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Measurements of fog water interception by shrubs on the California central coast

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Abstract Fog water deposition may be an important component of the water budget of herbaceous-shrub ecosystems on the central and southern coastal regions of California. This paper presents the first analysis of measured fog water drip rates and meteorological controls in shrublands of Big Sur, California. Seasonal totals of 1255 mm and 306 mm of fog water drip were recorded in 2014 and 2015 (respectively), for averaged fog deposition rates of 0.02–0.08 1 m^2 hr.$^{-1}$ to the soil under shrub canopy cover. The diurnal patterns of fog water drip showed that the majority of all trough water collected under shrubs on no-rain days occurred between the hours of 11 PM and 9 AM. During the study period from June 1 to October 31 of both 2014 and 2015, soil water content decreased significantly from average levels of 4–6 % at the shrub canopy center and middle locations, through 2–3 % VWC at the shrub edge locations, to levels at or below 2 % at 2-m distance locations from the shrub edge in open grass cover. Based on these results, we conclude that detectable rates of shrub canopy fog interception help sustain elevated soil water levels under shrubs and aid woody vegetation survival through periods of low rainfall.

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Introduction

The presence of fog on the California central coast to may be beneficial to vegetation survival and growth through the reduction of water vapor pressure deficits and the slowing of leaf transpiration rates during the warmest periods of the year (Azevedo and Morgan 1974; Burgess and Dawson 2004). Under certain wind conditions, vegetation foliage may trap advected fog water and drip moisture into the surrounding soil below to mediate water losses due to elevated evapotranspiration rates during summer days (Ingraham and Matthews 1995; Corbin et al. 2005). Fog drip has been measured in stands of mature conifers (*Sequoia sempervirens* and *Pseudotsuga menziesii*) located on exposed ridgelines in the Santa Cruz Mountains of northern California (Sawaske and Freyberg 2015). Harr (1982) found that the loss of fog drip from logged areas in Oregon caused a decrease in stream flow, and that rain gages in open areas collected as much as 30 % less water than under the forest canopy.

The physical processes leading to coastal fog formation on the Pacific coast have been studied for decades (Petterssen 1938). Warm surface air blowing over cold upwelling ocean water near the California coast is cooled to create a surface-based inversion. Radiative cooling of the fog layer, together with heating from the sea surface, initiates mixing and lifting of the marine inversion. The well-mixed marine boundary layer is topped by such an inversion at a height of 100–600 m (Pilie et al. 1979). Subsidence acts to strengthen the inversion above the stratus cloud top and forces lowering of clouds (Koračin et al. 2001), which can move ashore with sustained winds to generate fog over land.

A number of studies have examined the relationship between selected meteorological controls and the prediction of coastal fog. For example, Leipper (1995) predicted Pacific coast fog events by applying large-scale synoptic weather

events with inversion-based statistics. Others have attempted to apply large-scale numerical models to the prediction of fog on a meso- to large-scale basis (De La Fuente et al. 2007) or at a single site for the purpose of prediction of fog at an airport (Grace and Ferriere 2001). More regional scale studies have examined the direct relationship between relative humidity, temperature, and wind patterns in relation to fog water collection (Caceres et al. 2007).

In the only published study of fog deposition on the Big Sur coast of central California, Hiatt et al. (2012) reported that dew-point depression (difference between air temperature and dew point temperature) was a strong indicator for the presence and absence of ground-level fog. Using a threshold of hourly dew-point depression below 0.5 ° C, the rate of correctly predicting fog deposition when fog deposition occurred as measured by a standard fog collector (true positive rate) was 77 %. Grace and Ferriere (2001) likewise demonstrated at a site in southeast Australia that a dew point depression below 1.0 ° C predicted the occurrence of fog with a probability between 60 % and 90 %. The standard fog collector used in the study by Hiatt et al. (2012) was not, however, a natural vegetation feature, but instead was a standing polypropylene mesh-screen fastened to a metal 1 × 1 m vertical frame. It was hypothesized that fog interception amounts onto vegetation and soil surfaces could be of sufficient magnitude to affect the water budget of the shrub-dominated plant community measured for fog deposition in the current study.

Coastal shrub cover on ocean-facing ridges in this region have a high degree of biological diversity and endemism, and provide critical habitat for a large number of rare, endangered, and threatened animal and plant species (Henson and Usner 1993; Stow et al. 2008). The water budgets of mixed herbaceous-shrub communities are of interest because they dominate the central and southern coastal regions of California. The objective of this present study was to quantify frequency and magnitude of fog water interception by coastal shrub cover on the Big Sur coast by making direct hourly measurements of moisture drip rates under shrubs during the period of June through October during the years 2014 and 2015. Hourly measurements of soil water content under and around shrubs, along with stomatal conductance rates of shrub foliage, were also made to further characterize the water budget and plant physiology of this ecosystem.

It is worth noting that calendar year 2013 was the driest on record in California, with a total of just 30 % of average statewide precipitation (Hanak et al. 2014). The previous statewide record low was 56 % of average precipitation in 1976. The subsequent drought conditions during the years of 2014 and 2015 created a extended period of soil moisture shortage rarely experienced in Central California (Howitt et al. 2015).
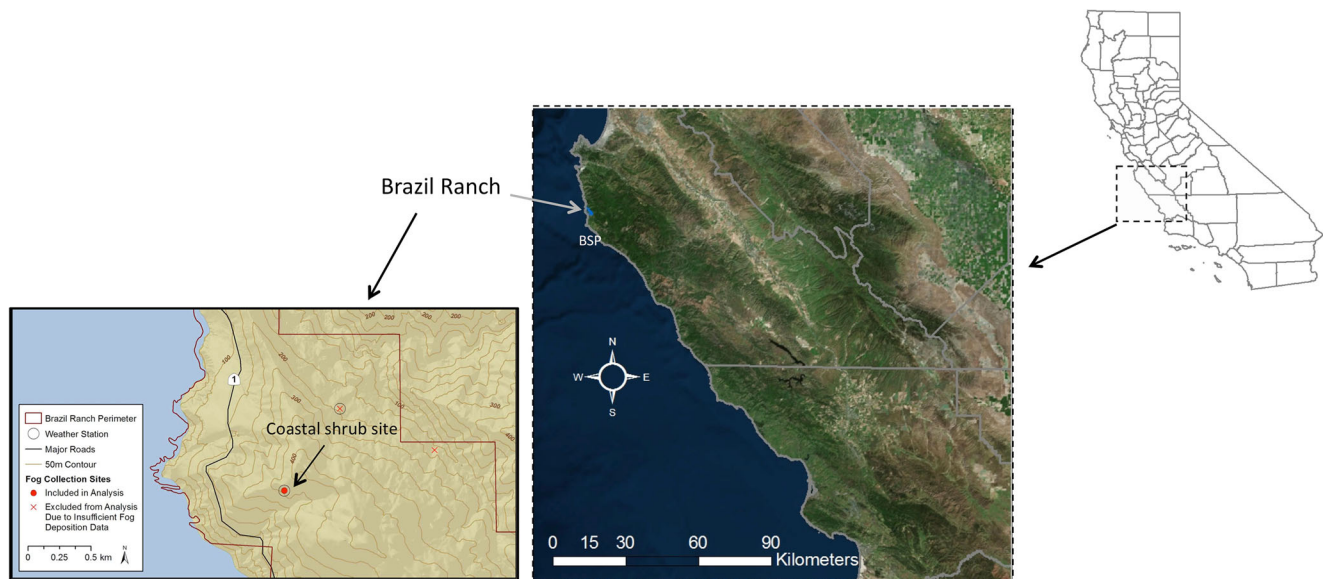
Study area

The research site was located at the Brazil Ranch (center coordinates: latitude 36.36° N, longitude 121.89° W) near Big Sur, California (Fig. 1). The Brazil Ranch is named after the pioneer family that worked to establish the land as a farm, ranch, as well as a dairy operation in the early twentieth century. Today, the property serves as a primary research site for the U. S. Forest Service to monitor and manage vegetation, wildlife, water quality, and sensitive coastal habitats.

The Big Sur region is characterized by a Mediterranean climate with rounded ridges, steep sides, and narrow canyons. The terrain is rugged and undulating with the steepest elevation gradients on the Pacific U. S. coast, ranging (over just several km inland) from sea-level up to 1570 m. Annual rainfall varies from 40 to 150 cm throughout the range, with most falling on the higher mountains in the northern extreme (Potter 2014). The majority of annual precipitation falls in the winter (November–March). During the summer, low clouds are frequently observed along the coast. Mean annual temperature ranges from 10 to 15 °C from canyon bottom to ridge top, respectively (Potter 2014).

South-facing slopes on Brazil Ranch (Fig. 2) share a relatively equal distribution of coyote brush (*Baccharis pilularis*) and California coffeeberry (*Rhamnus californica*) along with some California sagebrush (*Artemisia californica*) (Henson and Usner 1993). This coastal shrub study site for fog deposition is a successional plant community that, in the absence of fire, gradually moves into herbaceous cover where the soil depth transitions from the shallowest to intermediate depth. The herbaceous plant community at the study site includes California annual grassland series and oatgrass series (Potter 2014).

Hiatt et al. (2012) showed that coastal fog deposition at Big Sur peaked in July and August. This increase in fog deposition coincides with the summer season of low rainfall characteristic of California's Mediterranean climate. Most summer fog deposition measured at Brazil Ranch occurred during the night and early morning hours, between the hours of 10:00 PM and 2:00 AM, increasing to a peak at between 3:00 AM and 9:00 AM. After 9:00 AM, average fog deposition steeply declined, to nearly zero between the hours of 2:00 PM and 6:00 PM. Hiatt et al. (2012) reported that summer dew-point depression ranged from 0.3 ° C to 38.8 ° C with an average of 4.4 ° C, and 39 % of hourly records collected in the summer season had a dew-point depression below 1.0 ° C. The median dew-point depression followed an opposite diurnal trend indicating fog deposition occurred when the dew-point depression was below 0.5 ° C. High wind speeds typically accompanied increased rates of fog deposition during periods of low dew-point depression.

For the water year (October 1 to September 30) of 2012–2013, precipitation in the study region totaled to 69 cm, compared to the long-term (1950 to 2015) mean water year total of

Fig. 1 Location and map of the coastal shrub fog study area at Brazil Ranch in monterey county California

103 cm (Fig. 3) recorded 16 km to the south of Brazil Ranch at Pfeiffer Big Sur State Park (BSP station, Elevation 320 m, National Weather Service; available online at www.raws.dri. edu). Total precipitation during the water years of 2013–2014 and 2014–2015 were 47 cm and 82 cm respectively at the BSP station. Just prior to the extended drought period of 2012 to 2015, the water year of 2010–2011 recorded near-average precipitation of 101 cm at the BSP station.

Data and methods

A Campbell weather station equipped with a CR800 data logger, a 03,001 R.M. Young Wind Sentry Set, and an HMP45C

Fig. 2 True color image of the study site from September 2009 airborne NAIP (National Agricultural Imagery Program; www.fsa.usda.gov/ programs-and-services/aerial-photography/imagery-programs/naip-imagery/) northwest-facing imagery, with the shrub sampling area indicated by the box overlay. Shrub cover is shown in green shades, whereas grass cover is shown in *brown shades*, bare ground is shown in *white shades*, and Pacific Ocean in *dark blue shades*

Temperature and Relative Humidity Probe was installed at the Brazil Ranch in 2007. The on-going hourly meteorological data collection included air temperature, humidity, wind speed and direction, solar irradiance, and rainfall precipitation (Potter 2014). Meteorological and fog water interception data were collected at the Brazil Ranch coastal shrub site during 152 days (June through October) in both 2014 and 2015. Hours during which less than 0.3 mm of precipitation was recorded at the site gauge were considered to be no-rain periods and potential fog interception hours for shrub cover, depending on the hourly dew point depression.

Moisture that was intercepted and dripped from shrubs as a result of precipitation or fog water interception was collected under the vegetation by half-pipe plastic troughs, 61.0 cm long by 7.6 cm wide (24 × 3 in.; Fig. 4), representing a collection surface area of 0.0465 m^2. Each trough was drained by plastic tubing into a ECRN-50 rain gauge (Decagon Devices, Inc.) to measure hourly drip rates in mm of water collected. Therefore, for every mm of water measured by the rain gauges, the equivalent of 2.15 L m^{-2} water was collected by a trough under shrub cover. Three troughs were placed under each of five randomly selected coyote brush shrubs, all located within 100 m of the Campbell weather station (area delineated in Fig. 2). Due to the constant presence of strong gusty winds and animal activity, both grazing and native wildlife, at the study location, typically only 10–12 of the 15 troughs and rain gauges were in functionally operating mode at any one time.

Soil moisture probes were placed next to the center-most stems of all five shrubs and in an open (control) grass-covered location next to Campbell weather station at depths of 10 and 30 cm in the soil profiles. Volumetric water content (VWC) was monitored with EC-5 frequency domain probes (Decagon Devices Inc.). Soil water potential and

Fig. 3 Precipitation amounts recorded at the Pfeiffer Big Sur State Park (BSP) station since 1950
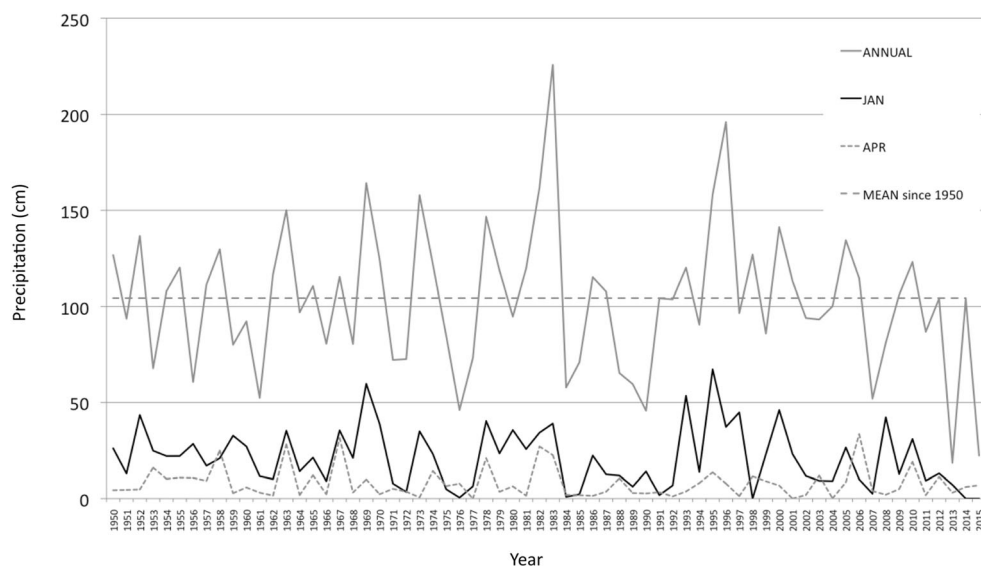
temperature at 10 cm depth was measured with MPS-2 dielectric sensors (Decagon Devices Inc.) under a single shrub at distances of 10, 30, and 70 cm from the center stems of the plant. Decagon Devices EM-50 data-loggers were programmed to collect continuous hourly data for the five shrubs.

Periodically during the study period, mid-day spatial measurements of surface soil VWC to 3.8 cm depth were made using a FieldScout 300 Soil Moisture Meter (Spectrum Technologies, Inc.). For each of the coyote brush shrubs, five VWC measurements were taken per date, starting on a gradient closest to the shrub center, then at the middle, at the shrub

Fig. 4 Fog drip collection troughs placed under shrub cover at the Brazil Ranch study area

edge, and at 1-m and 2-m distance from the shrub edge in open grass cover. On the same date, mid-day stomatal conductance measurements of the coyote brush were made with a SC-1 Leaf Porometer (Decagon Devices Inc.) for three leaves randomly selected on each shrub.

Results

Dew point depression and precipitation

Over the study period from June 1 to October 31, 2014, a total of 859 h were recorded with dew-point depression below 0.5 ° C, the majority of which were detected prior to August 15, 2014 (Fig. 5a). During this same time period, there were no hours recorded before September 27 with more than 0.3 mm of precipitation. Rainfall periods of greater than 0.3 mm per hour occurred on September 27, October 15, 25, and 31, 2014 (Fig. 5b), totaling 275 mm of precipitation.

Over the study period from June 1 to October 31, 2015, a total of 323 h (62 % fewer hours than during 2014) were recorded with dew-point depression below 0.5 ° C, the majority of which were detected prior to July 15, 2015 (Fig. 5a). With the exception of July 19, there were no hours recorded before September 30 with more than 0.3 mm of precipitation. Rainfall periods of greater than 0.3 mm per hour occurred on September 30, October 1, and on October 18–19, 2015 (Fig. 5b), totaling only 92 mm of precipitation.

Soil water content gradients

During the study period from June 1 to October 31 of both 2014 and 2015, soil VWC decreased significantly ($p < 0.05$) from average levels of 4–6 % at the shrub center and middle locations, through 2–3 % VWC at the shrub edge locations, to

Fig. 5 Hours of dew point depression (below 0.5 °C) and rain gauge precipitation amounts at the Brazil Ranch climate station in 2014 and 2015
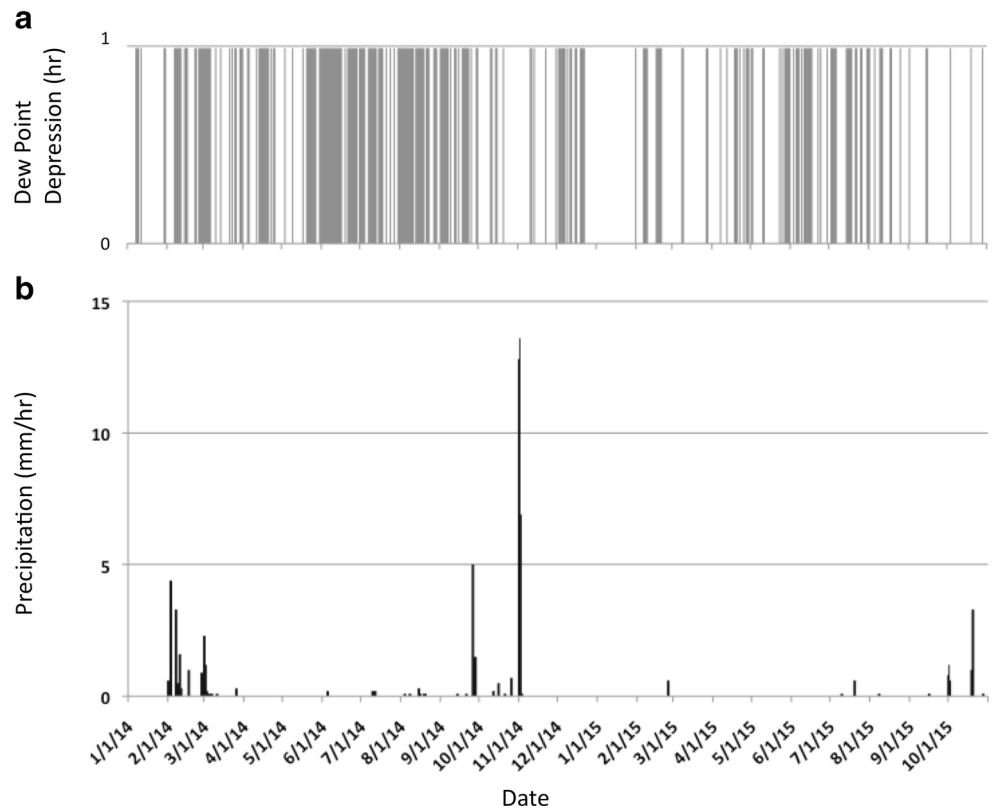
typical average VWC levels at or below 2 % at 1-m and 2-m distance locations from the shrub edge in open grass cover (Fig. 6). In contrast, on dates prior to June 1 of either year, the measured VWC gradient from shrub center locations to edges and to 1-m and 2-m distance locations did not decrease significantly, relative to average levels of 7–10 % at within-shrub canopy locations. In the third consecutive drought year of 2015, the VWC gradient measured in late May from the shrub center locations to edges and beyond did fall off slightly, to an average level of just under 4 % at the 2-m distance location.
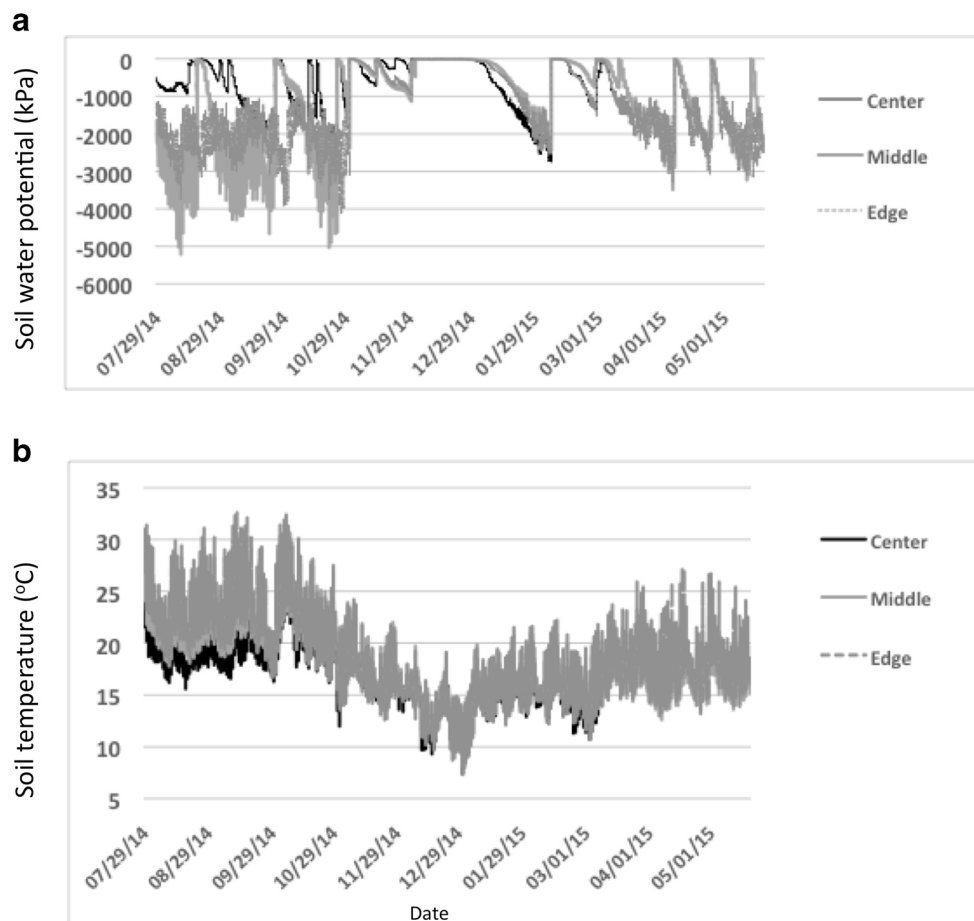
Hourly soil water potential and volumetric water content

During the study period from July 29 to October 31, 2014, soil water potential recorded at the shrub center location remained higher than at either the shrub middle or edge locations (Fig. 7a). The lowest water potential measured at the shrub center was around −1900 kPa (in mid September, 2014), whereas the lowest water potential measured at the shrub middle or edge locations at this same time was approximately −4600 kPa and −3000 kPa, respectively. Detectable rainfall on September 27, 2014 caused the soil water potential to
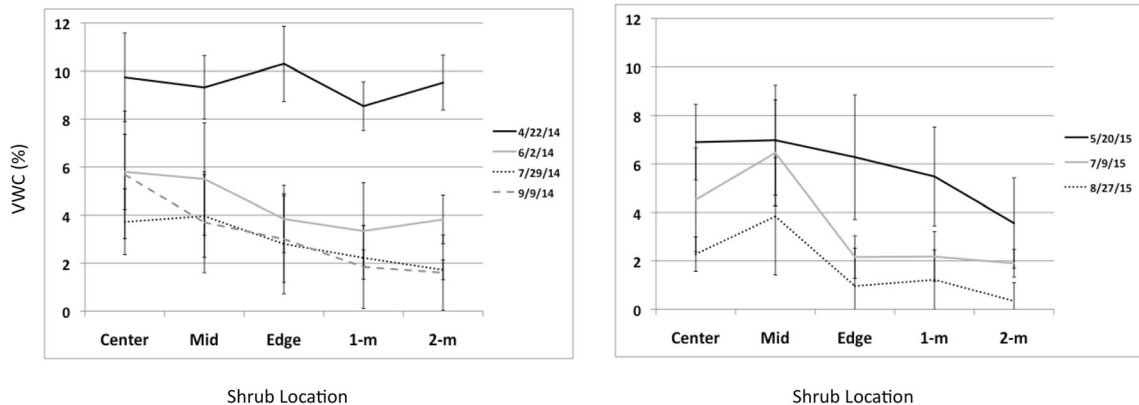
Fig. 6 Soil moisture gradients measured at five locations in and around shrubs at the Brazil Ranch study area, at the shrub center, middle, canopy edge, 1-m from canopy edge, 2-m from canopy edge

Fig. 7 Hourly soil water potential and soil temperature (10 cm depth) measured at shrub center, middle, and canopy edge locations

increase temporarily to under −100 kPa at the shrub center and middle locations, but did not affect the soil water potential at the shrub edge location, which remained at around −3000 kPa. During the rainfall season of November – December 2014, soil water potential recorded at all three shrub locations remained higher than −1000 kPa, but then decreased periodically to lower than −2000 kPa during the driest periods from January – May, 2015.

Hourly soil temperature measured at 10 cm depth during the study period from July 27 to September 26, 2014 was continuously lower at the shrub center location by about 2° C compared to hourly soil temperature at the shrub middle and edge locations (Fig. 7b). This notable difference in soil temperature between the shrub center, middle and edge locations was no longer present after the detectable rainfall on September 27, 2014. Maximum daily soil temperature at all three shrub locations dropped from around 30° C on October 6 steady to below 22° C on October 30, and typically to below 20° C by the regular rainfall period of mid-December.

Hourly VWC measured at 30 cm depth for all five shrub center locations remained at levels between 6 % and 9 % throughout the period of June 1 to October 31 in both 2014 and 2015 (Fig. 8). Hourly VWC measured at 10 cm depth was

more variable among the five shrubs measured, periodically dropping below 4 % for one or two of the shrubs, depending on the year.

The comparative impact of the 2013–2015 drought period could be detected in the soil VWC record of an open grass-covered area at the study site from 2012 to late 2015 (Fig. 9). Throughout the period of June 1 to October 31 in 2013, 2014, and 2015, hourly VWC measured at both 10 cm and 30 cm depth under open grass cover did not exceed 2 %, and frequently dropped to below detectable moisture levels of the sensors. These continuous hourly VWC measurements under open grass were consistent with average VWC levels below 2 % at 1-m and 2-m distance locations measured on selected dates between June 1 and October 31 in open grass cover (Fig. 6).

Detectable trough water drip recorded under any of the shrubs did not result in an immediate increase in VWC measured at 30 cm depth (Fig. 8), with the exception of the detectable rainfall amounts measured in late September and early October of 2014 and 2015. However, measured fog water drip rates under shrub canopies into troughs detected on July 8–13, 2014 and August 7, 2014 were associated with notable increases in VWC measured at 10 cm soil depth in the days immediately following.
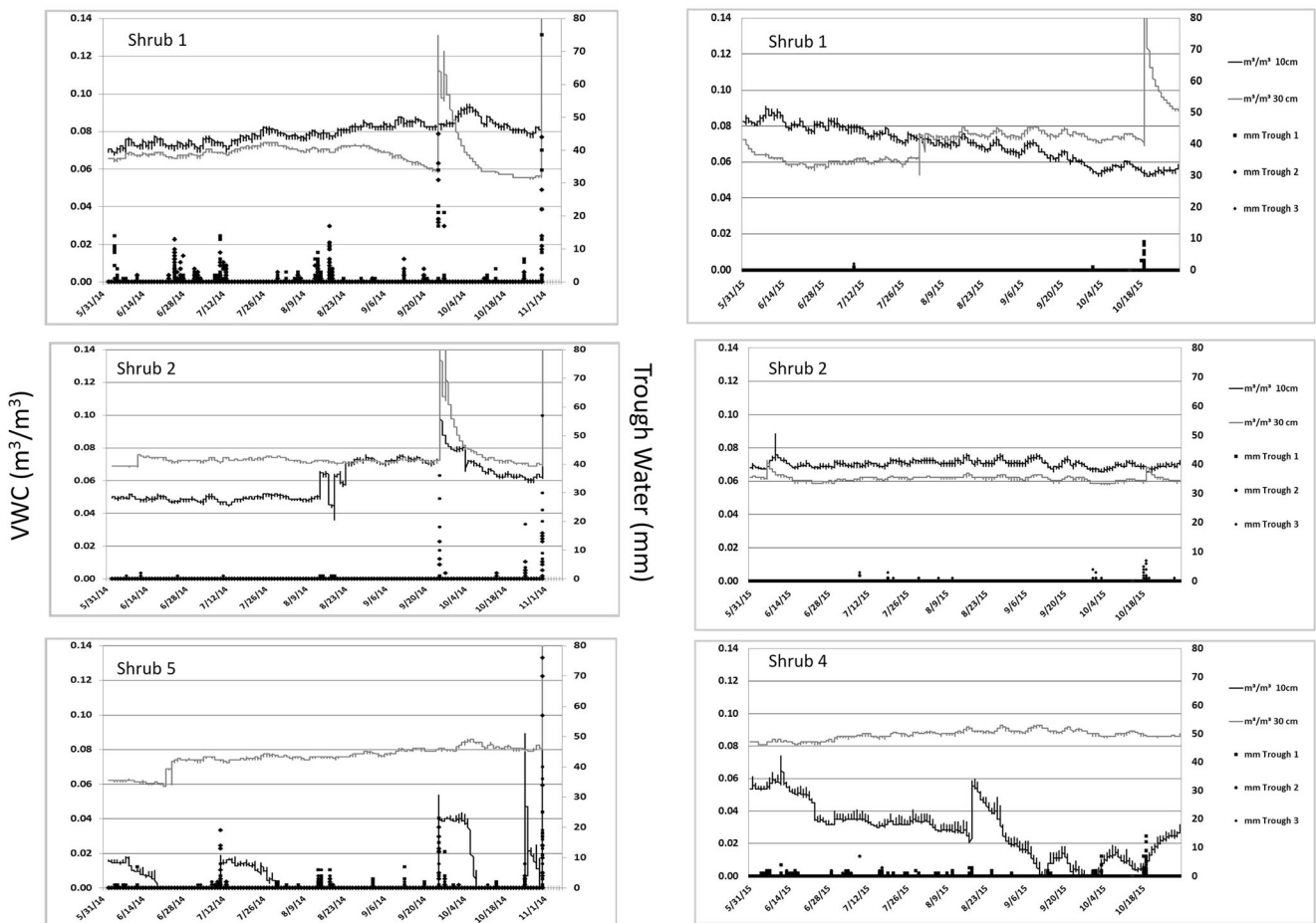
Fig. 8 Hourly soil moisture (at selected shrub center locations) and trough water flow rates (mm) measured under shrubs at the Brazil Ranch study area

Hourly fog drip

Trough drip rates measured during hours of no detectable rainfall on dates between June 1 and October 31 were considered to represent fog water intercepted by shrub canopy cover (Fig. 10). The periods of highest fog water drip from shrubs at the study site were recorded during early July and mid August of 2014. A total of 1225 mm of fog water drip was recorded in 2014 for an average hourly drip rate of 0.035 mm hr.$^{-1}$, based on a conservative number of ten troughs functioning during any given day. This drip rate was equivalent to an averaged fog deposition rate of 0.08 l m^2 hr.$^{-1}$ to the soil under shrub canopy cover between June 1 and October 31. The periods of highest fog water drip from shrubs recorded in 2015 were

Fig. 9 Hourly soil moisture content measured under open grass cover at the Brazil Ranch study area
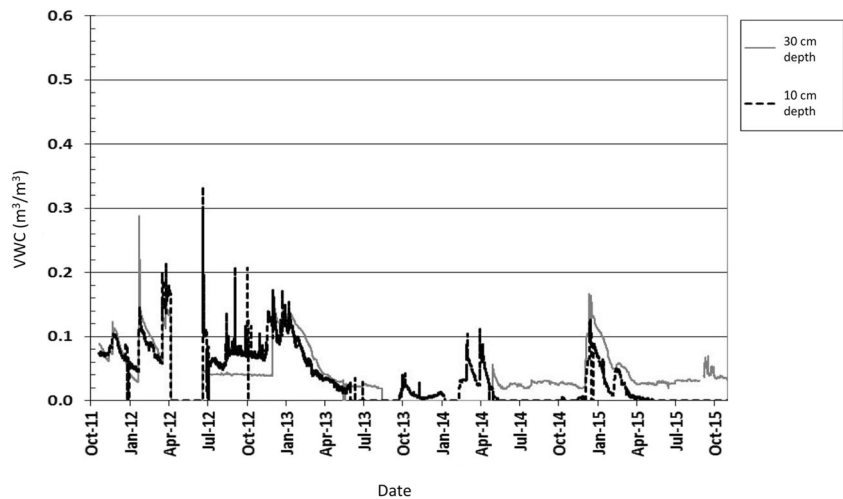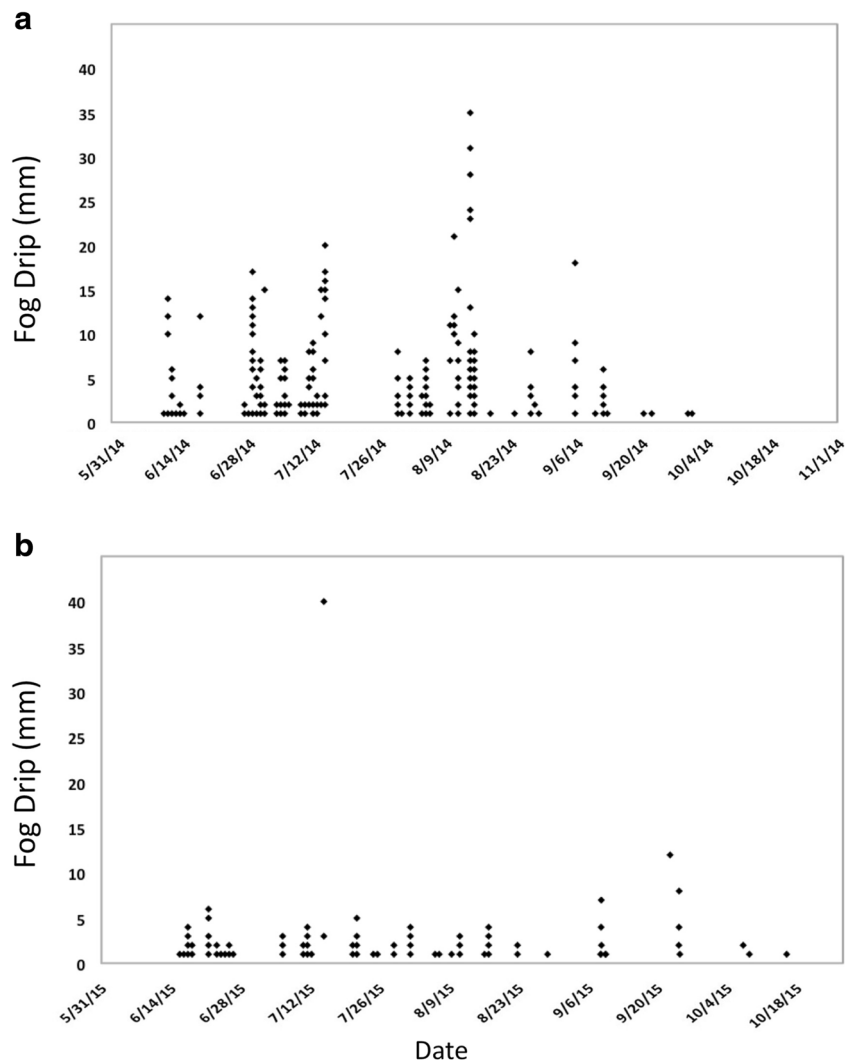
during late September (Fig. 10). A lower total of 306 mm of fog water drip was recorded in 2015, for an averaged fog deposition rate of 0.02 l m^2 hr.$^{-1}$ to the soil under shrub canopy cover between June 1 and October 31.

The diurnal patterns of fog water drip showed that the majority of all trough water collected under shrubs on no-rain days in 2014 and 2015 occurred between the hours of 11 PM and 9 AM. Daily plots of some of the highest fog drip dates showed peak rates most commonly occurred between 6 AM and 8 AM (Fig. 11).

Foliar stomatal conductance

On dates during the regular rainfall months of April and May, the average stomatal conductance of shrub leaves was estimated at higher than 300 mmol m^{-2} s^{-1} (Fig. 12). Average stomatal conductance rates declined significantly ($p < 0.05$) to less than 250 mmol m^{-2} s^{-1} during the frequent fog drip period of July–September. The lowest mean stomatal conductance rate of 124 mmol m^{-2} s^{-1} was measured on August 1, 2015.

Discussion

The results from this study demonstrated for the first time that shrub canopies on the California coast intercept and drip to the soil surface detectable moisture from fog water deposition, which may help sustain the productivity of this vegetation community through periods of low rainfall precipitation. Similarly, Joslin et al. (1990) demonstrated that trees can collect fog water at approximately the same rate as a passive string fog collector. On the Point Reyes peninsula, a California coastal area approximately 200 km north of Big Sur, Ingraham and Matthews (1995) compared water isotopes before and after the summer fog season and found the isotope matching fog drip permeated into the root zone and wood cores of conifer trees.

This study is an important step towards a better understanding of the quantities of fog deposition that occur on the California coast and how fog deposition may affect coastal vegetation ecology. Putting into context the average estimated fog water drip rates under shrubs of between 0.01 and

Fig. 10 Hourly fog drip rates (mm/hr) measured under all shrubs combined on days with no detectable precipitation at the rain gauge of the Brazil Ranch study area
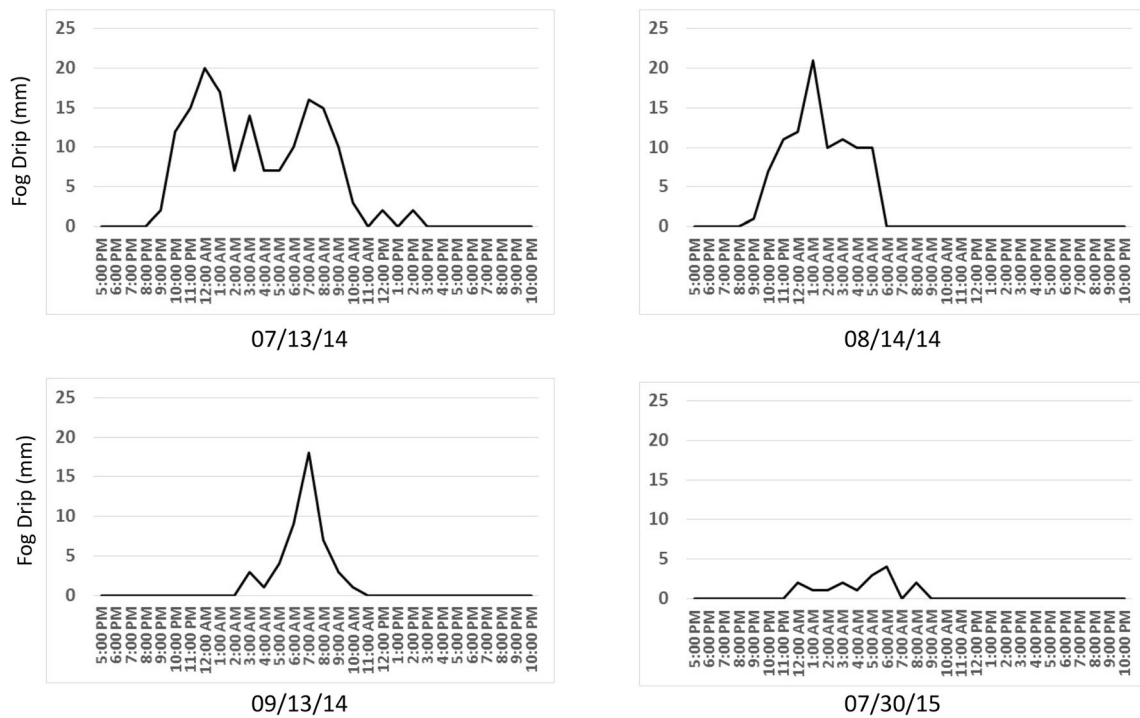
Fig. 11 Diurnal plots of the highest hourly fog drip rates at the Brazil Ranch study area

0.035 mm hr.$^{-1}$ (for the period of June to October 2015 and 2014, respectively), average rainfall rates for the full water year period of October to September (8760 total hours) for 2014 and 2015 were estimated at 0.054 and 0.094 mm hr.$^{-1}$, respectively. Based on this comparison, it can be concluded that, during the drought years of 2014 and 2015, fog water drip rates to soils under coastal shrub canopies can be equivalent to 30–50 % of annual average rainfall rates.

Patterns of soil water content and water potential measured under shrub canopies compared to open grass cover at the study site supported the finding that fog water interception by shrub foliage provides adequate moisture inputs around the shrub canopy center to maintain soil water levels near those measured during regular rainfall months of April and May. Although measured periods of fog drip under shrubs

did not routinely increase soil water content to statistically significant levels, gradual increases in VWC measured at 10 cm soil depth under shrubs were measured in days immediately following the highest fog interception periods of 2014.

The diurnal pattern of fog water drip under shrubs, measured at the highest rates between the hours of 11:00 PM and 9:00 AM, was consistent with the results reported by Hiatt et al. (2012), who found that deposition rates on a standard fog collector at Brazil Ranch occurred mainly during the hours of 10:00 PM and 9:00 AM, increasing to a peak after 3:00 AM. The highest fog drip dates measured under shrubs at the same study site commonly occurred between the hours of 6:00 AM and 8:00 AM.

Some of the influence of fog water interception on coast plant physiology could be inferred from this study. Stomatal

Fig. 12 Mid-day stomatal conductance rates averaged for five shrubs (N = 15; 3 leaves per shrub) for selected dates during 2014 and 2015 at the Brazil Ranch study area
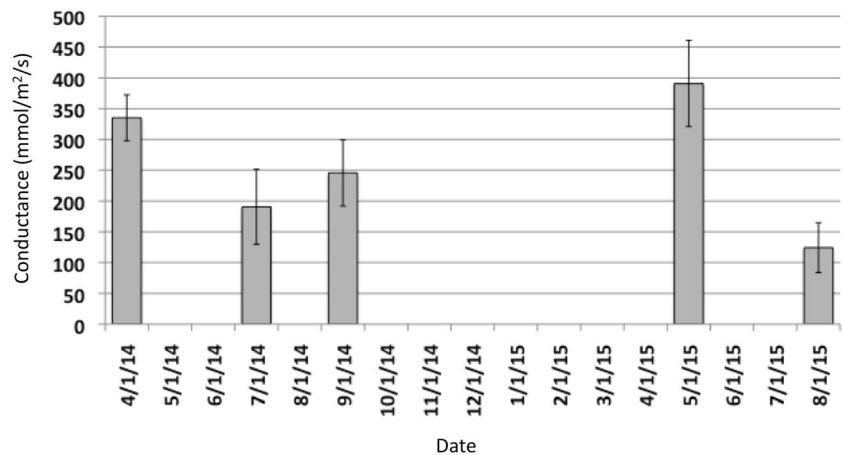
control of foliar conductance is an important means by which plants limit water loss and is often used as an indicator of water stress and photosynthesis (McDermitt 1990). The lowest average stomatal conductance rates measured for coyote brush leaves (during August 2015) at Brazil Ranch coincided with the lowest average soil moisture measured (of under 4 % VWC) during the study period, and also with a period of relatively infrequent fog water drip by shrubs. Stomatal conductance rates measured in a Mediterranean climate woodland in Spain by Castell and Terradas (1995) followed the same seasonal pattern measured at Brazil Ranch, with wet season rates near 300 mmol m^{-2} s^{-1} and dry season rates below 100 mmol m^{-2} s^{-1}. The conclusions from this related study were that low transpiring leaf area for young woody tree species was more limited by soil water availability than by vapor pressure deficit, compared to more mature plants with deep root systems that were more limited by atmospheric water deficit and less by soil water deficit. Similar studies in blue oak (*Quercus douglasii*) stands throughout central California by Matzner et al. (2003) showed that seedling stomatal conductance was correlated with percent extractable soil water (ESW) throughout the year, whereas adult tree and sapling stomatal conductance was correlated with ESW only between June and September.

From a broader ecological perspective, the conditions most favorable for coyote brush establishment are summer coastal fog, greater than average precipitation, and late rains, which reduce moisture stress (Da Silva and Bartolome 1984). Coyote brush seedlings initially grow slower than annual grasses, but can produce long taproots that can endure the drought during the first summer if root reaches adequate soil moisture. Conditions unfavorable for coyote brush establishment are early rains, lower than average precipitation, and drier sites, which favor grass domination before the coyote brush seeds can disperse and plants establish (Williams and Hobbs 1989). Coyote brush summer mortality can also be caused by severe soil cracking (McBride and Heady 1968).

Conclusions

Measurements of fog water drip rates and meteorological controls in Big Sur, California revealed detectable rates of summer fog interception by shrubs that can sustain elevated soil water levels through extended drought periods of low rainfall. During the study period from June 1 to October 31 of both 2014 and 2015, soil water content decreased from average levels of 4–6 % at the shrub canopy center and middle locations, through 2–3 % VWC at the shrub edge locations, to levels at or below 2 % at 2-m distance locations from the shrub edge in open grass cover. Seasonal totals of fog water drip were estimated at averaged fog deposition rates of 0.02–0.08 l m^2 $hr.^{-1}$ to the soil under shrub canopy cover. The

diurnal patterns of fog water drip showed that the majority of all trough water collected under shrubs on no-rain days occurred between the hours of 11 PM and 9 AM. Fog water drip to soils under these coastal shrub canopies can be equivalent to as much as 50 % of annual average rainfall rates.

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