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Fog Water Collection Effectiveness: Mesh Intercomparisons

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ABSTRACT

To explore fog water harvesting potential in California, we conducted long-term measurements involving three types of mesh using standard fog collectors (SFC). Volumetric fog water measurements from SFCs and wind data were collected and recorded in 15-minute intervals over three summertime fog seasons (2014–2016) at four California sites. SFCs were deployed with: standard 1.00 m² double-layer 35% shade coefficient Raschel; stainless steel mesh coated with the MIT-14 hydrophobic formulation; and FogHa-Tin, a German manufactured, 3-dimensional spacer fabric deployed in two orientations. Analysis of 3419 volumetric samples from all sites showed strong relationships between mesh efficiency and wind speed. Raschel mesh collected 160% more fog water than FogHa-Tin at wind speeds less than 1 m s⁻¹ and 45% less for wind speeds greater than 5 m s⁻¹. MIT-14 coated stainless-steel mesh collected more fog water than Raschel mesh at all wind speeds. At low wind speeds of < 1 m s⁻¹ the coated stainless steel mesh collected 3% more and at wind speeds of 4–5 m s⁻¹, it collected 41% more. FogHa-Tin collected 5% more fog water when the warp of the weave was oriented vertically, per manufacturer specification, than when the warp of the weave was oriented horizontally. Time series measurements of three distinct mesh across similar wind regimes revealed inconsistent lags in fog water collection and inconsistent performance. Since such differences occurred under similar wind-speed regimes, we conclude that other factors play important roles in mesh performance, including in-situ fog event and aerosol dynamics that affect droplet-size spectra and droplet-to-mesh surface interactions.

Keywords: Fog mesh; Fog water collection efficiency; Raschel mesh; Hydrophobic coating.

INTRODUCTION

Collecting fog drip as a source of water for human needs has a long history (Marzol-Jaén *et al.*, 2011; Fogquest, 2017). The growing worldwide scarcity and unavailability of potable water in many populated areas is causing increasing alarm (Gleick, 2000). This situation has led to an expanding interest in unique and innovative water collection methods (Qadir *et al.*, 2007) even in highly-developed industrialized regions, such as those within coastal California. While complete human reliance upon fog drip is unrealistic (Klemm *et al.*, 2012; Domen *et al.*, 2013), there are many applications

consumption and demand are lower than in most industrial countries, fog water harvesting has become a primary water source (Schemenauer and Cereceda, 1994a; Lummerich and Tiedemann, 2011; LeBoeuf and de la Jara, 2014; Batisha, 2015).

The non-profit organization Fogquest, was an early leader in identifying physical and social conditions where fog drip collection could yield sufficient water to justify the installation effort and cost of passive fog harvesting systems (Cereceda and Schemenauer, 1991). The most productive of these systems are located on mountain tops where large collecting mesh panels are placed perpendicular to prevailing winds that advect marine stratus onto the panels, such as in Chile and Morocco, or orographically-lifted fog such as in Nepal and Eritrea (Fessehayee *et al.*, 2014).

Optimizing the efficiency of large, passive fog water collectors continues to be a major challenge for the fog water harvesting community. One target for improving fog drip collection has been the relationship between the impaction surface and the fog droplets.

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and regions where fog water harvesting can be a significant source of water. In some areas where human

The 1.00 m² fog collector was first developed by Goodman (1985) to test the collection efficiency of flat versus cylindrical harp collectors strung with 0.8 mm diameter monofilament nylon. She found flat collectors more efficient when the prevailing wind direction consistently dominated.

Schemenauer and Cereceda (1994b) proposed the use of a flat-panel, double-layered 35% shade cloth of 1 mm polypropylene ribbon Raschel woven mesh as the standard fog collector (SFC) impact surface fitted within a standardized copper frame and trough design. Standardization facilitates comparative analysis of overall collection efficiency at multiple geographic locations (Cereceda and Schemenauer, 1991) with overall efficiency being defined as the liters of fog water collected by 1.00 m² of mesh per day. The efficiency of the SFC and of very large (48 m²) collectors was observed to increase with increased fog droplet diameter and increased wind speed (Schemenauer and Joe, 1989; Schemenauer and Cereceda, 1991). Detailed measurement of fog droplet size measured using Particle Measuring Systems Forward Scattering Spectrometer Probes (FSSP) and collection efficiency calculations based on Langmuir and Blodgett (1946) equations found an overall collection efficiency of 20%. Collection efficiency was highest (66%) at the center of a large fog collector when droplets were 11 μm at a wind speed of 3.5–6.5 m s⁻¹.

In order to effectively collect fog, the mesh must allow water droplets with diameters of 1–50 μm to pass through it and, at the same time, provide sufficient surface area for fog droplets to collide with and adhere to. At lower wind speeds, smaller droplets will tend to follow the air streamlines and pass around mesh fibers that are wider. As the wind speed and/or droplet size increase, the greater inertia of the droplets will increase their tendency to collide with the mesh fibers. Similarly, as the mesh fibers become more narrow, fog droplets suspended in the air that are directed by the wind toward the fibers will be less likely to follow the wind streamlines and more likely to collide with the mesh fibers (Spielman, 1977). A Stokes number, which is a measure of how well tiny water droplets can maintain their inertia and resist entrainment into a turbulent flow, provides an indication of the tendency of the fog droplets to collide with the mesh. Stokes numbers greater than one signify a greater chance for collision, and smaller Stokes numbers indicate less opportunity for collision. Increasing the capacity for air flow through the mesh increases the Stokes number, and thus increases the likelihood of a collision with mesh fibers. However, such increased air flow is also typically accompanied by a decrease in the mesh surface area, resulting in lesser opportunity for collisions between the droplets and the mesh. So, for a given wind speed and fog droplet size distribution, one type of mesh will likely prove to be more effective than another, with wider fibers more effective at greater wind speeds and with larger droplet size distributions and narrower fibers more effective at lesser wind speeds and with smaller fog droplet size distributions.

As droplets accumulate on an impacted surface, they coalesce, increasing in size and weight to overcome adhesive and gravitational forces and, depending on the characteristics of the mesh material, they either slide or, due to wind, may

be blown off the mesh into a trough subtending the collecting surface. The accumulated droplets then spill through the slightly-angled trough that allows the water to be collected for measurement and/or storage. For in-situ collectors, debris and aerosol particles can become critical at this stage, clogging the driplines and trough.

Underlying capture efficiency are fog droplet chemistry and microphysics. Fog droplet size spectra result from complex interactions of the fog formation, evolution, and dissipation system. Differences in fog-droplet size result from differential deliquescence of aerosols acting as cloud condensation nuclei (CCN) around which fog water droplets accumulate. Fog droplet evolution processes within an advecting air mass are fog-event specific and lead to differences in fog droplet size and relative impaction on collecting surfaces (Al-Dughaiter *et al.*, 2010).

Research into the broader topic of separation of entrained liquid from gas or vapor streams for industrial and manufacturing purposes has yielded insights into methods of calculating collector efficiency that are relevant for fog water harvesting research. Models developed by Brunazzi and Paglianti (2000) following Langmuir and Blodgett efficiency equations (1946) and subsequent modifications (Carpenter and Othmer, 1955), to investigate demister efficiency revealed that calculation of Stokes number using diameter values underestimates collection efficiency of polypropylene strands and overestimates collection efficiency of metal strands.

Innovative coatings that improve collection efficiency by modifying the hydrophobicity of the impacting surface have been proposed and tested in laboratory settings (Park *et al.*, 2013; Park *et al.*, 2014; Rajaram *et al.*, 2016; Zhang and Wang, 2016). Although such mesh have been tested in laboratory conditions or modelled to estimate their collection effectiveness, there have been relatively few published in-situ studies that have compared coated mesh with uncoated variants in the field (Feld, 2014; Regalado and Ritter, 2017). Furthermore, the in-situ comparisons that have been conducted between various mesh types typically measure fog water volumetric data over long periods of time, typically several months with, at most, daily resolution, rather than the higher-resolution, sub-hourly time intervals that are needed to examine wind-related impacts on collection efficiency.

The 2012–2017 five-year drought that impacted California heightened the search for alternative water sources. Unlike other areas described above with consistently dense fog advection, the fog and low cloud cover along the California coast varies considerably spatiotemporally (Torregrosa *et al.*, 2016). The present study observes that liquid water content variability between fog events is also high. A primary goal of this mesh comparison project is to examine fog water harvesting efficiency of different mesh types under different conditions. This will provide a richer context to assess the viability of fog water harvesting to supply water to grazing animals and wildlife during the arid Mediterranean climate summer season, within the context of coastal California variability.

METHODS

The Standard Fog Collector (SFC) design (Schemenauer and Cereceda, 1994b) was deployed in 2014, 2015 and 2016 at four sites in coastal central California during the Mediterranean climate summer fog season of May to mid-October. The four study sites are a representative subset of the California coastal environments where fog events take place. The sites vary in elevation, distance from ocean, and vegetation. The site locations, from north to south are: 1)

Pepperwood Preserve, 400 m above sea level (ASL), 40 km from the ocean, on a west-facing grassland slope with a mixed oak woodland upslope; 2) Montara Water and Sanitary District Headquarters, 8 m ASL, 20 m from the ocean, on a coastal grassland bluff; 3) Fritzsche Field, 40 m ASL, 5 km from the ocean, in coastal chaparral; and 4) Glen Deven Ranch, 300 m ASL, 1 km from the ocean, in a mixed grassland chaparral meadow within a landscape composed of redwood, cypress, oak and eucalyptus (Fig. 1).

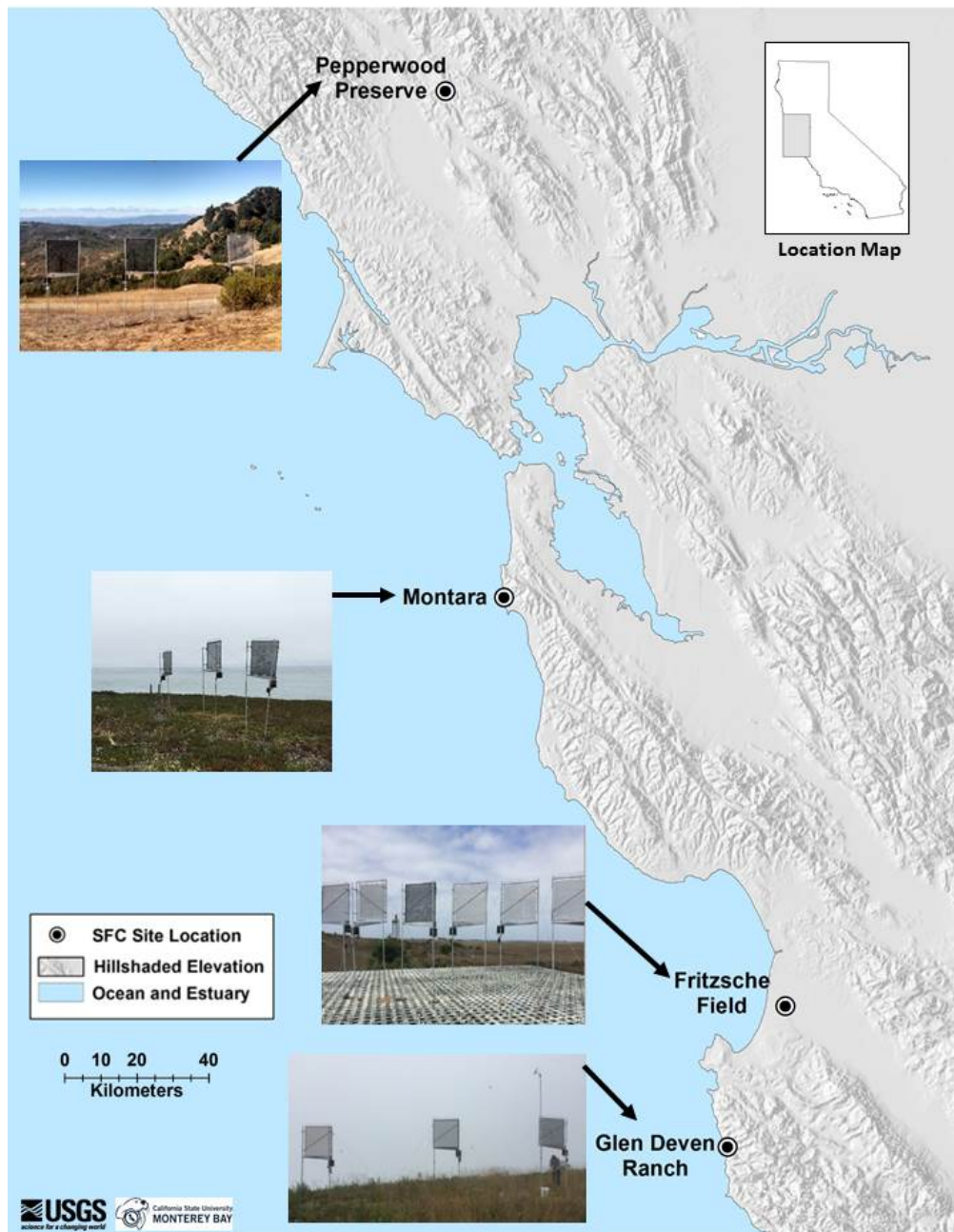


Fig. 1. Location map of study sites with photo insets of collector arrays from left to right. The sites from north to south and collector positions from left to right are: Pepperwood Preserve: Raschel, rotated FogHa-Tin, and MIT-14; Montara: Raschel, Rotated FogHa-Tin, and MIT-14; Fritzsche Field with 6 collectors in photo and only three of which are included in this study (the other three collectors are not examined in this paper); and Glen Deven: Raschel, FogHa-Tin, and MIT-14.

Fog water was collected at each site with a control SFC deployed with the standard mesh, a double layered 35% shade cloth of 1 mm polypropylene ribbon Raschel woven mesh (Fig. 2(a)) and as many as 3 modified SFCs for

comparison. Modifications included type of mesh and mesh orientation. Two mesh types were used to modify the SFCs, one with an innovative hydrophobic coating and the other an innovative weave design. These two mesh types were selected because they had been causing excitement in the fog water harvesting community when they exceeded SFC fog water collection rates in the laboratory or preliminary field trials. The hydrophobic coating is a POSS-PEMA compound designed to enhance fog collection capability by the Cohen research group at the Massachusetts Institute of Technology (MIT) Department of Chemical Engineering (Park *et al.*, 2013). The compound was coated onto a McMaster-Carr stainless steel mesh of 0.02” wire diameter with a hole spacing of 0.051” resulting in 196 (14 by 14) holes per square inch and a shade coefficient of 49%. Henceforth, we refer to this as the MIT-14 mesh type (Fig. 2(b)). The second mesh type, a 3-dimensional textile, was developed by the Institute of Textile Technology and Process Engineering, Denkendorf, Germany (Sarsour *et al.*, 2010) and branded as FogHa-TiN (Fig. 2(c)). The FogHa-

Tin textile was designed using biomimicry to be a more effective mesh for fog water collection purposes. It contains an elaborate interweaving of approximately 0.13 mm diameter polypropylene thread into a springy, 1.5 cm thick structure with interleaved sets of embedded hexagonal patterns. The FogHa-Tin mesh was deployed in a rotated orientation, with the warp of the weave in a horizontal orientation (Fig. 2(d)) at the beginning of the study. To facilitate comparison across sites, the rotated orientation was maintained throughout the study. A rotated versus non-rotated comparison was conducted in 2016. All fog collectors were aligned to face the direction of the prevailing wind, determined from historical meteorological observations at each location.

Volumetric measurements of fog water were collected from each SFC using a tipping bucket rain gauge at a 15-minute sampling interval recorded on an in-situ data logger. These volumetric data were later adjusted using an individual rain gauge “correction factor.” The correction was based on a calibration procedure where the number of “tips” were

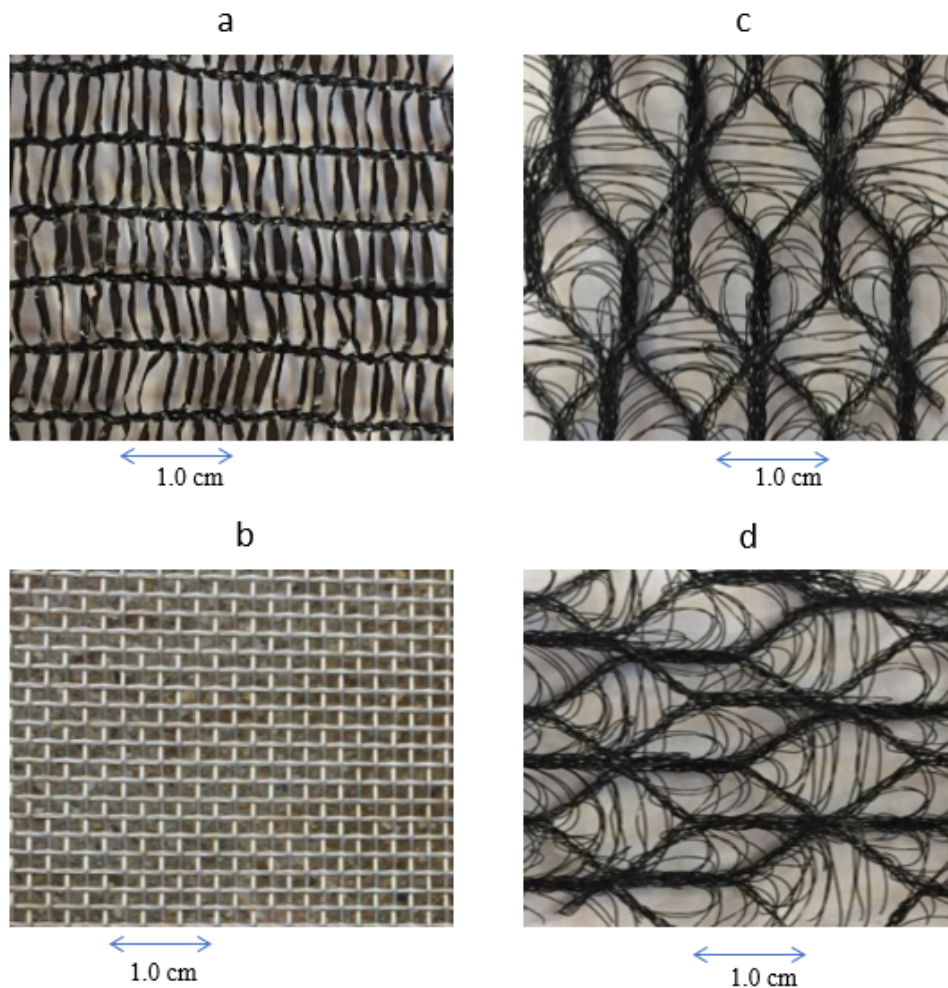


Fig. 2. Close-up photos of three types of mesh under comparison in this study: (a) Raschel weave polyethylene 35% shade cloth, (b) metal mesh coated with the POSS-PEMA formulation, known as MIT-14 (c) FogHa-Tin, a 3-D spacer textile shown in its proper orientation, and (d) the rotated version of the FogHa-Tin textile.

recorded as 0.5 liters of water were poured slowly through the gauge using a peristaltic pump. This calibration protocol

was instituted after the variability between rain gauges off-the-factory-shelf was found to be $\pm 10\%$ tips/liter. Volumetric

records that coincided with summertime rain events were excluded from the analysis. These rain events, based on precipitation records collected from nearby rain gauges, were a relatively rare occurrence in this seasonally arid Mediterranean climate region. Data were only collected during the summertime fog season, May through mid-October to avoid the wet season rain events.

Fritzsche Field and Pepperwood SFCs were co-located at existing meteorological stations. Meteorological stations were deployed at the Montara and Glen Deven sites. Wind speed was collected at a 15-minute interval at Montara, Glen Deven, and Pepperwood and at a 10-minute interval at Fritzsche Field. To better align time stamps between the wind data and the fog water volumes collected at the Fritzsche Field site, only wind data recorded on the hour and half hour were used.

Data were collected at four sites for three pairs of mesh types: Raschel and MIT-14, Raschel and Rotated FogHa-Tin, and Rotated FogHa-Tin and Regular (non-rotated) FogHa-Tin as summarized in Table 1. Comparisons are made based on the volume of fog water collected during each 15-minute interval.

DATA QUALITY

Every effort was made to ensure the highest quality of data for this study. Problems that were encountered during the study included failed wind sensors, fallen collectors, and failure of the rain gauge to tip due to plugging by debris. These problems were uncovered by continuous on-site monitoring of equipment and careful examination of the dataset to investigate when two adjacent fog collectors responded differently to the same event. Data were included only when both fog collectors in the pair being compared were operating simultaneously (although, as will be shown, one may have had nonzero records while the other, functioning properly, recorded zero values). Fog collector data and/or metadata were used to verify when collector rain gauges were plugged. Indication of plugged rain gauges often manifest in the data set typically as periods of zero collection interspersed with occasional single tips at sporadic times. It takes careful observation of a data set to consider

whether periods of zero collection from a fog collector are due to a plugged rain gauge or whether they are legitimate periods of no data. Thorough examination of high-resolution time series plots showing simultaneous collection activity of different types of mesh is critical to positing a mechanism that links the differential performance of the differing types of mesh to the same fog event.

RESULTS AND DISCUSSION

Raschel Mesh versus the MIT-14 Mesh

Data from the pair-wise combination of Rachel and MIT-14 mesh (e.g., the hydrophobic POSS-PEMA coated wire mesh) were collected from three of the four sites during the 2014 and 2015 summertime fog seasons (see Table 1). Pair-wise data are defined as being nonzero fog water volume data collected by at least one of the two mesh types simultaneously during a 15-minute interval when both SFC's were operating. Total fog water collection amounts from all three sites is summarized in Fig. 3 by mesh type and binned into wind speeds of 0–1, 1–2, 2–3, 3–4, 4–5 and 5+ m s^{-1} . As can be seen in Fig. 3, in the 1–2 m s^{-1} bin, both mesh types collected the same, maximum amount of fog water (18.5 liters) in comparison to the other wind speed bins. The discrepancy between mesh collection seems to grow with wind speed because, at higher wind speeds, the MIT-14 mesh tends to collect more water.

This result is somewhat surprising, given that we expect a double layer of 35% Raschel mesh to have a shade coefficient greater than that of the MIT-14's 49% shade coefficient. Additionally, the 1 mm ribbon width of the Raschel mesh is greater than the approximately 0.5 mm diameter of the metallic MIT-14 screen cylinders. Both of these factors would normally favor fog collection in higher winds than in lower winds. Perhaps the greater rigidity of the MIT-14 metallic screen required a greater wind speed to help to overcome blockages and promote drainage, thus enhancing its relative performance at higher wind speeds. Additionally, perhaps the very flexible, flat polyethylene fibers that comprise the Raschel mesh allow greater relative air flow through them at lower wind speeds than does the MIT-14 mesh. Neither of these considerations is explicitly

Table 1. A summary of the periods when fog water collection took place from each pair of mesh considered at each site. Viable dates refer to periods when both fog collectors were operating as well as when wind data exist. Mesh pairs that were not deployed at a site are indicated with an X.

Site (from north to south)	Raschel and MIT-14	Raschel and Rotated FogHa-Tin	FogHa-Tin and Rotated FogHa-Tin
Pepperwood Preserve	9/7/14–9/24/14, 6/10/15–9/15/15	7/17/14–9/30/14, 6/10/15–7/8/15, 7/14/15–9/15/15	X
Montara Water and Sanitary District Headquarters	X	6/24/15–10/1/15	X
Fritzsche Field	10/7/14–10/23/14 8/7/15–9/30/15	5/20/16–10/13/16	5/20/16–7/14/16
Glen Deven Ranch	8/6/15–10/3/15	8/6/15–10/4/15	X

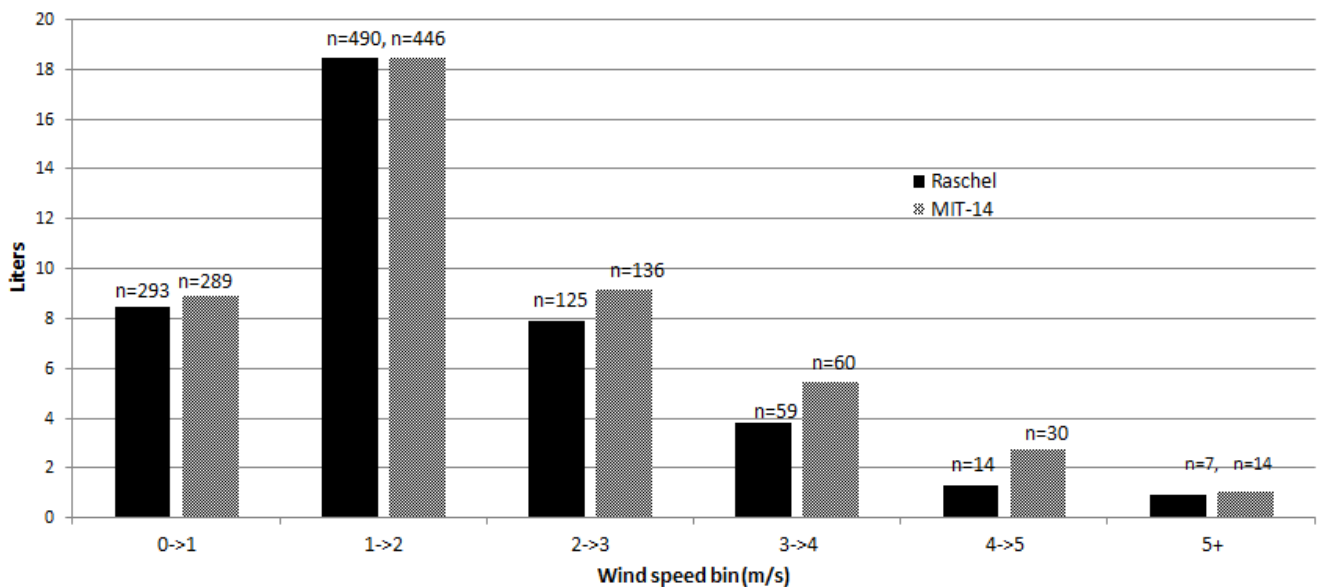


Fig. 3. Total water collected during 2014–2015 by Raschel and MIT-14 paired commensurate collectors, that is, both SFCs collected at the same place and over the same time period. Data are summarized from Glen Deven, Fritzsche Field and Pepperwood Preserve sites from the 2014–2015 fog seasons. The total number of intervals (n) with fog water collected by each mesh is listed above bar. The Raschel mesh collected more water per interval than the MIT-14 at 1–2 m s⁻¹ whereas the MIT-14 mesh had more intervals of collection than the Raschel mesh at higher wind speeds (4–5 m s⁻¹).

taken into account in the fog-capture modelling work of other researchers (Langmuir and Blodgett, 1946; de Dios Rivera, 2011; Rajaram, 2016; Regalado and Ritter, 2016). The effect of the POSS-PEMA coating on the MIT-14 mesh is ambiguous because a control steel mesh, identical but without the hydrophobic coating, was not deployed during the trial.

The total water collected by the MIT-14 mesh, as shown on the graph, was about 46 L and, for the Raschel mesh, 41 L. So, overall, the MIT-14 mesh appears to have outperformed the Raschel mesh by about 12%.

Raschel Mesh versus the Rotated FogHa-Tin Mesh

At the onset of the 2014 fog collection deployments, four standard fog collectors were deployed with the FogHa-Tin mesh. However, it was unclear at that point what the proper orientation was supposed to be and these mesh were all deployed in a fashion that, we were later told, was the wrong orientation. There were 2183 15-minute nonzero samples collected from the Raschel mesh and 2311 15-minute nonzero samples collected from the Rotated FogHa-Tin mesh during the commensurate periods of operation at all of the sites. The total water collected by the Raschel mesh over this period of time was about 77 liters and that collected by the Rotated FogHa-Tin mesh was about 82 liters, approximately 7% greater. Fig. 4 illustrates a graph for the Raschel vs. FogHa-Tin mesh similar to the one shown in Fig. 3, as a function of the wind speed bin. Apparent in this figure, as in Fig. 3, is that the greatest number of fog events recorded occur in the 1–2 m s⁻¹ wind speed bin, with nearly 1100 measurements from the Raschel mesh and nearly 1000 from the Rotated FogHa-Tin. The amount of fog per 15-minute interval also increases somewhat with wind

speed, particularly for the Rotated FogHa-Tin. Most notable is that the Raschel appears to outperform the Rotated FogHa-Tin at wind speeds below 2 m s⁻¹ but the Rotated FogHa-Tin appears to outperform the Raschel at higher wind speeds. As in the case with the MIT-14 mesh, this result is somewhat surprising. The thinner filaments associated with the FogHa-Tin mesh would at first glance seem to collect more water than the wider ribbons of the Raschel mesh at the lower wind speeds and vice versa. Some thoughts on why this is not what occurred are discussed in the subsequent section.

FogHa-Tin Mesh versus the Rotated FogHa-Tin Mesh

In order to examine how the data collected from the deployments of rotated FogHa-Tin mesh might compare to their non-rotated counterpart, we conducted a trial over several months during the summer of 2016 at the Fritzsche Field site. Two modified SFC designs were deployed, one with the FogHa-Tin mesh and the other, a rotated version of the FogHa-Tin mesh. Data were recorded by both mesh between May 20, 2016 and July 14, 2016 providing 175 nonzero, 15-minute samples from the non-rotated mesh and 171 samples from the rotated mesh. These are displayed in Fig. 5, showing that the winds at Fritzsche Field during the 2016 summer fog season greatly exceeded those recorded during the deployments of the preceding two years. This provides some explanation for the greater relative numbers of fog samples at the higher wind speeds shown in Figs. 4 and 5 in comparison with Fig. 3, which only illustrates wind speeds up to around 5 m s⁻¹.

A few observations stand out from Fig. 5. One is that while the non-rotated version collected slightly more water within most of the wind speed bins, the overall percentage

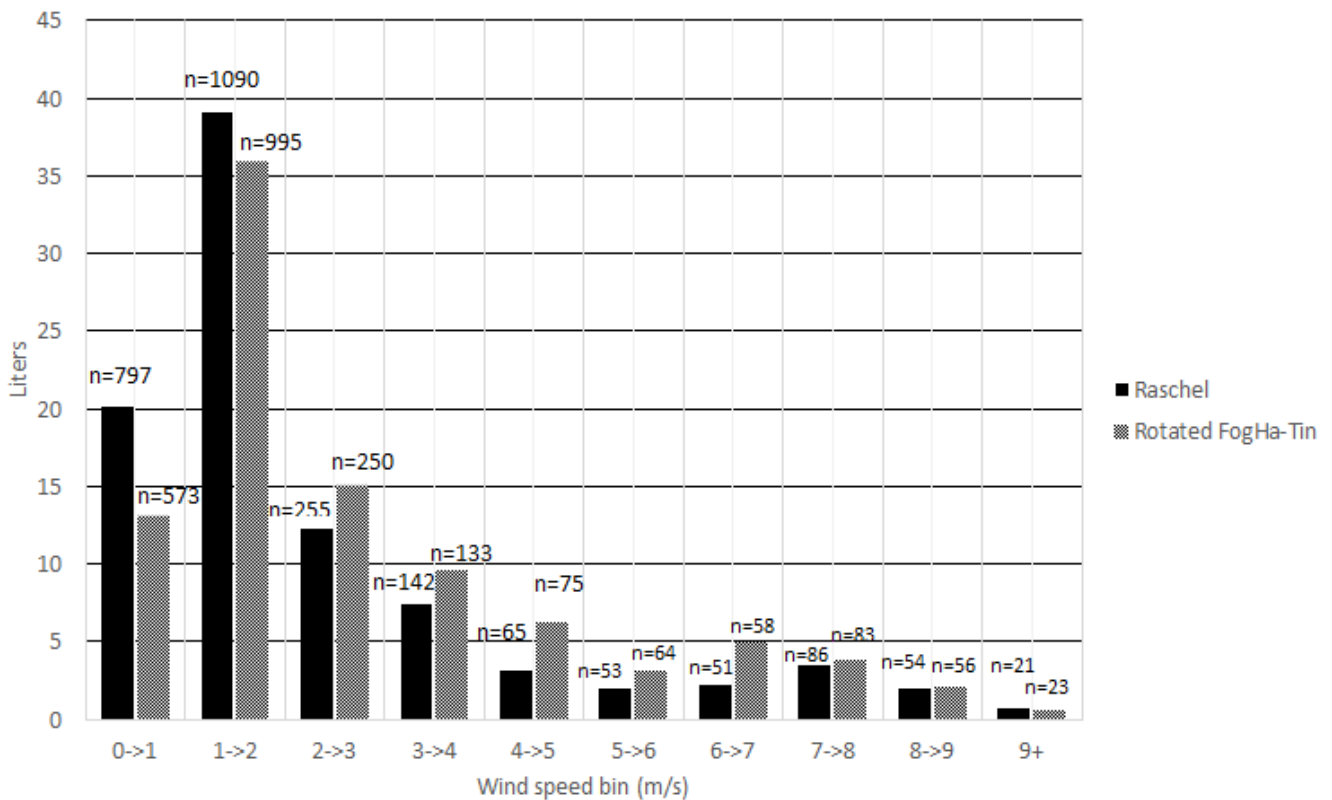


Fig. 4. Total water collected by Raschel and Rotated FogHa-Tin paired commensurate collectors. Data are summarized from Glen Deven, Fritzsche Field, Montara and Pepperwood Preserve from the 2014–2016 fog seasons. The total number of intervals (n) with fog water collected by each mesh is listed above bar. The Raschel mesh collected more water at wind speeds below 2 m s⁻¹ and the rotated FogHa-Tin mesh collected more water at greater wind speeds.

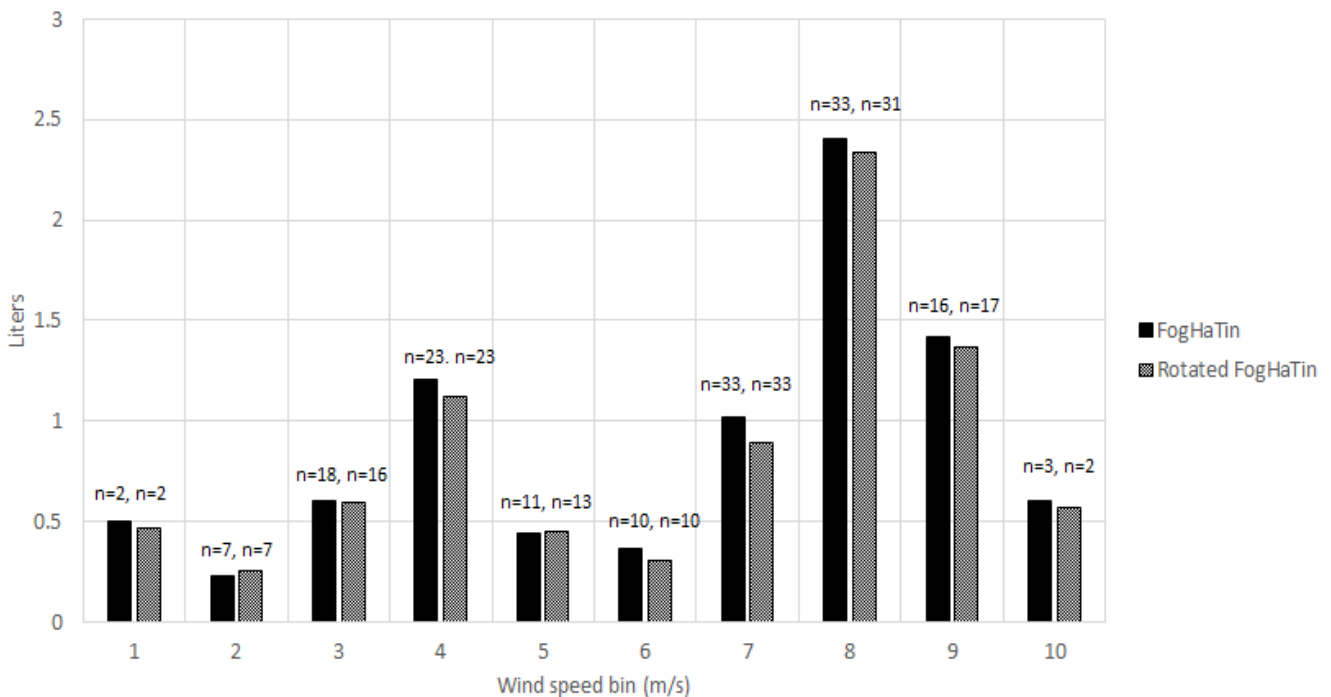


Fig. 5. Total water collected by properly-oriented FogHa-Tin mesh and Rotated FogHa-Tin paired commensurate collectors from the Fritzsche Field site during the 2016 fog season. The total number of intervals (n) with fog water collected by each mesh is listed above bar. The total fog water collected at all wind speed bins over a 2-month period was very similar between both FogHa-Tin SFC's, but the non-rotated version collected slightly more water overall.

difference between the two was about 4.5% in favor of the non-rotated mesh. However, the rotated version of the mesh tracked the non-rotated version quite closely within all of the wind speed bins.

Additionally, the wind speed bins that received the greatest amount of water as well as nonzero samples for this comparison at this site and over this time period were those in the range from 8 to 9 m s⁻¹ and from 9 to 10 m s⁻¹. While this may be partly explainable because this site happens to be one that experiences stronger winds in general, the degree to which this asymmetry is apparent in the data, coupled with the apparent preference of the Raschel mesh at lower wind speeds, is indicative of the tendency of the FogHa-Tin mesh to capture more fog at higher wind speeds. At first glance, this is somewhat surprising, since the relatively small diameter of the individual polypropylene filaments would seem to be an indicator of a larger Stokes Number at lower wind speeds than, for instance, the Raschel mesh. However, the density of the mesh coupled with the 1.5 cm thickness of the netting may effectively form some sort of a “blockage” at lower wind speeds that is overcome by higher wind speeds. In addition, the thickness of the FogHa-Tin netting results in the capture of some of the coalesced water droplets that may otherwise tend to re-entrain in higher winds, resulting in enhanced collection efficiencies at stronger wind speeds relative to the flatter mesh materials, such as the Raschel.

Fig. 6 illustrates a box-and-whisker plot of the nonzero fog water data from within each wind speed bin from the

Raschel SFC collected at all four of the sites across all three years of deployments. Of particular significance, and consistent with earlier figures, is that the greatest number of productive samples from the Raschel mesh appear to occur at relatively low wind speeds, particularly those of less than 2 m s⁻¹. This may be a result both of the predominance of low to-moderate wind speeds regionally during Central California’s fog season as well as the tendency of the double-layered Raschel mesh to collect more fog water at lower wind speeds.

VARIABILITY IN MESH RESPONSE TO FOG EVENTS

The 15-minute data contain interesting and important variability that is not apparent when looking at data at time intervals as coarse as monthly, daily, or even hourly.

Fig. 7 illustrates the relationship between the fog water collected from the SFC that contains the MIT-14 mesh and a commensurate SFC with a Raschel mesh. Of particular interest is the slope, which indicates that the MIT-14 mesh collected about 3% more water during the periods when both mesh collected nonzero amounts. Also of note are the many data points that lie along the y-axis which indicate that the MIT-14 SFC collected significant amounts of water during intervals when the Raschel collected none. A likely possibility, which is also apparent within the time series data, is that the MIT-14 mesh tends to collect water more quickly during some fog events than does the Raschel mesh.

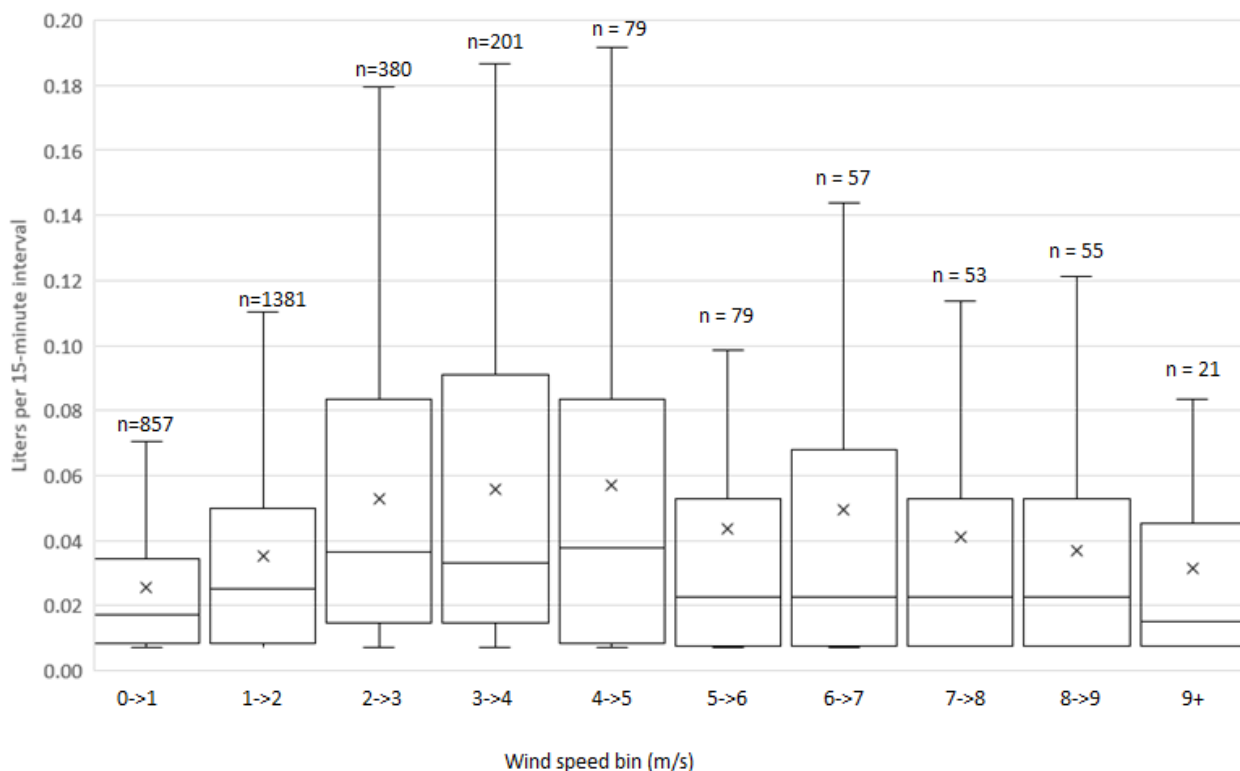


Fig. 6. Box-and-whisker plot for data from all four Raschel SFC’s during the entire time period observed (2014–2016). The highest number of 15-minute collection intervals (1381) occurred during the 1–2 m s⁻¹ wind speed category but it was in the 3–4 m s⁻¹ wind speed category that the most fog water was collected per interval.

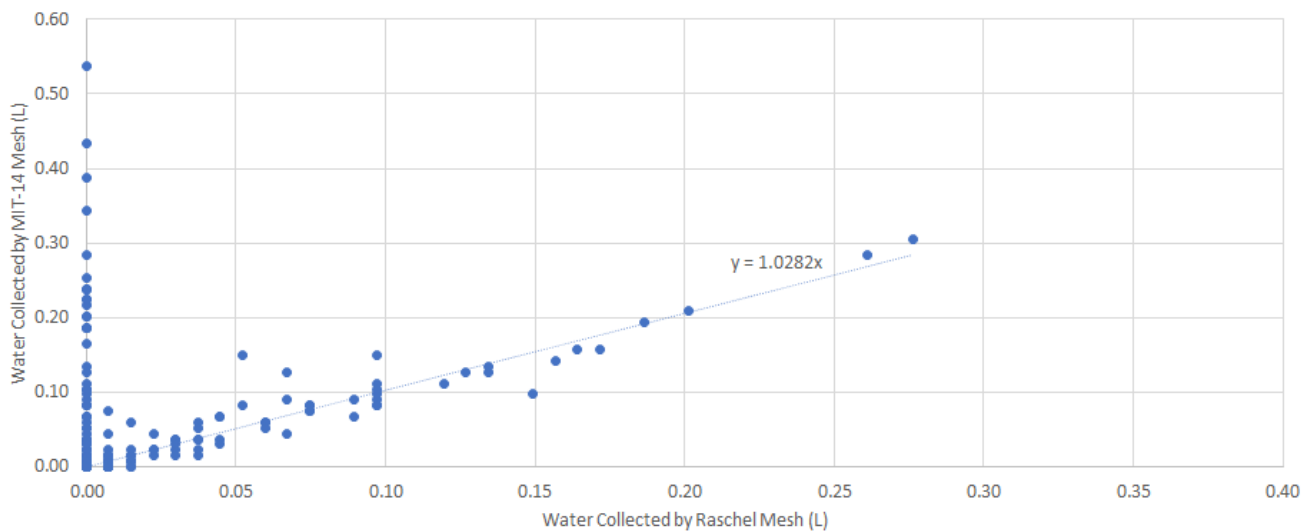


Fig. 7. The regression line for the paired commensurate fog water collection comparison between a Raschel mesh collector and an MIT-14 mesh collector shows a slope of 1.02 indicating a slightly larger amount of fog water was collected during each 15-minute interval from the MIT-14 mesh than the Raschel mesh during the 2015 fog season, a result consistent with overall totals (Fig. 3).

In other words the Raschel mesh exhibits a greater time delay in its response to some fog events in comparison with the MIT-14 mesh. The 15-minute interval data plotted in Figs. 8 and 9 show fog water collected and the accompanying wind speed and wind directions for two sample fog events at the Pepperwood Preserve site. Measurements for both events were collected during the summer fog season of 2015 from three simultaneously collecting SFCs. One SFC had a Raschel mesh, one, a rotated FogHa-Tin, and, the third, an MIT-14 mesh.

Fig. 8 shows an event that occurred in late July 2015 that illustrates distinct fog water collection signatures amongst these three mesh. The MIT-14 SFC was the first to collect. Then, after a 15-minute delay, the FogHa-Tin SFC began to collect, with the Raschel SFC collecting nothing until another hour had passed. During this event, the Raschel mesh collected significantly less water than the other two and also had a lower peak.

Conversely, Fig. 9 illustrates a very different situation from mid-August, 2015. In this case, the three matched each other relatively closely, though, with some differences between the amounts of water collected during the 15-minute interval times and a slightly delayed initial collection for the Raschel mesh. Winds during both events were between 1 m s^{-1} and 2 m s^{-1} with a predominantly southwesterly (200° – 250°) wind direction. This suggests that wind speed and direction alone are not sufficient to explain the relative differences between mesh efficiency and performance during these two events.

We hypothesize that the distinction between the relative performances of these mesh during a given fog event is related to changing droplet spectra during the event and that, at a given wind speed, different mesh respond differently to different droplet spectra. Langmuir and Blodgett's pioneering results (1946) indicate that larger droplets would be more likely to collide with the larger diameter mesh than would

smaller droplets. This suggests that, perhaps, the event at Pepperwood in late July (Fig. 8) began with a spectrum of smaller droplets whose size increased over time to the point that it began to be intercepted by the slightly wider Raschel mesh later in the event.

Likewise, the event illustrated in Fig. 9 may have initially contained droplets of larger size (and greater liquid water content) resulting in a more comparable performance of the Raschel mesh and greater overall liquid water collected by all of the mesh.

DISCUSSION

A number of new realizations and questions have arisen as a result of this study.

Through examination of the data collected over the 3-year period from 2014–2016 from multiple sites, each equipped with standard fog collectors holding different types of mesh, it becomes clear that the differences between mesh performance are more than a simple matter of scaling the performance of one (that is, by multiplying it by a constant factor) to obtain the performance of another. The significant number of points lying on the y-axis in Fig. 7, where the MIT-14 mesh collected water and the Raschel did not, support this statement. Factors that contribute to such effects may include variations in surface area for fog droplet impaction or an optimum mesh intersection angle that reduces drag or increases air flow.

The type of material that the fog droplets encounter as well as its physical characteristics, such as its rigidity, may play a role in the differential performances of mesh in different wind and droplet-size-spectra regimes. Figs. 3–5 show instances where one mesh performs better than another at a certain wind speed, but not at other wind speeds, suggesting a wind-speed dependence on mesh efficiency. However, absent from these graphs and the

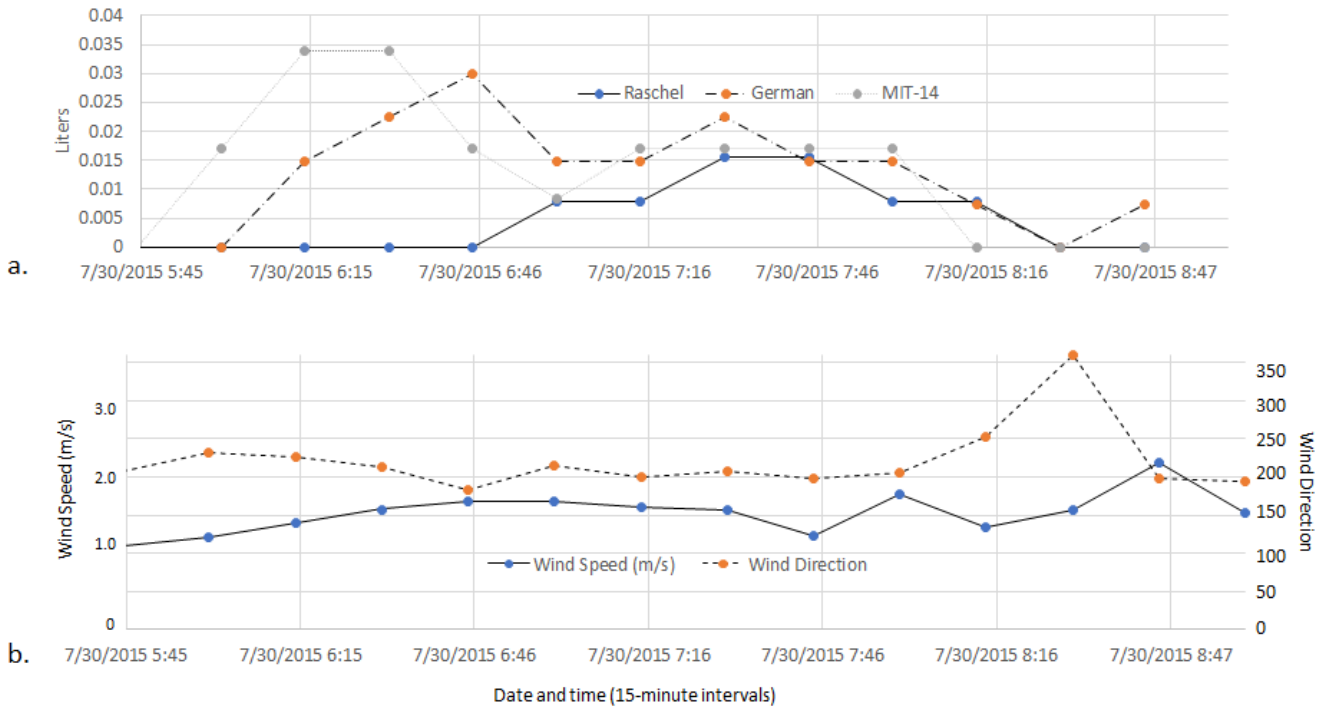


Fig. 8. Time series data for morning fog event of July 30, 2015 in 15-minute intervals at Pepperwood from the SFC's comprised of the three types of mesh (top, Fig. 8(a)) and wind speed and wind direction (Fig. 8(b)).

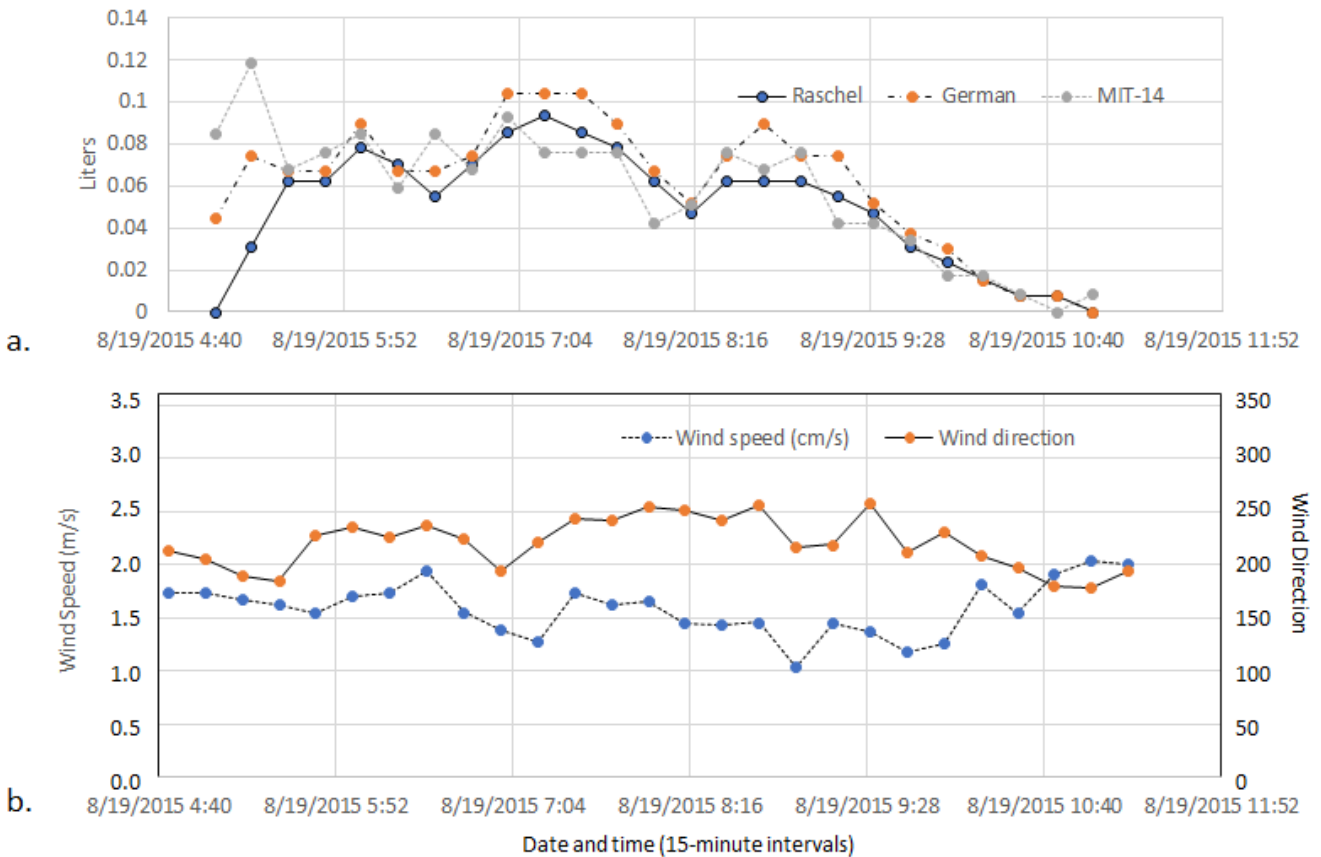


Fig. 9. Time series data for morning fog event of August 19, 2015 in 15-minute intervals at Pepperwood from the SFC's comprised of the three types of mesh (top, Fig. 9(a)) and wind speed and wind direction (Fig. 9(b)).

dataset are additional factors that could contribute strongly to variability, such as fog droplet spectra size and aerosol particle composition. Measurements and a description of how mesh collection efficiencies varied both with wind speed and droplet size is provided in Schemenauer and Joe (1989) where at the center of a large fog collector composed of a double layer of Raschel mesh they measured little dependency on wind speed for 11 μm droplets between wind speeds of 3 m s^{-1} and 7 m s^{-1} yet significant dependence for 15 μm droplets between 2 m s^{-1} and 4 m s^{-1} . This provides added evidence of the complexities associated with the interactions of the differently-sized fog droplets with the mesh under different wind speed regimes. Additional research that adds accompanying measurements of fog droplet size and density is needed to clarify the factors that contribute to mesh efficiency at a given wind speed.

Indeed, this result is consistent with the observation of Ritter *et al.* (2009), who suggest that fog collection is dependent upon wind speeds, which are partly dependent upon elevation. The present study looks at the differential effects of wind speed on the fog-collecting performance of different mesh, but is consistent with earlier observations of the importance of wind speed in this process. Regalado and Ritter's (2016) theoretical analysis of the fog droplet collection focused on the three elements that determine fog water yield: aerodynamics, impaction, and draining, resulting in models used to quantitatively identify an optimum fog-collecting structure. The overall collection efficiency associated with a mesh is given by the expression (from de Dios Rivera, 2011):

$$\eta = \eta_{ac} \eta_{capt} \eta_{dr} \quad (1)$$

where η represents the overall collection efficiency, η_{ac} represents the aerodynamic collection efficiency, which refers to the percentage of the unperturbed flow that would actually hit the mesh. η_{capt} represents the capture efficiency, which refers to the number of fog water droplets that the mesh retains once the mesh is in place within the airflow. Some of the droplets will follow streamlines that flow around the mesh and, even if they were originally on course to strike the mesh, they will flow around it. Others may hit the mesh, but bounce off of it. The capture efficiency addresses these losses.

The final term, η_{dr} , represents the drainage efficiency. This refers to the fraction of the collected water that actually reaches the gutter and measurement device. Some of the water that is collected will re-entrain into the wind and some may spill and not reach the gutter. The drainage efficiency addresses these losses.

de Dios Rivera (2011) and others (Rajaram *et al.*, 2016) provide a means to calculate η_{ac} , namely

$$\eta_{ac} = \frac{s}{1 + \sqrt{\frac{C_0}{C_d}}} \quad (2)$$

where s represents the shade coefficient of the mesh (which

is somewhere between 50% and 70% for the double layer of 35% shade coefficient Raschel), C_d represents the drag coefficient of the mesh, which for any of our square mesh is stated in Rajaram *et al.* (2016) to be about 1.18. C_0 represents the pressure drop coefficient and is related to the change in air pressure associated with the passage of the wind through the mesh obstacle. Idel'cik (1960) calculates this for a wire mesh to be

$$C_0 = 1.3s + \frac{s^2}{(1-s)^2} \quad (3)$$

For the MIT-14 mesh, with a shade coefficient of 49%, C_0 has a value of 1.56. For a silk mesh, which the Raschel mesh more closely resembles, Idel'cik (1960) adds an additional multiplicative factor such that:

$$C_0 = 1.62 \left(1.3s + \frac{s^2}{(1-s)^2} \right) \quad (4)$$

which increases the pressure drop coefficient for the double-layer Raschel mesh to a value of about 4.9 if we assume a shade coefficient of 0.6. These assumed values result in a theoretical aerodynamic efficiency of 0.20 for the Raschel mesh and about 0.23 for the MIT-14 mesh. Of course, this represents only one of three factors that de Dios Rivera (2011) and others (Rajaram *et al.*, 2016; Regalado and Ritter, 2016, 2017) consider to represent the overall efficiency.

Descriptions of the capture efficiency, η_{capt} , as can be found in Regalado and Ritter (2016) and are based upon work by Wyslouzil *et al.* (1997), Friedlander (2000), Demoz *et al.* (1996) and Davidson and Friedlander (1978). Regalado and Ritter (2016) illustrates a result for the droplet capture efficiency of a single cylindrical strand as

$$\eta_{cyl} = \frac{S_{tk}^2}{S_{tk}^3 + 0.753S_{tk}^2 + 2.7865S_{tk} - 0.202} \quad (5)$$

where S_{tk} , the Stoke's number, is $S_{tk} = \rho D_d^2 u) / 18 \nu_d$ with ρ (kg m^{-3}) being the water's density, D_d (m) is the fog droplet diameter, ν (Ns m^{-2}) is the dynamic viscosity of the air, and d (m) is the diameter of the assumed cylindrical screen elements. Regalado and Ritter (2016) describe factors that can affect the drainage and state that the cross-linked mesh can result in droplets that are more susceptible to clogging, which would thus reduce the aerodynamic efficiency of the mesh. They posit that this reduces the aerodynamic efficiency of knitted meshes in relation to strands and that an optimum mesh would therefore consist of parallel strands. From some of our experimental results, we argue that this may be true in some conditions, such as those at lower wind speeds, but, removing the cross-linked mesh also reduces the shade coefficient, and, would require the strands to be under higher tension to keep them from vibrating in the wind. Additionally, the costs and

challenges of producing large areas of stranded mesh are likely higher than those of producing a two-dimensional mesh. It may also be possible, as described in Rajaram *et al.* (2016), to stamp mesh in a process that results in a mesh that is not knotted, but is coated with an appropriate hydrophobic layer that may facilitate drainage and lessen the possibility of pore blockage by individual droplets.

DIRECTIONS FOR FUTURE WORK

The comparative studies illustrated in this paper provide results on relative efficiencies of different types of mesh for fog water collection. These results help to frame a new perspective on the spatial and temporal variability associated with fog events and the importance of environmental conditions. We observe that the wind speed is one factor that is strongly associated with different amounts of fog water capture. However, other factors that were not directly measured at the sites described in this paper, including fog droplet size and chemical variability within the droplets, could also be a factor in the relative effectiveness of the individual mesh. Additional studies are needed to understand the relationship between fog water capture, wind speed and turbulence intensity, droplet size and density and fog chemistry.

Also noted is the fact that different mesh perform differently in different environments, so a blanket statement that one type of material is more effective at fog capture should be substantiated in the context of the prevailing environmental conditions.

Furthermore, while three types of mesh were compared and measured as to their efficacy in fog collection, some discussion of practicality and cost will help to justify when one mesh should be used over another. For instance, the MIT-14 mesh is a metal mesh that is not effective and practical for larger fog collection sites due to its high mass per square meter and significantly higher cost than that of the polypropylene-based nets. One direction to consider is to coat polypropylene nets with various hydrophobic formulas designed to enhance their fog collection potential.

The FogHa-Tin mesh costs around ten to fifteen times more than the Raschel. While both are UV resistant and extremely durable, the FogHa-Tin mesh appears to bow less in a heavy wind than does the Raschel, which is an advantage from both a structural and a water-capture consideration. However, at some locations, it also appears to capture more bugs in its complex threaded structure than does the Raschel, which may also influence a place-dependent consideration in the decision of which mesh to adopt. A full economic analysis would have to include not only the cost of the mesh, but the cost and reliability of the entire system deployed and maintenance required (de Dios Rivera, 2011).

Follow-up research of the results presented in this paper will focus on measurements on an event-by-event basis of additional factors which predispose some SFC's to respond more or less quickly with greater or lesser water collection and, in some cases, no collection of fog water at all, even when others do collect. Scrupulous attention to data quality and on-site verification of proper functioning of instruments

give us confidence that these events, where only one or two mesh collect water from fog events while the other one or two collect little or nothing, is not an error. We observe this phenomenon across multiple sites where more than one fog collector was in operation, thus providing a unique insight into the small-scale physical and temporal structure of some fog events. A more comprehensive study of this unexpected result will require careful and regular measurements of the fog droplet size spectrum ideally taken both in front of and after an SFC with measurements similar to those of Schemenauer and Joe (1989) but using a device, such as the FM-120, with greater precision and accuracy (Dorman, 2017). Droplet chemical composition, which may factor into differences in fog droplet size spectra (Li *et al.*, 2017), may provide some insight into differential performance of different types of collector materials.

Within this paper, we observed environmental factors that affect the variability in the characteristics of the fog that will differentially favor one type of mesh over another. The factor we measured was the wind speed, but with evidence that other factors, including droplet size and, possibly, droplet chemical characteristics, also affect the relative mesh performances. Merging knowledge of the "typical" type of fog event at a specific location with an improved understanding of the relationship between the physical characteristics of fog and the collection capacity of meshes can lead to improved fog water capture through appropriate mesh characterization and selection for a given site at a given time.

It was more the norm than the exception within this study that one mesh type would exhibit periods of time when it would collect fog water while another mesh type would not. This is consistent with observations made by Weiss-Penzias *et al.* (2016) of passive fog collectors recording no data during an evening of fog collection while CASCC-modified active fog collectors (Collett *et al.*, 1990), for the same collection period had sample bottles filled with fog water.

In sum, these results open up significant questions and opportunities to study the differences associated with fog water in terms of its spatial, temporal and collector-surface variability.

CONCLUSION

Fog is a result of a complex interacting earth system embodying a delicate balance between ocean, atmosphere, and land surface processes that form, advect, and alter fog and its liquid water content (LWC) over time. Realizing the potential of fog water harvesting by improving the collecting capacity through mesh innovation is still a maturing endeavor. Comparative analyses of mesh efficiencies under field conditions exposes fog water collecting efforts to a long list of unpredictable variables and a significant site-to-site dependence.

While the MIT-14 mesh tended to collect more water than did the other mesh, it is to be noted that the improvement comes at significant cost (stainless steel mesh can cost upwards of several hundred dollars per square meter versus

pennies per square meter for the Raschel mesh) and significant increase in weight, making it much more difficult and expensive to deploy in large fog collectors. So, it does not necessarily mean that this type of mesh is optimal or practical for fog water collection. Similarly, while the FogHa-TiN mesh may collect more water than the Raschel mesh at some sites, its cost per unit area is about fifteen times higher. This may be balanced by other factors, such as greater resilience in high winds, but it points to the many factors that need to be taken into account when designing a site.

In addition to potentially yielding greater amounts of water, the study of different meshes' fog water collection efficiencies may promote fundamental insight into the basic chemical and physical processes associated with fog droplets and how they are captured.

Fog water harvesting to supply water to grazing animals and wildlife during the arid Mediterranean climate summer season has been posited to be viable in some locations. However, the high variability of fog water collection between fog events in coastal California suggests the need to carefully consider site-specific differences. Long-term meteorological records can provide information for prevailing wind conditions, however more research is needed to identify the additional factors that need to be used to identify and calculate the occurrence of different fog events and their relative potential for fog water collection.

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DISCLAIMER

Reference to any companies or specific commercial products is for descriptive purposes only and does not in any way constitute endorsement, support, or disdain for their product.

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