduced ET_a only made up 4 km^2, ~10% of the Sagehen area. At sub-basin and basin scale, the magnitude of year-to-year ET_a reduction was <15%, and there was no quantifiable increase in water yield. Instead, precipitation alone explained ≥85% of water yield variability at sub-basin and basin scale. Future forest management practices in the Sierra Nevada are essential for combating wildfire, but our results from Sagehen reveal that even at the sub-basin scale (~3 km^2), 56% thinning treatment by area did not result in increased water yield.

KEYWORDS
disturbance hydrology, forest treatment, runoff, Sagehen, water yield, wildfire

1 | INTRODUCTION

The future of the Western United States is threatened by both an increase in wildfire frequency and a decrease in water availability (Weber & Yadav, 2020). While a large body of research has focused on each of these issues individually, research on the nature and mechanisms of feedback between the two issues are less conclusive, especially in the context of mitigation efforts (Collar et al., 2020; Hallema et al., 2017; Saxe et al., 2018; Tague et al., 2019). Wildfire mitigation efforts or forest treatments, such as tree thinning, under burning, mastication and aspen restoration can impact the hydrologic cycle and thus water availability (Goeking & Tarboton, 2020; Saksa, Bales, et al., 2020; Tague et al., 2019).

The wide ecological and hydrological impacts of forest treatments have spurred discussion about whether forest treatment practices are a 'triple win' (Service et al., 2009; Tague et al., 2019). The first 'win' is that forest treatments mitigate the impacts of wildfire by reducing fuel loads (Service et al., 2009). The second 'win' refers to the potential to increase drought resiliency by reducing vegetation water demands (Saksa, Conklin, et al., 2020; Tague et al., 2019). The third 'win' refers to the potential for forest treatments to increase water available for runoff. The 'win-win-win' model addresses concerns regarding both increased fire severity and decreased water availability.

The idea that reducing forest vegetation will increase water yield (WY) is a long-standing hypothesis put forward by Alden Hibbert in 1967 (Goeking & Tarboton, 2020; Hibbert, 1967). The hypothesis is rooted in a mass balance: Water going into the watershed must either go out or be accounted for with a change in storage. Theoretically, the reduction of canopy cover following treatments can reduce canopy evapotranspiration (ET) and canopy interception, which could subsequently increase runoff (Goeking & Tarboton, 2020; Hibbert, 1967). While some studies find an increase in runoff resulting from forest vegetation reduction, the threshold of reduction at which this increase is detected, and the magnitude of increase that results, varies based on the type and scale of disturbance and hydrologic region (Goeking & Tarboton, 2020; Hallema et al., 2018; Kurzweil et al., 2021; Saksa, Conklin, et al., 2020). An older summary of paired catchment studies found that timber harvesting can lead to increases in WY as long as 15%–50%, depending on the region, of the forested area is removed (Stednick, 1996). A more recent growing body of literature on other types of disturbances, such as thinning from forest treatment, finds that the effect is variable, leading to increased runoff, decreased runoff or no change in runoff (Biederman et al., 2015; Collar et al., 2022; Goeking & Tarboton, 2020; Kurzweil et al., 2021).

The challenge of determining whether reduction in vegetation will lead to increased runoff is exacerbated by (1) regional climate effects and (2) ET compensation pathways (Goeking & Tarboton, 2020; Tague et al., 2019). Compared with humid regions, Mediterranean and semi-arid regions are less likely to experience an increase in runoff response following a disturbance (Tague et al., 2019). This difference may be attributed to the water-limited characteristics of Mediterranean and semi-arid regions, where excess water is utilized by the water-deficient environment instead of contributing to runoff (Dung et al., 2012; Saksa, Bales, et al., 2020). Additionally, the decrease in ET that would theoretically arise from the reduction in vegetation (and ultimately lead to an increase in runoff) may be offset by different ET pathways. These compensation pathways include increased transpiration in remaining vegetation, increased growth in the understory and increased soil evaporation/snow sublimation due to loss of canopy shade (Bart et al., 2021; Biederman et al., 2015; Reed et al., 2018). Such ET compensation pathways have been found primarily in response to disturbances that are spatially discontinuous (Adams et al., 2012).

Since forest treatments are typically in select areas of a watershed and intended to improve ecosystem function, they are often spatially and temporally discontinuous (Brotons et al., 2013; Service et al., 2009). There is currently a lack of detailed documentation on the spatially localized impacts of these disturbances on both ET and WY. This gap in knowledge may lead to misunderstandings regarding the extent of the 'third win' and could misinform water management decisions in the Western United States. Case studies that examine the impact of forest treatment on ET and WY are essential to test the hypothesis that forest treatment will increase WY. Using the Sagehen Experimental Watershed in the Sierra Nevada of California, where forest treatments have been conducted since 2014, this research quantifies the impact of forest treatment on ET and WY at the treatment (100 m), sub-basin (~3 km^2) and basin scale (~30 km^2).

2 | SITE DESCRIPTION

The Sagehen Experimental Watershed (Sagehen) is located 12 km north of Truckee, California, on the eastern side of the Sierra Nevada (Figure 1). The roughly 30-km^2 catchment has a relatively mild average elevation gradient of 9.8%, rising from 1877 to 2663 m over the span of 8 km. Located in a Mediterranean climate, Sagehen experiences cold, wet winters and warm, dry summers (Kirchner et al., 2020). Annual average precipitation is 800 mm, 80% of which falls as snow with peak flows occurring in spring months (April to May) as snow melts, and low flows occur in the end of the summer (August or September) (Kirchner et al., 2020). Sagehen Creek is part of the larger Truckee Watershed; it drains into Stampede reservoir which then connects to the Truckee River, the main water source for the town of Reno, Nevada (*Sagehen Creek Field Station – UC Natural Reserve System*).

Historically, land cover and vegetation at Sagehen have been impacted by timber harvesting, grazing and wildfire, but activity has been limited since the early 1950s (Andrews et al., 1986; Service et al., 2009). Today, roughly 90% of the overstory vegetation at Sagehen is a dense mix of conifers including Sierra lodgepole pine (*Pinus contorta*), Jeffrey pine (*Pinus jeffreyi*), western white pine (*Pinus monticola*), white fir (*Abies concolor*) and red fir (*Abies magnifica*). Vegetation in the understory is dominated by Pinemat manzanita. The remaining 10% of land cover at Sagehen grows in meadows and fens. These dense, marshy regions are nestled in low gradient, water collecting zones along the main channel of Sagehen Creek (Staff, 2005).

In 2011, the US Forest Service released a plan to apply strategically placed area treatments (SPLATs) throughout Sagehen to reduce hazardous fuel loads, enhance habitat, create heterogeneity in forest stand conditions and restore declining aspen stands (USDA, 2013). Distributed throughout the region, SPLATs were planned over 34% of the Sagehen area. The treatments include plantation thinning, variable thinning, underburning and aspen restoration, with thinning being the

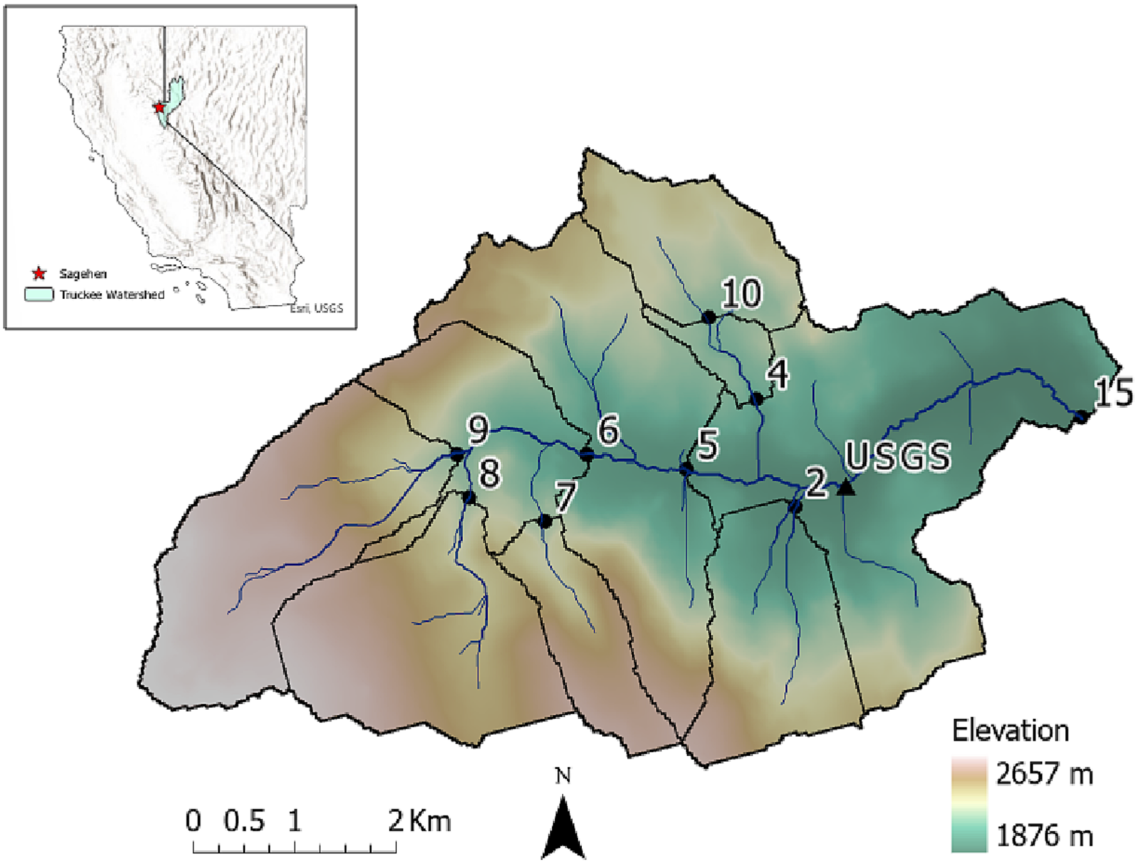

FIGURE 1 Elevation gradient of Sagehen basin and locations of the USGS gauge and nine pressure transducer gauges. Black lines denote the areas of sub-basin, and thinner blue lines represent the stream network.

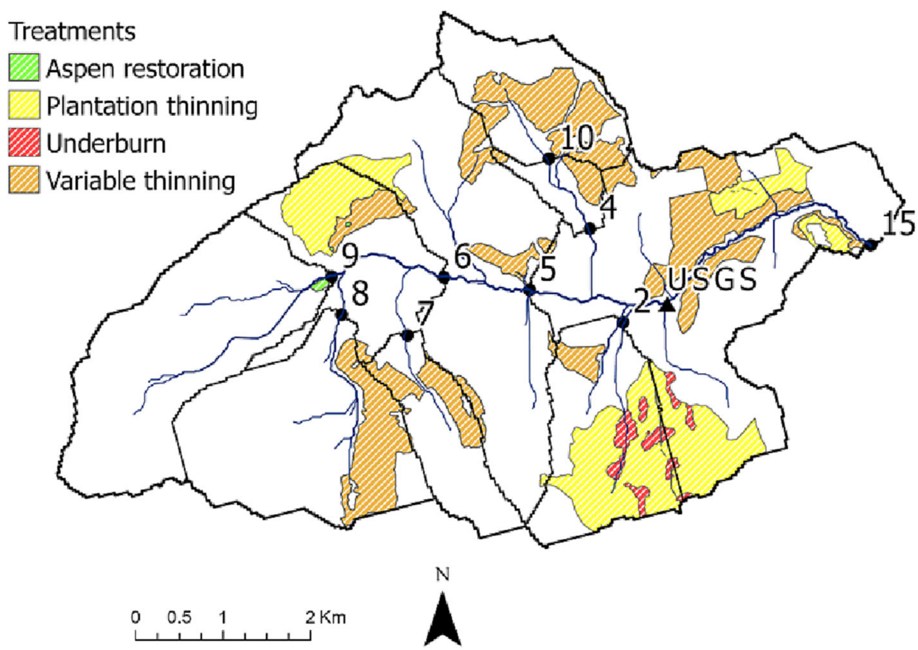

FIGURE 2 Location and type of strategically placed area treatments (SPLATs) throughout Sagehen. Black lines denote the areas of sub-basin, and thinner blue lines represent the stream network.

dominant treatment method (Figure 2). One other treatment performed and not shown in the map is mastication, a method used to break down brush, small trees or branches and redistribute these materials across the forest floor. As the implementation of the SPLATs in Sagehen is expected to serve as a prototype for forest management in similar watershed systems, studying their impacts will provide critical insight into how forest management practices will influence water availability (Service et al., 2009).

3 | METHODS

3.1 | Sub-basin characteristics

We evaluated the impacts of SPLATs on ET and WY at three scales: basin, sub-basin and treatment area. Basin scale accounts for processes across the 34 km^2 of the Sagehen watershed and is monitored by gauge SGH 15 (Figure 1). Sub-basin scale accounts for processes within 2–20 km^2 and is monitored by the associated gauge (Table 1). Treatment scale accounts for areas that overlap with the 2011 treatment plan (Figure 2) and was analysed at 100-m pixel resolution.

Table 1 summarizes important hydrologic and land cover characteristics for the main basin and each sub-basin. Gauges SGH 09, SGH 06, SGH 05 and SGH 15 provide measurements for the main channel of Sagehen Creek; all the other gauges provide measurements for the tributaries to Sagehen Creek (Figure 1). Flow is perennial on the main channel but is intermittent on the tributaries. SGH 15 is the farthest downstream and serves as the outlet gauge for the Sagehen basin.

3.2 | Data

To quantify changes in canopy cover, ET and WY, data were collected and analysed throughout Sagehen at the three study scales (basin, sub-basin and treatment) from 2012 to 2021. Canopy cover, WY, precipitation and actual evapotranspiration (ET_a) data were collected from various sources and resolutions (Table 2). Unless otherwise noted, all years represent water years (October 1 to September 30).

We estimated canopy cover using aerial Light Detection and Ranging (LiDAR), which sends and receives laser pulses, flown by the US Forest Service and US Geological Study in June 2014 and summer 2018 (*OpenTopography*, *2014*; *USGS*, *2018*). Canopy cover was determined by a software called 'TerraScan' to classify points into ground and non-ground. To reduce noise, the data were aggregated to 100 m.

Continuous 15-min pressure measurements were collected from nine pressure transducers located throughout Sagehen (Figure 1). Total pressure was converted to water pressure by adjusting for atmospheric pressure; water pressure was then converted to discharge using rating curves developed and updated yearly for each channel. Finally, average daily discharge was converted to daily runoff depth using Equation (1).

$$R = \frac{Q}{A} \cdot t \tag{1}$$

A is watershed area [L^2], *t* is time [T], *Q* is flow rate [L^3/T] and *R* is runoff depth [L]. Annual runoff depth (WY) was computed as the sum of the daily runoff depth over the water year.

Daily total precipitation data at 800-m spatial resolution were obtained from Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (*PRISM*, *2020*). These data are based on long-term climate observations and statistical inferences. Daily total precipitation depth at the basin and sub-basin scale was computed as the spatial mean of the 800-m data. Annual precipitation depth was computed as the sum of daily precipitation for each sub-basin over each water year.

ET was quantified using monthly total actual evapotranspiration (ET_a) at 30-m spatial resolution was estimated using the Operational Simplified Surface Energy Balance Model (SSEBop). SSEBop estimates an ET_a by using satellite data to correct a reference ET (ET_o) (Savoca

TABLE 1 Characteristics for the main basin (SGH 15) and the sub-basins including area, treatment, nested status, gauge elevation and slope.

Gauge	Area (km^2)	% Area treated	Gauge elevation (m)	Slope (°)
SGH 02	3.02	56%	1958	7.8
SGH 04	2.95	38%	2035	4.6
SGH 05[a]	19.96	14%	1972	9.2
SGH 06[a]	13.79	16%	1995	9.7
SGH 07	1.71	24%	2096	10.3
SGH 08	4.48	19%	2098	8.7
SGH 09[a]	4.87	0.40%	2066	11.3
SGH 10	2.36	41%	2047	4.6
SGH 15[a]	34.22	34%	1890	8.3

[a]Denotes that the gauge is along the main channel of Sagehen creek.

TABLE 2 Data types, sources, temporal and spatial resolutions and time periods of collection.

Data	Source	Temporal resolution	Spatial resolution	Period
Canopy cover	LiDAR	Two aerial surveys	<1 m	2014 and 2018
Water yield	Pressure transducers	15 min	Sub-basin	2012–2021
Precipitation	PRISM	Daily	800 m	2001–2021
ET	SSEBop	Monthly	30 m	2001–2021

Abbreviations: ET, evapotranspiration; LiDAR, Light Detection and Ranging; PRISM, Parameter-elevation Regressions on Independent Slopes Model; SSEBop, Operational Simplified Surface Energy Balance Model.

et al., 2013; Senay et al., 2011). ET_o is calculated using the Penman–Montieth equation assuming full vegetation coverage and unlimited water supply (Senay et al., 2011). The SSEBop data in this study utilized Landsat imagery and were generated in Google Earth Engine. We also note that CONUS-wide 30-m Landsat-based SSEBop ET_a is available through OpenET (OpenET, 2022).

3.3 | Spatial analysis of forest treatment and ET_a

We quantified the impact of forest treatment on vegetation at Sagehen by comparing canopy cover in June 2018 (post-treatment) to June 2014 (pre-treatment). The percentage-change-in-canopy-cover pixels were separated into treated and untreated groups according to the proposed treatment areas (Figure 2). Within both the treated and untreated pixel groups, the percentage-change-in-canopy-cover pixels were binned into consecutive integers. The median change in June ET_a was then computed across each percentage-change-in-canopy-cover bin. The median was used due to small sample size in some of the bins ($n < 10$) and lack of normality in the associated ET_a pixel distributions. We analyse June ET_a to be consistent with when LiDAR was flown. To evaluate the correlation between the change in canopy cover and change in ET_a across Sagehen, we applied a least squares linear regression on treated and untreated pixels. Only areas representing more than five pixels (0.05 km^2) were used in the regression to remove the effect of outliers.

3.4 | Annual water budget and water yield regression

To investigate variability in annual ET_a and WY, we utilized water budgets and linear regressions. Data-driven components of the annual water budget (Equation 2) included precipitation (P), ET_a and WY. Using these data, we computed an annual change in storage ΔS, assuming a yearly balanced water budget:

$$\Delta S = P - ET_a - WY \quad (2)$$

We assumed a linear relationship between annual variability in WY, P and ET_a according to Equation (3):

$$WY = \beta_0 + \beta_1 P + \beta_2 ET_a + \varepsilon \quad (3)$$

where β_i are the regression coefficients and ε is the error term.

A stepwise regression (stepwiselm; MATLAB R2021a) was used to determine if each coefficient of the regression was statistically significant using the Akaike information criterion and p-values of <0.05 (Akaike, 1981). When β_2 was determined insignificant (and thus ET_a not a necessary explanatory variable), it was set to zero and a bivariate regression was used.

4 | RESULTS

4.1 | Forest treatment results in decreased ET at pixel scale

Focusing on the sub-basin with the greatest amount of treatment by area (SGH 02) and the whole basin (SGH 15), we compared the change in June ET_a between 2014 and 2018 in treated and untreated areas at the 100-m pixel scale. In untreated areas, there was no significant correlation between relative change in canopy cover and ET_a ($p > 0.1$) (Figure 3; blue scatter plots). Untreated areas experienced a positive change in ET_a, while canopy cover varied from −50% to 50%, and averaged 0% change across the basin. The increase in ET_a but lack

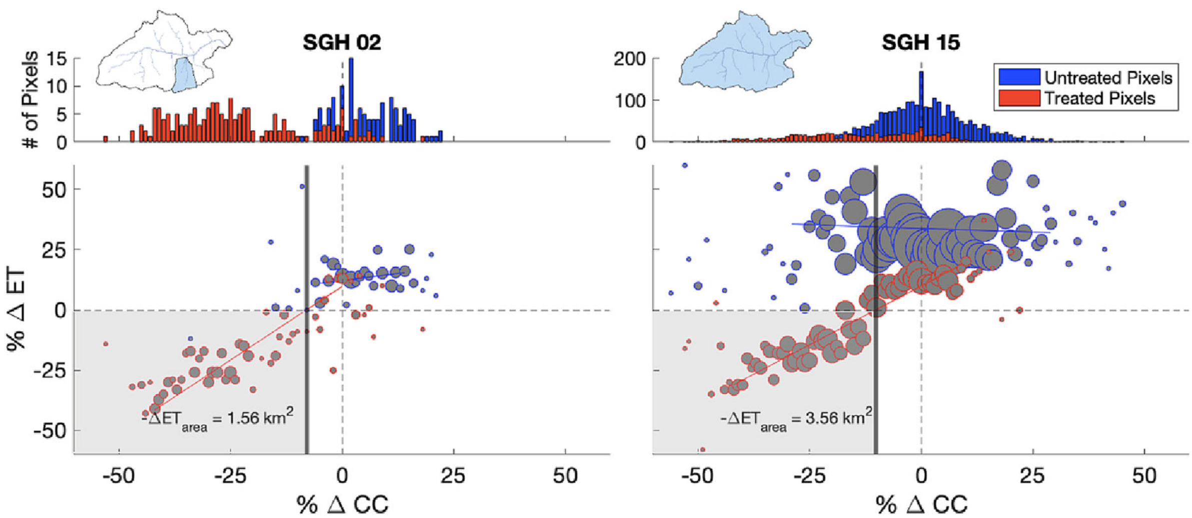

FIGURE 3 Comparing untreated (blue) and treated (red) pixel-scale change in canopy cover (ΔCC) and ET_a (ΔET) at sub-basin and basin scale (June 2018 vs. 2014). Pixels are binned based on discrete changes in CC, and size of points represents the number of binned pixels. Histograms on top show the pixel distributions. The vertical black line is the x-intercept for the linear regression on treated pixels and represents the threshold, where a decrease in CC results in decreased ET_a. The grey box and −ΔET refer to the treated area with decreased ET_a.

of change in canopy cover between these years is likely explained by other influences on ET_a. For example, there was 38% more precipitation in 2018 compared with 2014, which may have led to increased ET_a without a LiDAR-observed increase in canopy cover.

Within treated areas of Sagehen, at both sub-basin (SGH 02) and basin scale (SGH 15), the relative change in ET_a was linearly correlated to the relative change in canopy cover, with Pearson correlation coefficients of >0.9 and *p*-values of <0.05 (Figure 3, red scatter plots). From this relationship, it was determined that reduction in ET_a occurred only when the reduction in canopy cover associated with treatment was at least 10%. Beyond this threshold, ET_a linearly decreased with added loss in canopy cover. Above this threshold, ET_a increased, even despite decreased canopy cover (area between the threshold line and the dashed vertical line at 0). This 10% threshold is specific to the 2 years studied, which differed in climate conditions and is not statistically robust to be generalized.

Even though treatments leading to canopy cover loss can be correlated to decreased ET_a at pixel scale, at basin and sub-basin scale, average change in June ET_a between 2014 and 2018 was positive for all basins except SGH 02 (Table 3, row 3). Excluding SGH 02 for the time being, the impact of treatment on ET_a within the sub-basins was minimal. Treatments that led to decreased ET_a in the sub-basins only affected up to 6% of sub-basin area, which was not enough to offset the untreated areas and increased precipitation, and the result was a net increase in sub-basin ET_a (Table 3, row 3). Across the entire basin, treatments that led to decreased ET_a impacted <4 km^2 of the Sagehen area, only 10% of the watershed (Table 3, SGH 15). The sub-basin that is the exception is SGH 02, where 56% of the sub-basin was thinned and there was a net June ET_a reduction of 6%.

4.2 | Minimal variability in annual ET_a despite treatment and precipitation variability at sub-basin and basin scale

The annual trends in precipitation, WY and ET_a were similar across basin and sub-basin scale; ET_a was relatively constant, while P and WY were covariates (Figure 4). For all sub-basins, except SGH 07, P and WY were highly correlated (Pearson correlation coefficient (ρ) > 0.9, $p < 0.05$) but P and ET_a were uncorrelated ($\rho < 0.5$, $p = 0.12$–

TABLE 3 The impact of treatment between June 2014 and 2018 at sub-basin and basin scale expressed by a comparison of sub-basin area to the negative change in June ET_a associated with treatment and the spatially averaged change in June ET_a across the sub-basin.

	SGH 02	SGH 04	SGH 05	SGH 06	SGH 07	SGH 08	SGH 09	SGH 10	SGH 15
Sub-basin area (km^2)	3.02	2.95	19.96	13.79	1.71	4.48	4.87	2.36	34.22
% of area with $-\Delta$ET	50%	6%	3%	4%	0%	0%	0%	4%	10%
Sub-basin averaged ΔET	−6%	18%	12%	12%	9%	6%	17%	19%	10%

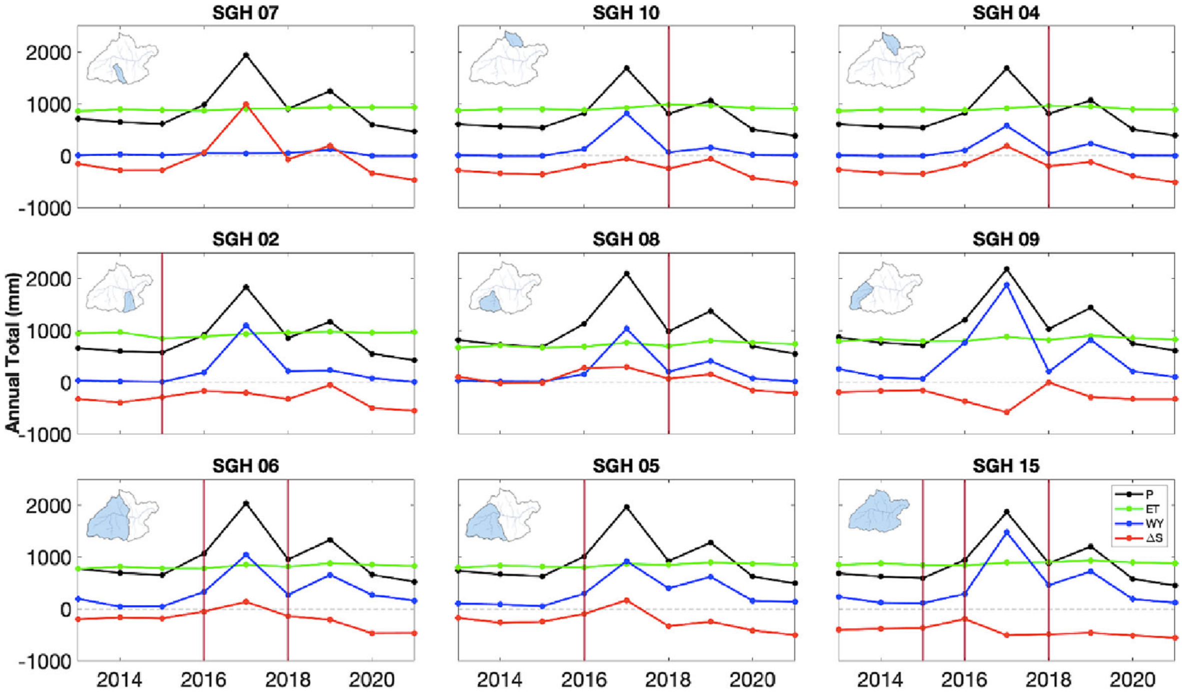

FIGURE 4 Annual water budgets for water years 2013–2021. The vertical red line denotes treatment years. Organized left to right and top to bottom by size, SGH 07 is the smallest sub-basin at ~2 km^2 and SGH 15 is the whole basin at ~35 km^2.

0.72). The uncorrelated relationship between P and WY at SGH 07 was likely due to lack of streamflow during the study period.

Despite year-to-year variations in P and treatment, ET_a was nearly constant for all sub-basins and all study years; with deviations of <10% of the average 850 mm/year. Related to the nearly constant ET_a at all sub-basins was the consistently negative ΔS, suggesting yearly water demands (ET_a and WY) at Sagehen rely on water stored in the subsurface. The exceptions were SGH 07 and SGH 08, where less demand (either WY or ET_a) resulted in positive ΔS, recharge. The potential influence of subsurface water at the other sub-basins was especially evident during dry years (2013, 2014, 2015, 2020, 2021). During these years, meeting water demand, driven mostly by ET_a, required a drawdown in storage exceeding 500 mm. These results suggest that sub-surface water storage at Sagehen may be buffering ET_a against dry precipitation years and that water made available from treatment may be used for recharge, not runoff.

4.3 | Forest treatment did not contribute to variability in WY at sub-basin or basin scale

Despite treatment that occurred over the study period, there was no statistically significant relationship between yearly total ET_a and WY at any scale. Instead, only a strong relation between P and WY existed (Figure 5). At all sub-basins except SGH 07, over 85% of the variability in WY is explained by P alone. SGH 07 had minimal flow, thus minimal variability across time. SGH 02, the sub-basin with the largest treated area (56%), had a lower R^2 than other sub-basins, at 0.88, but there was no evidence that treatment resulted in increased WY. The strength of the bivariate linear regressions across all sub-basins and the whole basin suggests that treatments were not large enough to be of significance to WY, especially given the dominance of precipitation.

5 | DISCUSSION

5.1 | Uncertainty in SSEBop ET_a

Annual sub-basin and basin scale ET_a was within 10% of average over the entire study period (Figure 4). The lack of variability in annual ET_a is unexpected given both treatment and the large swings in precipitation (Figure 4). In fact, 2012–2015 was a historic drought in California both in terms of lack of precipitation and higher temperatures. On average, the Sierra Nevada received only 50% of its annual precipitation during these 4 years, while temperatures were 1°C warmer than in the previous decade (Bales et al., 2018). Our results at Sagehen show minimal precipitation during these years, but no significant change in annual ET_a across all sub-basins and the main basin (Figure 4). That ET_a was unperturbed by drought may be attributed to two potential causes: (1) that the uncertainty in SSEBop ET_a data overwhelms any potential signal of change in ET_a; and (2) that the water supply for vegetation at Sagehen is buffered by subsurface storage acting on longer time scales than the study period.

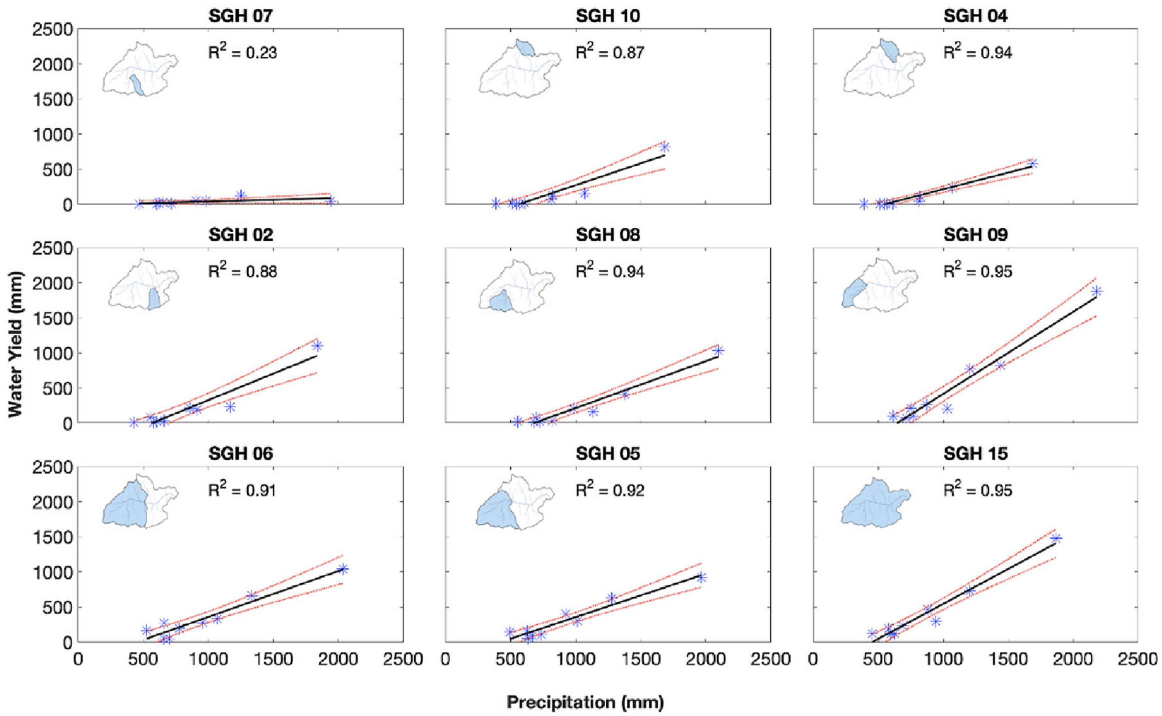

FIGURE 5 Bivariate linear regression between precipitation and water yield for all study basins. Blue asterisks represent data, the black solid line is the fitted regression and the red dotted lines represent 95% confidence intervals. Organized left to right and top to bottom by size, SGH 07 is the smallest sub-basin at ~2 km^2 and SGH 15 is the whole basin at ~35 km^2.

All modelled ET_a datasets have associated uncertainty, and SSEBop is no exception. For the last two decades, SSEBop has been validated against other satellite-based models, such as METRIC and ground-based eddy covariance flux towers (Savoca et al., 2013; G. B. Senay et al., 2011; Gabriel B. Senay et al., 2013). Using the same Landsat 7 images, METRIC and SSEBop ET_a were compared in south Idaho revealing $R^2 = 0.9$ for terrain of <2000 m (a majority of Sagehen is <2000 m). Compared with flux towers across the entire CONUS, SSEBop has been shown to capture 64% of observed ET_a variability (Gabriel B. Senay et al., 2013), and more recent studies in forested landscapes find the correlation between SSEBop and ground-based AmeriFlux eddy covariance to have $R^2 = 0.84$ (Chen et al., 2016). In our own study, we demonstrate that spatially localized 30-m SSEBop ET_a decreases in response to forest treatment (Figure 3), as expected. Other studies that used the same Landsat driven 30-m SSEBop data also found decreases in ET_a following landcover disturbances (Collar et al., 2022). Thus, on both the local and CONUS scales, SSEBop is capturing at least a portion of expected ET_a variability.

It is possible that SSEBop is underestimating annual ET_a variability and overestimating annual magnitude. Over the course of our 9-year study, annual ET_a demands were ~800 mm, and ET/P > 1 for six of the years. Keeping up with these ET_a demands during the multi-year drought led to sub-surface water storage losses of ~500 mm/year (Figure 4). However, the magnitude of ET_a that appears to be driving this sub-surface storage loss agrees with past work. According to ground-based flux tower measurements, ET_a for Sagehen in water years 2012 and 2013, both of which were drought years, was >1000 mm/year (Knipper et al., 2016). These ground-based ET_a estimates are greater than our SSEBop data and suggest even more drawdown from the sub-surface than what is reported in Figure 4.

Our results and previous studies suggest that sub-surface storage plays a large role in the Sagehen water cycle. Hydrogeology studies at Sagehen indicate the presence of significant groundwater reserves not only capable of supplying the necessary water for ET but to buffer it against multi-year drought (Brumm et al., 2009; Goulden & Bales, 2019; Kirchner et al., 2020; Rademacher et al., 2005; Urióstegui et al., 2017). The geology of Sagehen is primarily volcanic with >400 m of penetrable rock available to host a sub-surface aquifer (Brumm et al., 2009). Chemical studies on springs throughout Sagehen find the mean age of groundwater to be between 15 and 28 years, suggesting storage timescales greater than our 9-year study (Rademacher et al., 2005). Thus, it is possible for Sagehen ET_a to exceed precipitation for the duration of our study period due to large-scale sub-surface storage. How long the sub-surface can keep up with these large ET_a demands is an open question and continues to be explored at Sagehen and throughout the Sierra Nevada (Godsey et al., 2014; Klos et al., 2018; Meyers et al., 2021).

5.2 | ET_a and forest treatment

We found that treatments between summer 2014 and 2018 were associated with a strong linear relations between change in canopy cover and change in ET_a at the 100-m scale. Treatments that exceeded 10% decrease in canopy cover resulted in decreased ET_a (Figure 3). However, above this threshold, ET_a increased. In this study, treatments with less than 10% reduction in canopy cover were too small to overcome other factors leading to increased ET_a between these years, such as increased precipitation, which was 38% higher in 2018 than in 2014. Aggregating the 100-m treated areas to the sub-basin and basin scale (3–30 km^2) revealed that only one sub-basin, SGH 02, which received thinning treatment on 56% of its area, had sub-basin scale reduction in ET_a of 6% between the 2 years (Table 3). This suggests that while 10% reduction in canopy cover was needed at the 100m scale, >50% reduction in canopy cover was necessary to impact ET_a on a hydrologic scale, given the precipitation conditions.

5.3 | Precipitation-dominated watersheds

At both the sub-basin and basin scale, the strongest predictor of WY variability in Sagehen is precipitation. Over the study period, which includes pre- and post-treatment years, precipitation alone accounts for ≥85% of WY variability at the sub-basin and basin scale (Figures 4 and 5). A significant portion of the variability in WY is explained by precipitation; thus, there is little variability that can be attributed to other factors, such as ET. The highly correlated linear relation between precipitation and WY is expected; based on the USGS gauge 10343500, precipitation accounts for 93% of WY variability for the last 67 years (*USGS Current Water Data for the Nation*, *2018*). Strong correlation between WY and precipitation is also found at other disturbed forested watersheds in the Western United States. Biederman et al. (2015) found that precipitation was the strongest predictor of WY for eight snow-dominated watersheds in the Colorado River Basin ($R^2 = 0.79$–0.96). In these basins, bark beetle infestations led to massive tree death, but there was no detectable increase in WY. Thus, quantifying the impacts of forest disturbances on WY is extremely difficult in watersheds that experience highly variable year-to-year precipitation.

6 | CONCLUSION

This work is one of the first to investigate the impact of forest treatment on ET_a and WY at a range of scales; pixel (100 m), sub-basin (~3 km^2) and basin (~30 km^2). The largest planned forest treatment at Sagehen composed of 56% of sub-basin area and corresponded to a 15% decrease in yearly total ET_a. However, linear regression analysis revealed that ≥85% of the variability in WY at both sub-basin and basin scale was accounted for by precipitation alone and ET_a was not a significant explanatory variable. Thus, forest treatments did not lead to any quantifiable increase in WY at any hydrologic scale. Our findings highlight three challenges facing the use of forest treatment to increase WY in Mediterranean climates:

1. Minimal reduction to ET_a. At the 100-m pixel scale, it was possible to see the impacts of treatment on canopy cover and ET_a, revealing a linear relationship. However, averaged across the sub-basin scale, a 50% reduction in canopy cover resulted in only 6% reduction in June ET_a and did not increase WY.
2. WY controlled by precipitation. During the study period, WY variability at Sagehen and all the associated sub-basins was determined by precipitation and was independent of ET_a. Thus, forest treatments must overcome the dominant influence of precipitation to quantitatively increase WY. The treatment plan at Sagehen, which at its maximum influenced only 34% of basin area, was insufficient to do this.
3. Groundwater buffered ET. ET in Sagehen relies on stored water, which is based on our annual water budgets that show ET_a exceeding precipitation in dry years and for multiple years in a row. Understanding groundwater residence time, flow paths and water uptake for ET is critical for identifying where and when a reduction in ET will lead to an increase in WY. We also note that watersheds with different sub-surface storage capacities may respond differently to forest treatments.

As climate change alters fire patterns and water availability in mountainous terrain in the Western United States, it is critical that we investigate the feedbacks between fire mitigation efforts and water availability in the context of the 'triple win'. We encourage future studies to investigate the role of subsurface storage, treatment thresholds and drought resiliency in the context of climate change.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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