Fog water as an alternative and sustainable water resource

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REVIEW

Fog water as an alternative and sustainable water resource

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Abstract As the world's population and demand for fresh water increases, new water resources are needed. One commonly overlooked aspect of the water cycle is fog, which is an important part of the hydrology of coastal, high-altitude, and forested regions. Fog water harvesting is being investigated as a sustainable alternative water resource for drinking water and reforestation. Fog water harvesting involves using mesh nets to collect water as fog passes through them. The materials of these nets, along with environmental factors such as wind speed, influence the volume of water collected. In this article, a review of current models for fog collection, designs, and applications of fog water harvesting is provided. Aspects of fog water harvesting requiring further research and development are identified. In regions with frequent fog events, fog water harvesting is a sustainable drinking water resource for rural communities with low per capita water usage. However, an analysis of fog water harvesting potential for the coastal areas of northern California (USA) showed that fog yields are too small for use as domestic water in areas with higher household water demands. Fog water shows particular promise for application in reforestation. Fog water irrigation can increase growth rates and survivability of saplings in reforestation efforts in regions with frequent fog events. Using fog collectors, denuded areas once dependent on natural fog drip can be restored, benefiting local hydrology and ecosystem recovery. Improvement in fog collector designs, materials, and models to increase collection efficiency, perhaps by inclusion of ideas from natural systems, will expand the regions where fog harvesting can be applied.

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Abbreviations

SFC Standard fog collector
ACE Aerodynamic collector efficiency

List of symbols

q	Rate of water collection (L h^{-1})
w	Water content of air (g m^{-3})
A	Cross-sectional area of fog collector mesh (m^2)
V	Wind speed (m s^{-1})
η_{imp}	Efficiency due to impaction
Stk	Stokes number
σ	Water surface tension (N m^{-1})
ρ	Density of water (kg m^{-3})
D'	Droplet diameter (m)
g	Gravitational constant (m s^{-2})
D	Diameter of attached surface (m)
Fw	Fog water volume (L)
f_c	Fog collector efficiency
FPI	Fog potential index
$f(H)$	Relative humidity function
$f(W)$	Wind speed function
T	Ambient dry temperature (°C)
T_d	Dew point temperature (°C)
e	Vapor pressure, millibar
e_s	Saturated water vapor pressure (millibar)

RH Relative humidity (%)
η_{coll} Aerodynamic collection efficiency
η_{AC} Proportion of drops that will collide if unperturbed
η_{capt} Proportion of drops that actually collide
η_{dr} Proportion of water that reaches the trough
s Shade coefficient
C_d Drag coefficient of non-permeable screen
C_0 Pressure loss coefficient of mesh

Introduction

As the world's population and the demand for fresh water continue to grow, greater stress is placed on current sources of potable water. It is estimated that almost a third of the global population faces a scarcity of fresh water, due to water stress and shortages (Kummu et al. 2010). In order to preserve global water supplies, it is imperative that alternative and sustainable technologies for the collection and distribution of fresh water be explored.

One commonly overlooked source of freshwater is fog. Fog water harvesting, a passive, low cost, and low maintenance system, is a sustainable option that has the potential to supply fresh drinking water to communities where fog conditions are common. Fog water can also be used to supplement rainfall in arid climates for reforestation projects. Fog water collection has been studied in over 20 countries across six continents, and is typically done only in areas that meet specific conditions, including a high occurrence of fog (Abdul-Wahab and Lea 2008). Additionally, fog harvesting is useful when other sources of water are scarce and is typically limited to remote arid and semiarid regions with tropical or subtropical climates (Schemenauer and Cereceda 1994b; Abdul-Wahab and Lea 2008; Klemm et al. 2012).

The objectives of this article are to provide a review of current models and designs for fog water harvesting and to describe how fog water is being utilized around the world as a sustainable fresh water source. We also provide a case study of the California coastal region to evaluate the feasibility of fog water harvesting in that region.

Fog characteristics and ecosystem role

Fog, the presence of suspended liquid water droplets in the air at ground level, is a natural part of the global water cycle. Fog droplet diameters typically range from 1 to 50 μm (Ritter et al. 2008), and originate from water lost through evapotranspiration, creating masses of humid air over land or sea. Advection fog formation often occurs over the ocean, where moist air passes over cooler waters forming low altitude clouds that are then blown toward the coast by the wind (Hiatt et al. 2012). Radiation fog occurs overnight as the cooling ground causes the condensation of water vapor in the air above it (Straub et al. 2012). Regardless of the type of fog, there must be the presence of humid air along with a drop in temperature below the dew point for fog formation to occur. Environmental conditions such as high dew point temperatures, high humidity, and high elevation are known to favor fog formation. Due to geological factors, fog formation is usually highest among mountainous areas near the coast.

Fog as a natural ecosystem input

Fog is a vital source of moisture in many coastal ecosystems throughout the world (Dawson 1998). In California's coastal watersheds, dominated by redwood forests, it is estimated that approximately 34 % of the total annual water input originates from fog drip off of redwood trees. Redwoods have adapted to collect fog water as a means of thriving during the summer months when precipitation can drop from 240 to less than 25 mm per month. During the dryer summer months, redwoods require up to 600 L day^{-1}, up to 40 % of this comes from fog. Fog drip is also vital for a myriad of understory species, some of which obtain up to 100 % of their water intake from fog drip from the canopy (Dawson 1998).

The coastal rainforests that dominate the mountaintops of semiarid regions in Chile also demonstrate the viability of fog water to sustain ecosystems (del-Val et al. 2006). While these forested areas only receive around 147 mm of annual rainfall, typically only enough to support shrubs, fog water contributes an additional 200 mm of water annually, allowing rainforests to flourish. Forested areas in these types of climates tend to grow toward the direction of the wind and fog, and to recede at the opposite edge, indicating the importance of fog in the growth and maintenance of the forest ecosystem (del-Val et al. 2006).

In other areas of the world, where there is virtually no annual rainfall, plants and animals have adapted to survive by collecting fog water. For example, Namib Desert beetles have adapted to live in an area with as little as 12 mm of annual rainfall by collecting fog water, as it drips off of its back (Henschel and Seely 2008). The back of the beetle is composed of a hydrophobic surface covered in smooth hydrophilic bumps (Fig. 1), which serve to collect passing fog water and drain it along the channels formed by the bumps to the beetle's mouth (Parker and Lawrence 2001). Nature provides both evidence for fog water collection as a viable fresh water source and inspires possible designs for man-made fog collection systems.

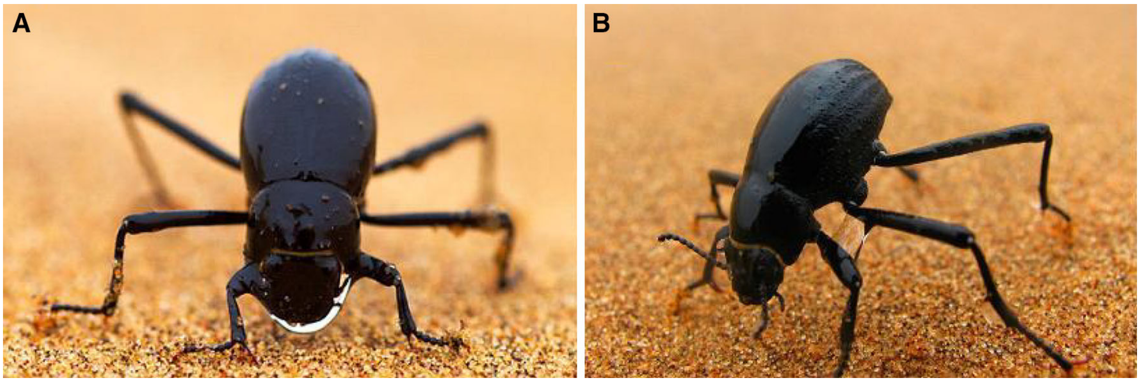

Fig. 1 Fog-basking behavior of a Namib Desert beetle **a** © Martin Harvey/AfriPics **b** © James Anderson

Alteration of the fog cycle

Humans have impacted the natural fog cycle primarily through deforestation. Other events such as fires and landslides can also disrupt fog dependent ecosystems. In fog dependent ecosystems, trees are self-sustaining as they collect fog water that drips down to their roots and the understory (Lummerich and Tiedemann 2009). As more trees are removed, there is less surface area to intercept fog water and supplement annual rainfall, resulting in dry seasons that are unsurvivable for the remaining flora (Lummerich and Tiedemann 2009). The alteration of the natural hydrological cycle causes the death of ground-covering flora, resulting in dry, warm landscapes that are more prone to erosion (Dawson 1998). Disruptions in the fog cycle due to deforestation can have long-lasting impacts on surface water runoff and the recharge of groundwater from fog drip (Lummerich and Tiedemann 2009).

Global climate change

Studies on fog have observed a continued reduction in dense fog among many parts of the world, including the California coast, major cities in the U.S., and many parts of Europe (Witiw et al. 2003; Johnstone and Dawson 2010; van Oldenborgh et al. 2010; LaDochy and Witiw 2012). However, others areas, such as China and India, have shown an increased occurrence of fog (Niu et al. 2010; Syed et al. 2012). Increases in fog occurrence are usually attributed to increased air pollution due to rapid development, while decreases in fog are attributed to global warming and the reduction of air pollution (LaDochy and Witiw 2012). Global warming is theorized to reduce fog occurrences in certain areas by influencing atmospheric circulation patterns, along with local wind and inversion patterns (LaDochy and Witiw 2012). However, accurately modeling and understanding the effects of global warming on fog is still a challenge, and further investigation is needed (Gultepe et al. 2007).

Fog water harvesting

Fog water harvesting methods are relatively simple, involving the use of mesh nets attached to a sturdy frame. As fog passes through the mesh, fog droplets are deposited on the mesh, accumulating and eventually running down the mesh into gutters leading to a collection reservoir. However, predicting fog collection rates is difficult, in part due to the lack of standards in measuring and reporting data (Klemm et al. 2012). Studies sometimes only consider annual averages or maximum collection values, and may lack quality control procedures or the reporting of uncertainties. Standardization of reporting data and the inclusion of uncertainties will enable future studies to draw a clearer relationship between environmental conditions and fog collection rates. Currently, two models, an impaction model and an efficiency model, have been developed to describe the processes occurring during fog harvesting with a mesh collector (Walmsley et al. 1996; Ritter et al. 2008; Imteaz et al. 2011).

Impaction model to predict fog water potential

Fog water is collected on the mesh through the mechanisms of impaction, direct interception, and Brownian diffusion. Impaction is the physical collision of fog water droplets with the mesh due to inertial forces and is the primary contributor to fog water deposition (Ritter et al. 2008). Fog water droplets that pass close by the mesh material, typically within one droplet radius, but do not directly impact it are captured via direct interception. Brownian diffusion generally has very little impact on fog collection, as it is only a significant factor in droplets with diameters less than 0.1 μm. For most practical purposes, the contributions from Brownian diffusion and direction interception can be ignored, and impaction is the primary mechanism of fog water collection (Ritter et al. 2008). The amount of fog water collected by a mesh screen can be predicted using the following equation (Walmsley et al. 1996; Ritter et al. 2008),

$$q = 3.6wA\eta_{\mathrm{imp}}V \quad (1)$$

where q is the rate of water collected (L h^{-1}), w is the water content of the air (g m^{-3}), A is the cross-sectional area of the mesh (m^2), η_{imp} is the efficiency of the fog collection due to impaction (unitless), V is wind speed (m s^{-1}), and 3.6 is a conversion factor to express q in terms of L h^{-1}.

Assuming inviscid flow, the efficiency of fog collection due to impaction is given by (Ritter et al. 2008),

$$\eta_{\mathrm{imp}} = \begin{cases} \frac{Stk^2}{(Stk+0.6)^2}, & Stk \geq 0.08 \\ 0, & Stk < 0.08 \end{cases} \quad (2)$$

where Stk is the Stokes number of the fog (unitless). The Stokes number is the ratio of the stopping distance of a fog particle in air relative to the characteristic dimension of the fog collector mesh. The Stokes number for fog increases with both droplet diameter and wind speed, but typically ranges from 0.6 to 60.7 for the majority of droplets (5–50 μm in diameter) when the wind speed is 1 m s^{-1} (Ritter et al. 2008). The Stokes number can be optimized by selecting mesh with the proper characteristic dimension for site specific wind speeds and droplet diameters.

As droplets form on the mesh, they coalesce, and eventually run down the mesh into a receiving gutter and are directed to a reservoir. While, the coalescence of droplets is difficult to predict due to the random nature of deposition and the layout of the mesh material, fog drip from the bottom of the mesh can be estimated using a simplified two-dimensional force balance of surface tension and gravity (Hung and Yao 1999):

$$\sigma 2D = \frac{\pi D'^3}{6}\rho g \quad (3)$$

where D' is the droplet diameter (m), D is the diameter of the mesh (m), where the drop forms before dropping to the gutter or collector, σ is surface tension (N m^{-1}), ρ is density (kg m^{-3}), and g is the acceleration due to gravity (m s^{-2}). Due to the difficulty in accurately measuring the solid–liquid contact interface, it was assumed in Eq. 3 that the drops are in contact with the mesh over a length of $2D$. Thus, fog drip from the bottom of the mesh is dependent on the size of the droplet, diameter of the bottom of the mesh, and surface tension of the liquid.

Efficiency model to predict fog water potential

Another model, based on atmospheric conditions and fog collector efficiency, was developed by Imteaz et al. (2011) for the prediction of fog water yield (Fw, L),

$$\mathrm{Fw} = f_c \times (\mathrm{FPI}) \times f(H) \times f(W) \times A \quad (4)$$

where f_c is the fog collector efficiency based on the mesh material (unitless), FPI is the fog potential index (from the difference between the air temperature and dew point temperature, (unitless), f(H) is the relative humidity function (unitless), f(W) is the wind speed function (unitless), and A is the area of the fog collector mesh (m^2). The proposed model was calibrated using data from a collection site in Saudi Arabia to determine the parameter f_c (in this case f_c was 1.0) and may not accurately model fog collection in all regions.

The effect of temperature was taken into account in the fog potential index (FPI) (Imteaz et al. 2011). As air temperature drops below the dew point, fog formation will occur. However, depending on the location and altitude, fog formation can sometimes occur when the ambient air temperature is higher than the dew point (Imteaz et al. 2011). The equation for FPI accounts for fog events at air temperatures higher than the dew point by assuming fog formation occurs at temperatures up to 1 °C above the dew point for the location of the study (Saudi Arabia),

$$\mathrm{FPI} = \begin{cases} (T_d + 1.0 - T) \times 2.6; & \mathrm{for}(T_d + 1.0) > T \\ 0; & \mathrm{for}(T_d + 1.0) \leq T \end{cases} \quad (5)$$

where T_d is the dew point temperature (°C) and T is the dry bulb temperature (°C). The dew point temperature is calculated using a modified National Oceanic and Atmospheric Administration equation (Imteaz et al. 2011),

$$T_d = \frac{243.5 \times \ln(e/6.112)}{17.67 - \ln(e/6.112)} \quad (6)$$

where e, the actual vapor pressure (millibar), is determined from relative humidity (RH, %) and the saturated water vapor pressure (e_s, millibar),

$$\mathrm{RH} = 100 \times \frac{e}{e_s} \quad (7)$$

From the model (Imteaz et al. 2011), it is clear that locations with average temperatures below the dew point are ideal for fog collection. Additionally, changes in altitude impact the saturated water vapor pressure, e_s, which will influence e. While higher altitudes are generally more ideal for fog formation due to lower temperatures, regions with thermal inversions, where temperature increases with altitude, can limit the height of fog clouds (Schemenauer and Cereceda 1994b). Nevertheless, working altitudes for fog collection vary from 10 m up to well past 2,000 m (Schemenauer and Cereceda 1991).

Humidity is accounted for in the model (Imteaz et al. 2011) by the following equation:

$$f(H)_i = \frac{\mathrm{RH_i} + \mathrm{RH_{i-1}}}{2 \times 100} \quad (8)$$

where RH_i represents the relative humidity at time "i", and RH_{i-1} represents the relative humidity at the time step previous to RH_i. Time steps are based on the frequency at which wind speed and temperatures are measured. Since relative humidity must be near 100 % for fog to form, *f*(H) does not significantly influence water volume Fw when fog is present.

In general, at higher altitudes, higher wind speeds lead to higher yields, primarily because greater volumes of fog pass through the collectors (Abdul-Wahab and Lea 2008). However, in the model proposed by Imteaz et al. (2011), the influence of wind speed (V, m s^{-1}) on fog water volume changes at a threshold value of 4 m s^{-1}.

$$f(W) = \begin{cases} 0.4 \times V, & \text{for } V < 4\ \mathrm{m\ s^{-1}} \\ 3/V, & \text{for } V \geq 4\ \mathrm{m\ s^{-1}} \end{cases} \quad (9)$$

Imteaz et al. (2011) proposed that as wind speeds approach 4 m s^{-1}, fog formation is encouraged by the continual replacement of moist air, but at speeds above 4 m s^{-1}, wind speed disrupts the formation of fog, reducing the overall yields.

The model developed by Imteaz et al. (2011) gave a good fit to data collected in Saudi Arabia. However, the proposed relationship between wind speed and fog water yield was not supported by studies in other regions, which suggest fog water yields increase linearly with wind speed, even at speeds above 4 m s^{-1} (Abdul-Wahab et al. 2007b; Hiatt et al. 2012). Additionally, the calculations for FPI (Eq. 5) may differ based on site location and altitude, due to fog occurring at varying temperatures above the dew point, perhaps by as much as 2.5 °C (Imteaz et al. 2011). As a result, further investigation is needed to verify the accuracy of this model in other areas of the world.

As evident from both models, fog water potential at a specific site is dependent on both environmental factors and fog collector design variables. Because environmental factors cannot be controlled, it is important to optimize design variables, such as mesh designs, to maximize fog water collection efficiency.

Standard fog collectors for site evaluation

The evaluation of sites for fog water harvesting is conducted using a standard fog collector (SFC), as designed by Schemenauer and Cereceda (1994a) (Fig. 2). The SFC consists of a 1 m × 1 m frame covered in mesh, connected to a 2-m-high support base. The frame should have a 10 cm standoff from the support base to prevent any contact between the mesh and support structure. Immediately underneath the frame is a trough, 1.04 m long, 15 cm wide, and 10 cm deep, which is used to collect fog water that drips down from the mesh. The trough should be positioned 2 cm in front of the frame on the windward side, and the edges of the trough should be level with the bottom of the frame. The positioning of the trough prevents the collection of rainfall from the front of the SFC, while capturing fog water that drops from the mesh at an angle due to high winds (Schemenauer and Cereceda 1994a). The trough should be sloped to promote drainage through a 7–10 mm inner diameter plastic tube that leads to a closed storage container. The diameter of the drainage tube allows for passage of sediments to occur without clogging the collector. The base of the SFC usually consists of two posts, set in concrete for stability. Single-post variations of the SFC exist to reduce cost and allow omni-directional movement of the mesh, resulting in better fog water collection. However, single-post variations must integrate an increase in the standoff distance to prevent the mesh from contacting the post during high wind events. The frame and base should be made of metal, preferably aluminum to resist corrosion. The entire SFC should be oriented perpendicular to the predominant wind direction for optimal performance (Schemenauer and Cereceda 1994a).

The mesh of the SFC is typically made of polyethylene or polypropylene Raschel mesh (Schemenauer and Joe 1989; Schemenauer and Cereceda 1994a; Klemm et al. 2012); however, it is also important to consider other locally available materials that may be used for full-scale implementation. Early fog collection experiments with multiple types of meshes and designs resulted in the selection of polymer based Raschel meshes as the best available material, and Raschel meshes have been the standard ever since (Schemenauer et al. 1988; Gioda et al. 1993). Polyethylene and polypropylene Raschel meshes are typically used because they are efficient at capturing fog, inexpensive, available as a food-grade material, durable enough to withstand wind, sun, UV-radiation, and rain, and can rapidly drain water (Schemenauer and Cereceda 1994a; Klemm et al. 2012). However, it may be possible to use other materials that also have the appropriate properties.

Typical Raschel mesh used in fog collectors has flat fibers with widths of 0.5–1.5 mm (typically 1 mm), pore sizes of 1.0–1.3 cm, and a triangular knit that links fibers together to prevent unraveling due to tears or wind (Schemenauer and Joe 1989; Gioda et al. 1993; Briassoulis et al. 2007b). The mesh should have a shade coefficient, defined as the percent area capable of collecting water droplets, of 35 % (Schemenauer and Cereceda 1994a; Rivera 2011). Dimensions may vary due to stretching of the mesh when covering the frame.

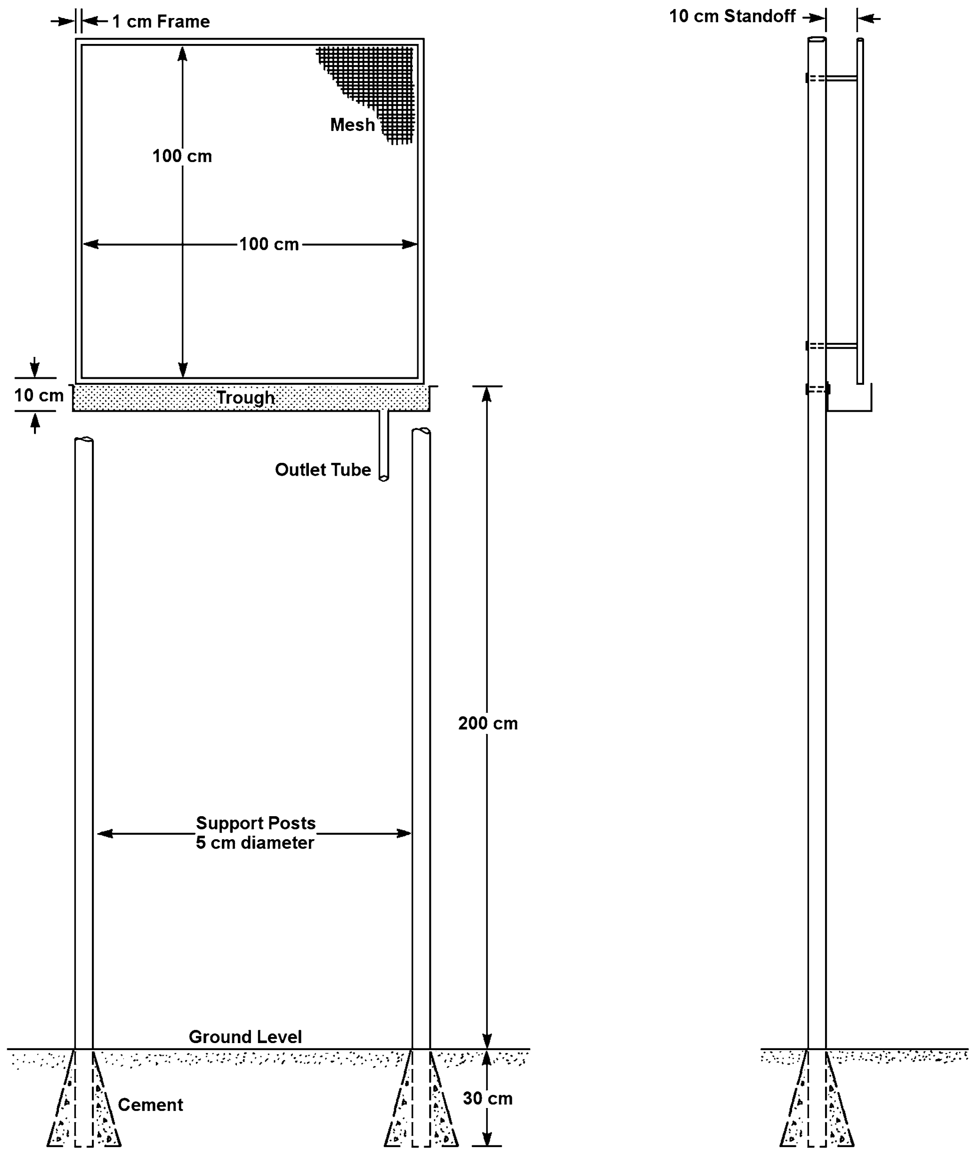

Fig. 2 Standard fog collector (SFC) (adapted from Schemenauer and Cereceda 1994a)

The mesh should be used in double layers, as the rubbing of the two layers promotes the run-off of water (Schemenauer and Cereceda 1994a; Klemm et al. 2012). Although Raschel meshes are widely used in agriculture for providing shade, limited data on their mechanical properties is available in literature (Briassoulis et al. 2007a). Briassoulis et al. (2007b) analyzed the properties of select polyethylene Raschel meshes, but it is unclear if they are of the same shade coefficient used in fog collectors. As a result, further investigation on the properties of the meshes (mechanical strength, hydrophilicity, etc.) used in fog collectors is needed.

The SFC has many advantages (Schemenauer and Cereceda 1994a). The materials are durable and able to withstand high winds. The study of potential fog water collection sites can be accomplished on a budget ranging from \$78 to \$233 USD. The expected life span of the mesh is approximately 3–10 years, but will vary based on environmental conditions. Additionally, while there can be up to a 15 % difference between the SFC and a full-scale fog collector in a given hour, the long term average collection rates (collection times >6.5 h) are in excellent agreement, giving an accurate estimate for full scale operations (Schemenauer and Cereceda 1994a).

Design of fog collectors

Current full-scale fog collectors typically have mesh areas ranging from 40 to 48 m^2, with aspect ratios (ratio of width to height) of around 2.5 (Schemenauer and Cereceda 1994b, Klemm et al. 2012). Mesh is not supported by a frame, but instead is stretched 2 m off the ground between two supporting posts, forming a natural concave shape in the wind. Supporting posts are anchored into the ground and secured using guy-wires. Multiple collectors are often used based on

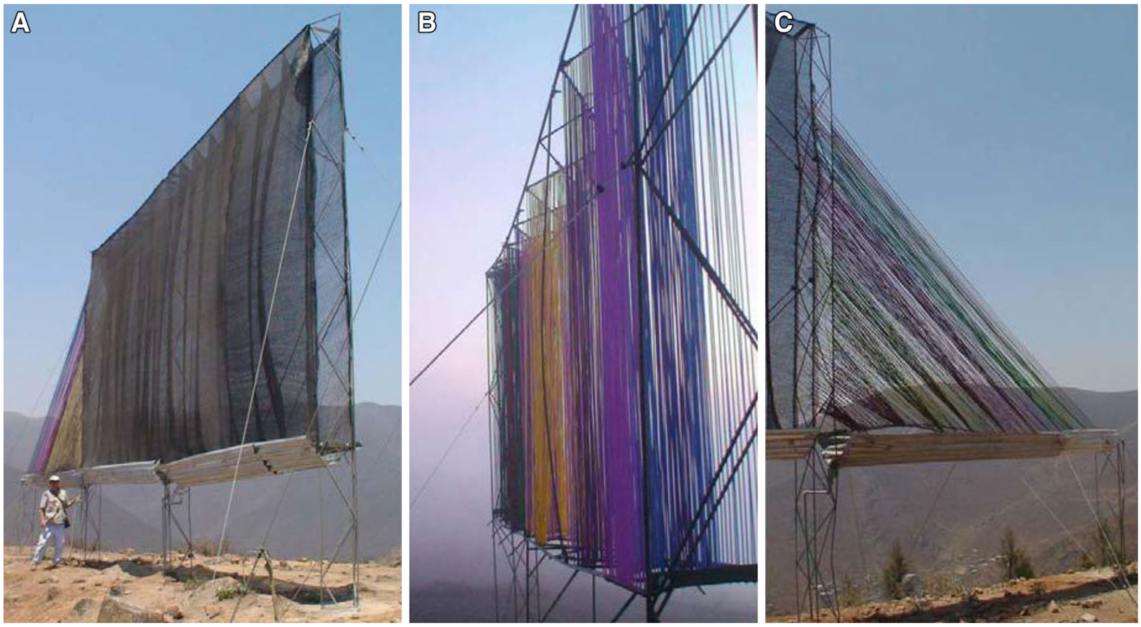

Fig. 3 Pilot testing of new fog collector designs. **a** "Eiffel" collector consisting of two layers of Raschel mesh with 10 strips between them; **b** "Harp" collector with 1.5 mm rubber strings running vertical; **c** "Diagonal Harp" collector with 1.5 mm strings running diagonally (Lummerich and Tiedemann 2011)

the water supply desired. In most cases, collection rates range from 1 to 10 L m^{-2} day^{-1}, but are known to be as high as 40 L m^{-2} day^{-1} in some regions (Schemenauer and Cereceda 1994a). To provide potable water to a typical rural village of 200 people with a target goal of 25 L $capita^{-1}$ -day^{-1}, an estimated 25 full scale fog collectors, or around 1,000 m^2 of mesh would be needed, at total startup cost of around $75,000 USD (Klemm et al. 2012).

Because of the relatively simple design of full-scale fog collectors, operation and maintenance are straightforward. Operators are not typically needed due to the passive nature of the system; however, periodic maintenance is vital to project success. Maintenance includes inspecting and tightening guy-wires, examining and patching any rips in the mesh, ensuring the mesh and collection system are free of debris or algae growth, and inspecting reservoirs and distribution systems (Klemm et al. 2012). Depending on the local cost of labor, number of fog collectors, and repairs needed, the annual cost of operation can range from $500 to $2,500 USD (Lummerich and Tiedemann 2011; Klemm et al. 2012).

Fog collector design variations

Although the design and implementation of fog collectors has changed very little, since the introduction of the SFC (Lummerich and Tiedemann 2009), pilot studies were carried out to determine the effectiveness of novel designs. Three prototype designs are presented in Fig. 3 (Lummerich and Tiedemann 2011). The "Eiffel" collector (Fig. 3a) showed the most promise, producing ten times the amount of water as a similarly sized 8 m × 4 m standard full-scale fog collector, with 281.2 L day^{-1} for the "Eiffel" as opposed to 28.7 L day^{-1} for the standard fog collector. The "Eiffel" collector incorporated 10 strips of mesh attached diagonally between the two layers of 8 m × 4 m 50 % shade coefficient Raschel mesh 0.3 m apart, forming a three dimensional structure that was more efficient at collecting fog blown by winds parallel to the collector (Lummerich and Tiedemann 2011). The "Harp" (Fig. 3b) and the "Diagonal Harp" (Fig. 3c) collectors both consisted of 2 m × 4 m × 0.3 m metal frames, with 2,256 m of 1.5 mm rubber strings installed vertically for the "Harp" collector, and 1,520 m of 1.5 mm rubber strings installed diagonally for the "Diagonal Harp" collector (Lummerich and Tiedemann 2011). The strings allowed the "Harp" and "Diagonal Harp" collectors to collect fog from winds blowing in all directions and resulted in water yields of 62.7 and 28.6 L day^{-1}, respectively (Lummerich and Tiedemann 2009). The "Eiffel" collector was determined to be the best design based on simplicity, reproducibility, robustness, and water yield per ground footprint rather than cost, because areas with ideal conditions for fog collection are limited (Lummerich and Tiedemann 2009). An economic analysis of a site near Lima, Peru for a proposed 100 "Eiffel" collectors, at $350 USD per collector and $500 USD annual maintenance, shows promise, with an investment of $35,000 USD being paid back after a period of 8 years (Lummerich and Tiedemann 2011).

Shade coefficient optimization

The shade coefficient of a mesh is the percentage of the total mesh area that is capable of collecting water droplets (Rivera 2011), and is the mesh material surface area divided by the total area spanned by the mesh. The Raschel mesh commonly used in fog collectors has a 35 % shade coefficient. However, when using the mesh in double layers, as is standard, the shade coefficient is usually closer to 50 %, depending on how the two layers align. It is important that the shade coefficient does not greatly exceed these values as the mesh may begin to act as a solid surface, causing the fog to flow around the mesh rather than through it (Rivera 2011). Determining the optimal mesh shade coefficient balances the surface area of the mesh available for fog collection, with the flow of fog through the mesh to maximize collection efficiency.

Rivera (2011) developed a model to determine the effect that the shade coefficient has on the aerodynamics of fog collectors. He determined the maximum percentage of fog that can be captured by a fog collector, called the aerodynamic collection efficiency (η_{coll}, unitless):

$$\eta_{coll} = \eta_{AC}\eta_{capt}\eta_{dr} \quad (10)$$

where η_{AC} is the proportion of fog droplets that would collide with the mesh if unperturbed (unitless), η_{capt} is the proportion of droplets that actually collide with the mesh (unitless), and η_{dr} is the proportion of fog water that drains to the trough (unitless). Equation 10 takes into account the various losses at all stages of fog collection due to fog bypassing the collector, fog that flows through the opening in the mesh or bounces off the mesh, and water that is lost due to spillage and evaporation. While, Eq. 10 is simplified to ignore complex three-dimensional flow patterns and ground boundary layer interactions, its purpose is to demonstrate the existence of an ideal shade coefficient and provide a rough estimation of maximum efficiency, rather than accurately predict fog collector yields (Rivera 2011).

The parameter η_{AC} is calculated by,

$$\eta_{AC} = \frac{s}{1 + \sqrt{C_0/C_d}} \quad (11)$$

where s is the shade coefficient (unitless), C_d is the drag coefficient of a non-permeable screen (unitless), and C_0 is the pressure loss coefficient of the mesh (unitless) (Rivera 2011). Drag coefficients for meshes of different dimensions reveal that meshes with larger aspect ratios have higher drag coefficients, thus increasing η_{coll}, according to Eqs. 10 and 11. Additionally, concave shaped fog collectors have larger drag coefficients, and thus different η_{coll} values are compared to flat fog collectors. Assuming that all other variables are equal and that η_{capt} and η_{dr} do not change with shade coefficient, Rivera (2011) varied the shade coefficients, along with the aspect ratios and shapes to find an ideal shade coefficient to maximize η_{coll}, as shown in Fig. 4.

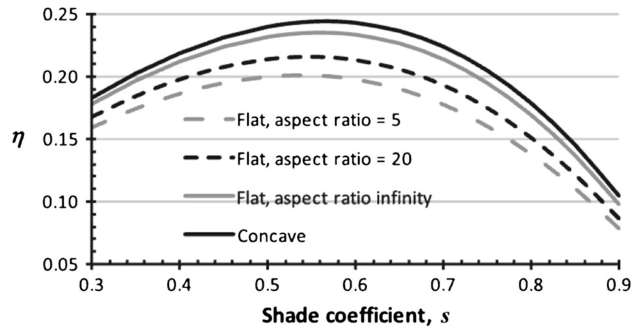

Fig. 4 Aerodynamic collection efficiency η in relation to shade coefficient for different aspect ratios of fog collectors (Rivera 2011)

Rivera (2011) reveals that the ideal shade coefficient for maximum collection efficiency ranges from 0.5 to 0.6 (Fig 4). While, this model only approximates shade coefficients that will maximize the flow of fog through the mesh, fog collectors can be made more efficient by varying the size and amount of ribbons in the mesh (within the constraints of the given shade coefficients) to reduce air resistance and further increase yields (Schemenauer and Joe 1989).

Alternative mesh materials and design

Research has been done to develop and test new mesh materials to collect fog water more efficiently. In addition to increased efficiency, new mesh designs also offer better durability, cost, availability, or water draining properties compared with the standard Raschel mesh (Fig. 5a).

In an area where Raschel mesh was not available, experiments were done using Aluminet greenhouse shade nets, a high density polyethylene mesh coated with aluminum (Shanyengana et al. 2003). The results indicated that while, the Aluminet worked best at a shade coefficient of 40 % and at low wind speeds, it averaged 96 % of the production of the standard Raschel mesh, which had a daily average of 1.235 L m^{-2} (Shanyengana et al. 2003). Even though Aluminet was not as efficient as the Raschel mesh, because it was widely available, Aluminet was preferred to Raschel mesh at this site.

Other mesh types have been developed to meet the needs of specific fog collection sites. In South Africa, gale force winds along with constant abrasion caused the entire system of fog collectors to fail (van Heerden et al. 2010). New mesh was needed to withstand such conditions, and a poly-yarn mesh, co-knitted with stainless steel for additional strength, was developed (Fig. 5b). The new mesh was not optimized for fog collection performance, but rather to withstand the environmental conditions in the area. However, any reduction in fog collection

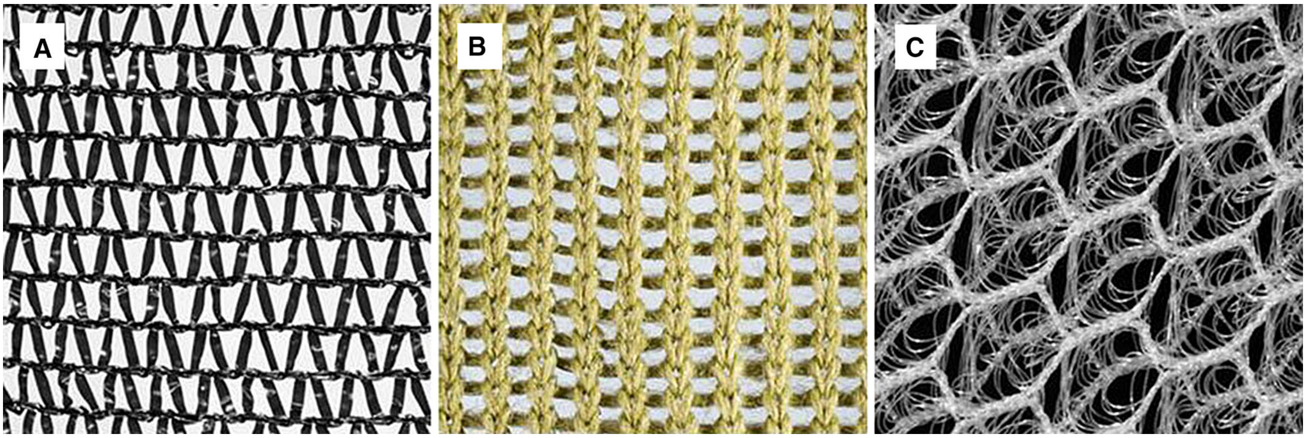

Fig. 5 Mesh netting materials. **a** 35 % shade coefficient single layer Raschel mesh; **b** stainless steel poly-yarn mesh used in South Africa; **c** 3-D prototype poly-material mesh (Klemm et al. 2012)

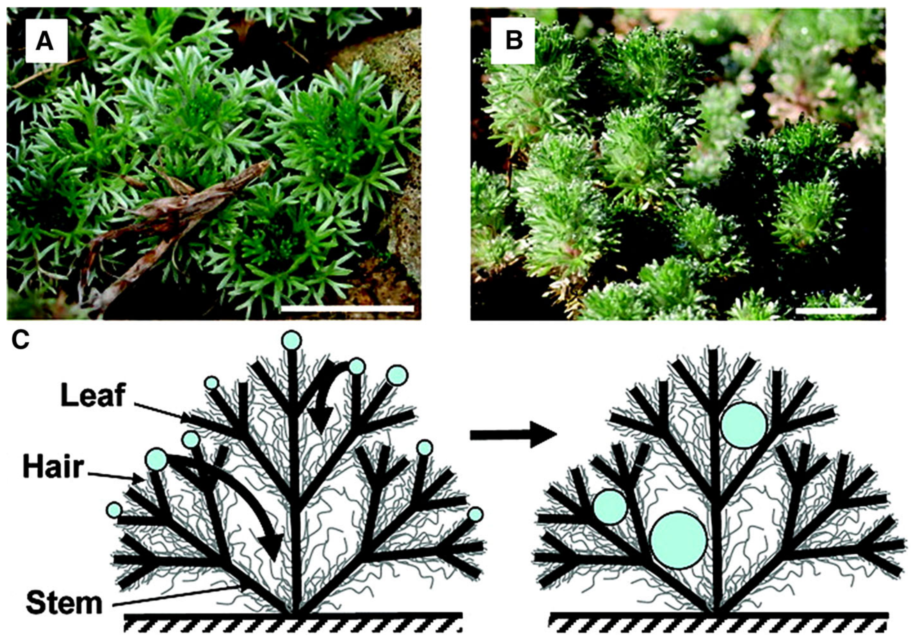

Fig. 6 Water collection by *Cotula fallax*, *scale bar* 20 mm. **a** Dry plant; **b** wet plant; **c** illustration of *Cotula fallax* water collection (Andrews et al. 2011)

performance by the more durable material was compensated by the reduced maintenance costs and failure rates.

Bio-inspired materials

The application of biomimetic mesh designs for fog collectors may be effective in increasing fog collection efficiency. One such design inspiration comes from the leaf structure of *Cotula fallax*, a tufted plant native to South Africa (Andrews et al. 2011). The hierarchical three dimensional layout of its leaves, along with its hydrophobicity, allows the plant to efficiently collect and channel fog water to its stem (Fig. 6). The 3-D structure of fog collecting plants has influenced prototype meshes, such as a polymeric 3-D mesh currently under development in Germany (Fig. 5c) (Klemm et al. 2012). 3-D meshes allow for increase yields due to greater surface areas and effectiveness at draining water, and are also more efficient than the standard 2-D Raschel mesh when winds are blowing parallel to the fog collector. However, the cost and availability of 3-D meshes may be prohibitive.

Research is also being conducted on developing fibers that mimic the wetting ability of spider silk. Spider silk has a unique capability to allow water droplets to form and be suspended from the silk due to naturally occurring spindle knots (Hou et al. 2012). Spindle knots act to facilitate the collection of smaller water drops at specific points, freeing more area for water collection and reducing losses of small water drops to wind and heat (Fig. 7). By recreating the layout of spindle knots in natural spider silk, new fibers can be designed to channel smaller water drops into larger water drops at certain locations, allowing for more efficient

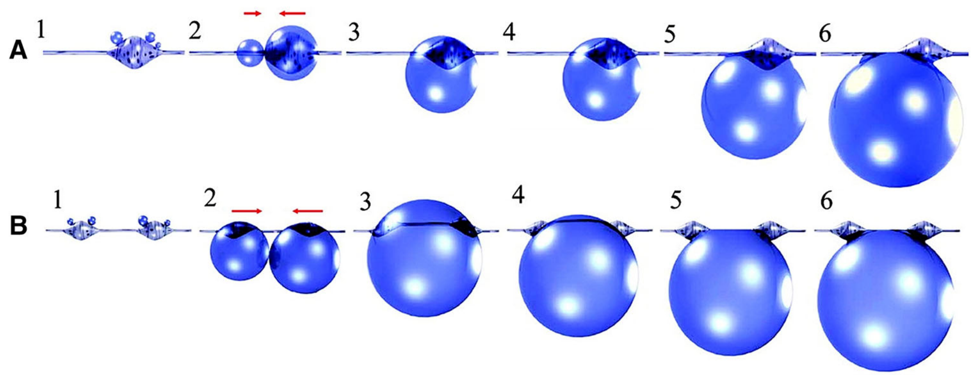

Fig. 7 Illustrations of water droplet formation on bio-inspired fibers with spindle knots. **a** Fiber with one spindle knot; **b** fiber with two spindle knots (Hou et al. 2012)

water drainage and reduced losses to wind and evaporation (Hou et al. 2012).

Another source of inspiration from nature is the Namib Desert beetle (Fig. 1), which collects fog water using hydrophilic bumps surrounded by a hydrophobic layer on its back (Parker and Lawrence 2001). Garrod et al. (2007) has developed a plasma deposition method to make a hydrophilic polymer array on a superhydrophobic background, comparable to the pattern on the back of the beetle. They have also shown that this pattern of hydrophilic and hydrophobic surfaces is more efficient at collecting suspended water droplets than a pure hydrophilic or hydrophobic surface (Garrod et al. 2007).

Water quality

Water collected via fog collectors is affected by both the air quality of the surrounding area, and also the build-up of particles on the mesh. Generally, fog water has a higher concentration of soluble particles than rainwater, primarily due to the droplet-forming process occurring at lower elevations, where air quality is impacted by human activities (Klemm et al. 2012). Fog water quality is affected by urban and industrial emissions. While particle build-up on the mesh, such as bird droppings, dust, insects, or algae, can contaminate fog water, a systematic approach of flushing the first batch of water after a prolonged period without fog, along with routine maintenance, can eliminate much of the associated contamination problems (Klemm et al. 2012). Typical contaminants in fog water include low levels of total dissolved solids, calcium, sodium, chloride, and bicarbonate; however, most of the full-scale fog water harvesting operations around the world meets the standards set by the WHO for ions and heavy metals in drinking water (Abdul-Wahab et al. 2007b; Klemm et al. 2012). A comparison of fog water quality studies revealed that when WHO standards were not met, low pH values, followed by high levels of iron and nitrate were to blame (Abdul-Wahab et al. 2007b).

Emissions from local industries have been shown to increase the level of particles and heavy metals in fog droplets (Ritchie et al. 2006). Studies in the Bay of Fundy reveal that fog droplets absorb mercury present in the atmosphere from industrial emissions (Ritchie et al. 2006). While the levels are still relatively low, around 7–72 ng L^{-1}, it demonstrates the ability of fog to absorb potentially toxic pollutants in the air and become unsafe for human consumption (Ritchie et al. 2006). Urban areas also tend to exhibit higher levels of total organic carbon, nitrate, and sodium, and other ions in comparison to rural fog, and as a result, urban fog has low pH values ranging from 4 to 5 (Raja et al. 2008).

Studies performed in rural agricultural areas have shown abundant levels of ammonium, sulfate, and other dissolved organic carbon compounds in fog (Straub et al. 2012). The elevated ammonium levels typically result in rural fog having slightly elevated pH values ranging from 5 to 6, when compared to urban fog (Raja et al. 2008).

Current applications of fog water

Fog water is being collected in various locations throughout the world as shown in Fig. 8 (Schemenauer and Cereceda 1991; Abdul-Wahab and Lea 2008; Klemm et al. 2012). Many of these locations are arid mountainous coastal regions, but fog collection can be viable on islands where there are few fresh water alternatives. Most current applications of fog water involve drinking water or reforestation. Reports of other applications, such as for agriculture irrigation, are minimal, probably due to the large volumes of water needed.

Fog water as drinking water

In regions with a high occurrence of fog, fog water harvesting is a sustainable source of drinking water due to its passive collection, minimal maintenance, and minimal energy requirements. Table 1 summarizes the fog water harvesting potentials for a variety of locations around the

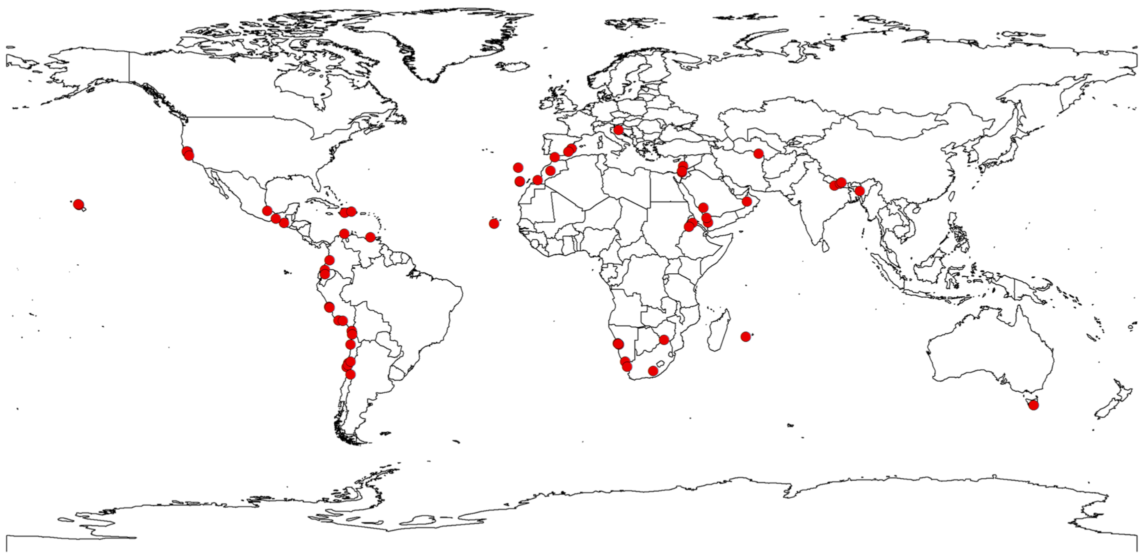

Fig. 8 Locations where fog collection has a high potential for success (adapted from Klemm et al. 2012)

Table 1 A summary of fog water harvesting potential for select locations

Location	Average yield[a] (L m^{-2} day^{-1})	Fog events per year	40 m^2 Collector average yield[a] (L day^{-1})	No. of people supplied per 40 m^2 collector[b]	Source
South Africa	4.6	80	184	24.5	Olivier and de Rautenbach (2002)
Nepal	6.8	192	272	36.3	Karkee (2005)
Chile	3	365	120	48	Schemenauer and Cereceda (1994b)
Peru	9	210	360	48	Schemenauer and Cereceda (1994b)
Oman	20	77	800	106.7	Abdul-Wahab et al. (2007a)
Canary Islands	9.5	230	380	50.6	Marzol (2008)
Namibia	2.4	120	96	12.8	Shanyengana et al. (2002)
Saudi Arabia	4.0	45	160	21.3	Gandhidasan and Abualhamayel (2012)
Morocco	7.1	141	284	37.8	Marzol and Megía (2008)

[a] Average yield during fog events

[b] Calculated using a minimum drinking water usage of 7.5 L $capita^{-1}$ day^{-1} (WHO 2011)

world. Fog water is typically used as drinking water in regions that have a high number of fog events per year, such as Chile or the Canary Islands (Table 1), or in regions with less frequent year-round fog events but larger storage capacity (Schemenauer and Cereceda 1994b). In other areas where fog only occurs a few months out of the year, such as Oman (Table 1), the storage of fog water for use as drinking water throughout the remainder of the year may be impractical (Schemenauer and Cereceda 1994b).

In the coastal area of El Tofo, Chile, a series of 75 fog collectors, each with an area of 48 m^2, was constructed to provide 330 villagers with fresh water (Schemenauer and Cereceda 1994b). The system produced roughly 3 L m^{-2} day^{-1}, averaging 11,000 L day^{-1}, or about 33 L day^{-1} per person in the village. Before the fog collectors were constructed, the villagers depended on water trucked in from 40 km away and used roughly 14 L day^{-1} per capita. The fog collection system became the sole water source for the village, while improving water quality, reducing cost, and resulting in water independence (Schemenauer and Cereceda 1994b).

In Nepal, in a region that lacks consistent fog throughout the entire year, fog water harvesting was seen as a way to supplement existing rainwater supplies to meet the needs of the growing population (Karkee 2005). With almost 30 % of the country lacking access to safe drinking water, two fog water collections systems were piloted in ridge top communities with high fog frequencies where the target daily water use per capita was 15 L. Pilot studies resulted in a fog water collection rate of 6.75 L m^{-2} day^{-1}. It was determined that 12 m^2 fog collectors, together with existing rooftop rainwater collection systems of at least 12 m^2 would provide a large enough area to provide a family of seven with the target daily allowance. While fog alone was not frequent enough to completely provide for the community needs, a combination of both fog water and rainwater was determined to meet the minimum daily water requirements in areas of need (Karkee 2005).

Throughout the world there have been other successful applications of fog water for drinking water. In Peru, a 1,200 m^2 collector system successfully supplied a school with sufficient fresh water on a daily basis (Schemenauer and Cereceda 1994b). In South Africa, two collection systems supplemented other water supplies in a small community and a rural school with 323 and 144 L day^{-1}, respectively (Olivier and de Rautenbach 2002). These successful implementations of fog water harvesting used to supplement or replace existing sources, indicate its potential.

Fog water for reforestation

Another major application of fog water collecting is for reforestation. Arid regions that normally rely on fog drip to sustain forest plants, but have suffered the effects of deforestation or wildfires are candidate locations for fog water irrigation (Estrela et al. 2009). Without human intervention, these areas are very slow to recover, if at all, because there is no way for new plants to grow without the additional water input from fog drip that is normally provided by existing plants (Lummerich and Tiedemann 2009). However, it is believed that with human intervention, the ecological and hydrological restoration of these areas is feasible (Lummerich and Tiedemann 2009). Once the planted trees grow large enough to sustain themselves from fog drip, they become natural fog collectors. The return of natural fog drip, over time, restores the local ecology, reducing erosion and contributing to groundwater recharge. Regions where the frequency of fog events prevents the practical use of fog water for drinking water may be well-suited for reforestation and irrigation via fog water (Schemenauer and Cereceda 1994b).

A year-long study using fog water to restore a forested area affected by wildfire was done in the Valencia region of Spain by Estrela et al. (2009). After the occurrence of a wildfire, the area of study showed little recovery of pines and other trees, and instead became dominated by shrubs. To restore the natural ecology, 620 one-year-old Mediterranean pine seedlings were planted in a cleared 2,500 m^2 plot at regular intervals. An 18 m^2 fog collector was deployed for a 6-month period from April to September. The collector was connected to a 3,000 L storage tank complex, which fed a network of tubes that directly irrigated the seedling holes. Seedlings were given different treatments throughout the year: natural rainfall (control), rainfall exclusion, one water event of 3.5 L per hole in the summer, and two water events of 3.5 L per hole in the summer. Seedlings were only irrigated during the summer months as needed, and thus the single fog collector was sufficient to fill up the storage tanks for the duration of the experiment. The results showed that those seedlings that were irrigated by fog water during the summer months had a significantly higher survival rate (above 90 %) when compared to the rainfall exclusion group (78 %) and the control (84 %). The seedlings also showed a correlation between higher water availability and growth, indicating that fog water irrigation is a viable technology to increase survivability and the rate of growth of trees in reforestation applications (Estrela et al. 2009).

Another study of the long term feasibility of using fog water to restore a deforested hillside took place in the outskirts of Lima, Peru, as described by Lummerich and Tiedemann (2009). Three full sized fog collectors were used to irrigate roughly 800 trees of different species for a year, during which the mean tree height increased from 93 to 142.7 cm, with a survival rate of roughly 90 %. After the first year, the trees were left to grow independent of irrigation and showed another increase of mean height to 148.7 cm, indicating the trees began to grown on their own through self-irrigation via fog collection. Additionally, there was a noticeable increase in natural flora at the study site. The results indicate that fog water irrigation is effective when used in reforestation applications, and such applications can potentially restore local ecology and hydrology (Lummerich and Tiedemann 2009).

Additional reforestation efforts using harvested fog water were conducted by Ramírez et al. (2012) near the deserts of southern Peru. Twelve fog collectors, each with an area of 48 m^2, were set up and connected to a system of four reservoirs. The system was designed to irrigate 2-year-old *Myrcianthes ferreyrae* trees with treatments of 0, 20, 40, 60, and 80 mm of fog water a month. The results showed that all irrigated seedlings had greater increases in stem diameter and height than the control trees, indicating faster growth. While the variation in treatment was meant to simulate natural fog water drip from trees, it revealed a threshold effect for the treatment. Growth was limited where irrigation water supplied less than 20 mm of water per month, but all treatments above 20 mm per month showed similar increased growth rates. The results indicate that there is a lower limit to the amount of water that is needed for ideal growth, and those levels are normally reached only with the additional fog drip from existing trees. However, in areas without existing trees, harvested fog water can supplement natural rainfall to reach this lower limit and encourage reforestation until the natural fog cycle is reestablished (Ramírez et al. 2012).

Case study: California coast

Water is in high demand in California (USA), and as part of this review a case study was conducted on the feasibility of applying fog collection along the California coast. California coastal fog typically occurs in the summer, between late June and mid October (Ingraham and Matthews 1995). Summer coastal fog frequency in the northern and central regions averages between 40 and 44 % during the fog season, with the greatest frequency occurring in early August (Johnstone and Dawson 2010).

Fog water collection studies were conducted by Hiatt et al. (2012) near the Big Sur area of California's central coast. Fog water was harvested throughout the 2010 and 2011 summer fog seasons using SFCs, and the average fog water collected was 289.2 L m^{-2}, or approximately 3.01 L m^{-2} day^{-1}, during the summer months. These values represent a conservative estimate of fog water potential at this site is due to the exclusion of data during rain events, and the limited time period in which fog water was collected.

A full-scale fog collector with a 40 m^2 mesh deployed in this area was estimated to cost approximately $3,000 USD (Klemm et al. 2012), and would collect an estimated 11,568 L per fog season or 120.4 L day^{-1} during the summer. Fog water yields were calculated by multiplying seasonal (289.2 L m^{-2}) and daily averages (3.01 L m^{-2} day^{-1}) by a 40 m^2 fog collector. If the expected lifespan on the fog collector is 5 years and maintenance costs are minimal, the total cost per liter of water is approximately $0.05. Regional water usage for the central California coast is 413 L $capita^{-1}$ day^{-1} for both single and multi-family residences; however, most of this water is used for purposes other than drinking (California Department of Water Resources et al. 2010). Multiple full-scale fog collectors would be required to supply one household with all water needs, but one 40 m^2 collector could supply sufficient drinking water for even a large family if drinking water consumption was 7.5 L per person per day. This analysis suggests fog collectors could be used to supplement household water supplies on the coast of California.

Fog collectors may also have application in restoring deforested areas on the coast of California. Coastal areas have been heavily logged in the past and are frequently denuded by landslides and wildfires and active restoration of denuded areas can decrease erosion of coastal watersheds. Using the landscape coefficient method (University of California Cooperative Extension 2000), one 40 m^2 collector could fully irrigate a 100–300 m^2 plot of mixed native vegetation, assuming the use of an efficient drip system. This may not irrigate an area sufficient enough to scale to large wildfires or other events, but the use of collectors could have application in increasing establishment of ground cover species in critical areas (such as slopes) or as part of long-term restoration efforts. Further investigation is needed.

Another potential application of collected fog water may be to supplement natural fog drip in California's coastal redwood forests during the summer months. The importance of natural fog water drip to California's redwood and coastal ecosystems has been well-studied (Azevedo and Morgan 1974; Ingraham and Matthews 1995; Dawson 1998; Burgess and Dawson 2004; Corbin et al. 2005; Fischer et al. 2009). However, current trends indicate fog frequency has begun to decrease by 33 % in some coastal redwood habitats, since the early twentieth century (Johnstone and Dawson 2010). Fog collectors can act as a supplemental on-site source of freshwater for redwoods, encouraging the recruitment of new trees and reducing water stress during the dry summer months, while avoiding the need for water infrastructure or transportation. Maintaining healthy redwood forests is vital for local and global ecology, as they have the largest land biomass concentrations on earth, and can act as carbon sinks for over 1,000 years (Busing and Fujimori 2005).

Beyond California, the entire West Coast, stretching from Seattle to Los Angeles is considered one of the top three regions in the United States that experiences frequent fog events (Leipper 1994). Although fog frequency is greatest in the northern and central California coast, summer fog frequency is still greater than 25 % as far south as San Diego, and well into Oregon to the north (Johnstone and Dawson 2010). However, a 25 % fog frequency represents a 40 % decrease as compared to the northern and central California regions, further reducing fog harvesting yields, and increasing cost per liter. The use of harvested fog water to supplement local water supplies deserves further investigation.

Effects on wildlife

To our knowledge, there have been no studies focused on the impact of fog collectors on local wildlife. However, it is implied that there will be a positive impact on wildlife when fog water is used for reforestation, due to the restoration of wildlife habitats (Lummerich and Tiedemann 2009). Because California lies in the Pacific Flyway for migratory birds, the impact on these species must be taken into consideration. Due to the lack of moving parts and relatively low heights of fog collectors (6 m), birds are not anticipated to be significantly impacted. Regardless, further research is necessary to fully quantify the impacts of fog collectors on wildlife.

Conclusion

Fog water harvesting has great potential to supply communities with little annual rainfall, but frequent occurrence of fog events, with a source of fresh water. Current studies and full scale applications indicate the technology is both feasible and sustainable.

While fog water harvesting is most suitable for providing water to developing and rural regions, it is nevertheless a valuable water source that should be considered in other regions as well. Having no on-going energy requirements, fog water harvesting can be beneficial for isolated communities that have become dependent on outside water supplies and scarce or erratic rainfall.

Fog water harvesting used for reforestation is beneficial to the environment. Reforestation provides habitat for local flora and fauna, increases biodiversity and reduces erosion. Additionally, the re-growth of forests encourages natural fog water collection in the canopy layers, which transfers water to the ground, replenishing ground water sources while restoring the local hydrology.

A case study of fog water harvesting along the central California coast reveals that fog collection could conceivably supplement household water supplies in the region. Additionally, fog harvesting could have application in restoration of denuded landscapes. These and other applications, such as supplementing natural canopy drip as climate change decreases fog frequency, deserve further investigation.

While the current state of fog water harvesting is promising, standardized methods must be established for reporting data, and further research is needed for improving fog collector designs, mesh materials, and modeling to increase the efficiency of fog collectors. Reductions in cost and increases in collection efficiency will help solidify fog water harvesting as a safe, simple, consistent, and sustainable fresh water source for both reforestation and drinking water.

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