Fog as unconventional water resource: mapping fog occurrence and fog collection potential for food security in Southern Bolivia

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Abstract

"Valles Cruceños" rural region, Bolivia, is characterized by an intrinsic water scarcity and an increasing pressure for food production by the neighboring and fast-sprawling city of Santa Cruz de la Sierra. Here, orographic fog is a daily phenomenon occurring all the year round, representing a sustainable water source for improving farmers' resilience to dry spells and for promoting food security and sovereignty. With the present study, we aim at a first assessment of the potential of fog collection in the area by a 1-year experimental analysis made through 1-m^2 fog collectors in 10 different locations. Starting from these data, we design under safe assumption (including a sensitivity analysis) a fog water irrigation system providing water for a standard theoretical field with four local crops (maize, green beans, potato, and tomato) in the dry season. The present paper represents the first study on fog collection in Bolivia, showing that, on annual basis, an average of 6.01 l/m^2/d can be obtained from most productive areas, with peaks up to 8.93 l/m^2/d.

Moreover, to the best of our knowledge, the work represents one of the first consistent studies on the productive use of orographic fog, while large part of the literature focuses on advection fog, mostly occurring in the Pacific Coast of South America.

Keywords: water scarcity, fog harvesting, irrigation, rural water supply, South America, Andes.

Highlights

- Orographic fog can improve farmers' resilience to dry spells in sub-Andean Bolivian ridges
- An average of 6.01 l/m^2/d can be obtained from most productive areas, with peaks up to 8.93 l/m^2/d
- Such fog collection rates can enhance crop production in the dry season
- The study represents the first fog collection study for the Country,
- and one of the firsts on orographic fogs for the region

1. Introduction

Fog collection is a water harvesting technique used in arid tropical and subtropical areas characterized by low rainfall amounts but frequent fog events, due to local weather conditions (Klemm et al. 2012; Kaseke and Wang, 2018). Fog water can be used for human and animal consumption (Kaseke and Wang, 2018), subsistence agricultural activities (Correggiari et al., 2017), or afforestation and environmental restoration (Certini et al., 2019). In areas where normally the water for human uses is carried in villages by truck, it can increase the average quantity of water per capita (Fessehaye et al, 2015; Kaseke and Wang, 2018), and, in such contexts, it is considered as a fundamental mean to achieve water security (UN-Water, 2020).

The technique is implemented by using fog collectors (or *Atrapanieblas* in Spanish): vertical polypropylene meshes supported by two wooden posts set up perpendicularly to the predominant wind direction (Schemenauer and Cereceda 1994, Franceschetti, 2000). A part of fog water droplets carried by the wind touches the nets and, as they converge by gravity, they run down the meshes into underlying plastic gutters and subsequently into storage tanks (Franceschetti, 2000).

Fog collectors are classified in two major typologies: Standard Fog Collectors (SFCs) and Large fog Collectors (LFCs). SFCs are smaller (mesh area of 1 m^2) and are mainly used in pilot experiments while LFCs are much larger (mesh area of 40-48 m^2) and are used in project implementations (Klemm et al. 2012).

In the Bolivian Altiplano (or highlands), a dryland region, rainfed cultivation can only take place during the summer months (Garcia et al., 2007). Due to low temperatures in winter, irrigation cannot sustainably increase crop intensification (Satgé et al., 2019). However, it could be crucial for sustaining agricultural production during periods of drought in the summer months and it could allow watering of artificial pastures, reducing the problems derived from overgrazing of natural grasslands. Moreover, in some areas, irrigation could also allow for an increased cultivation of high-value agricultural products such as vegetables (FAO, 2015).

Among many areas of the countries, Valles Cruceños region (a macro-region including the three provinces of Florida, Vallegrande and Manuel María Caballero) represents a remarkable hotspot for potential water scarcity issues (Zabalketa, 2008). Despite a relatively lower altitude with respect to the western highlands, which would allow crop intensification, the area is characterized by many urban-rural dynamics, potentially harmful for environmental health (Cantini et al., 2019), since it represents the main source of food for a large part of the population of the city of Santa Cruz de la Sierra (1.7 million residents in the urban area). The city is the second Bolivian city for population, with an estimated growth rate of 2.15% for 2019 (UN, 2020). Given the fast growth of the urban population, there is a tremendous increase in food demand, requiring the continuous expansion of cultivations and rangelands (Castelli et al., 2017; Cantini et al. 2019).

Precipitation in Valles Cruceños is concentrated from December to March, while in the rest of the year it hardly appears. There is, however, a constant presence of fog (Zabalketa, 2014), generated by the orographic effect of Eastern Andean escarpment, facing the Amazon basin. Such resource could fulfill irrigation needs of local populations and could serve as an integration for satisfying drinking water demands. For drinking purposes, in fact, local population relies on temporary springs and on rural aqueducts based on the water supply provided by local Reservas del Patrimonio Natural (REPANAs, Zabalketa, 2008). However, such water sources often reduce their discharge or even dry up during dry season. They can therefore be integrated with fog water.

Following these practical needs, the present research aims at evaluating the potential for fog water harvesting in Valles Cruceños area by: 1) analyzing 12-month time series of fog volumes collected by 10 1-m^2 fog collectors installations in different locations, 2) analyzing the feasibility of a suitable, scalable, fog-based irrigation system that can enhance the resilience and the food security of rural settlements of Valles Cruceños.

While large part of fog collection projects are based on the collection of advection fogs (Schemenauer and Cereceda, 1991; Certini et al., 2019), namely fog which is formed by the slow passage of relatively warm, moist, stable air over a colder wet surface (like the South Pacific Coast bordering the Andes) and it is then advected (moved) by orographic winds to coastal mountains and hills (Fessaye et al., 2014), our paper focuses on the rather less common collection of orographic fog, originated on Andean Eastern escarpment (Cereceda et al., 2002; Estrela et al., 2008; Estrela, 2008; Molina and Escobar, 2008). Advection fog collection rates may reach 12 l/m^2/d (Fessehaye et al. 2012), while orographic fog collection rates observed so far are considerably lower, ranging from 4.2 (Colombia, Molina and Escobar, 2008) to 1.1 l/m^2/d (Chile, Cereceda et al., 2002). However, due to the limited availability of literature, it is needed to extend the research efforts on orographic fog collection and assess relative fog collection rates, especially in countries where fog water collection is unexplored. To the best of our knowledge, our analysis represents the first scientific study on fog collection in Bolivia.

2. Study area

2.1. Valles Cruceños

The Valles Cruceños macro-region has an area of 1382705 ha and population of 82727 inhabitants (INE, 2012). It is constituted by the provinces of Florida, Vallegrande and Manuel María Caballero in the southwest of the department of Santa Cruz, Bolivia (figure 1), located between the Andean Cordillera and the Amazon lowlands (Gobierno Departamental Autónomo de Santa Cruz, 2009). The main economic activity in the region is agriculture which is mostly small-scale and rainfed, and water scarcity represents a key constraint (Zabalketa, 2016).

During the year, the temperature generally ranges from 6 °C to 23 °C and is rarely below 2 °C or above 27 °C. Rainfall is variable (from 400 mm to 2000 mm/y), with the rainy period running from December to March, while the rest of the year is mostly dry. The area is characterized by a large morphological and landscape diversity, from the highest areas (3300 m a.s.l.) of the Sub-Andean zone, to lower areas (460 m a.s.l). The ecoregions present in Valles Cruceños include the Tucuman-Bolivian forest, the Inter-Andean Dry forest, Chaco Serrano and Yungas forest (Ibisch and Mérida, 2013).

2.2 Fog generation and occurrence in Valles Cruceños

During the austral summer, from December to March, the study area is affected by the combined effect of the South American summer monsoon and South Atlantic Convergence Zone (SACZ, a cloud strip oriented in the NW-SE direction extending from the Amazon to the South coast of Brazil). The summer monsoon leads to intense rainfall and carries warm, moist air from the tropical Atlantic into the Amazon Basin upon reaching the Andes Mountains. Therefore, during early summertime, in Bolivia there are intense rainfalls (Latrubesse et al., 2012).

At this time of the year, an area of low pressure (Chaco Low) is established in the interior of the continent, combined with the orographic barrier of the Andes to the west, directs the trade winds that arrive from the east and northeast in the Amazon to the southeast of the continent (Garreaud, 2009). The SACZ implies a significant export of moisture from the Amazon towards the continent. As the SACZ enters its most active stage (December, January and February) the upper-level anticyclonic center moves from the Amazon basin to the Bolivian altiplano setting up the "Bolivian High" a warm anticyclone creating a pressure gradient that leads to enhanced upper-air coming from the east, passing over the Andean ridge, increasing eastward upslope flow and moisture transport from the interior of the continent towards the western Altiplano (Vuille, 1999).

Garreaud (1999) presented a convincing linkage between large scale upper-air easterly winds over the Altiplano during rainy periods and the regional easterly upslope flow moisture from the continental lowlands towards the Altiplano. His results suggest that the large scale upper-level easterly flow produces an acceleration of the eastward upslope flow and moisture transport on the Andean ridge (Vuille, 1999). This eastern trade-wind runs through the continent, and when the wind intercepts the Andean ridge, the air mass is forced from a low elevation to a higher elevation as it moves over rising terrain, therefore forcing moisture convergence at those elevations. Garreaud (2009) confirmed the studies expressed in 1999 about the effect of the Andes on weather systems, mainly in subtropical latitudes, asserting the existence of a wet and dry period at high elevations (between 2000 and 5000 m a.s.l.) due to a positive relation between this range of altitude and trade winds blowing from the Amazon basin. It can be concluded that fog in Valles Cruceños is predominantly orographic and present from December onwards.

3. Materials and methods

3.1. Data collection

Ten experimental sites were selected to cover a range of elevations (from 420 to 3334 m a.s.l.), across different mountain ridges (Figure 1, Table 1). The collection of hydrometeorological observations, including fog collection, was made from January to December 2018. In each of the experimental sites, three 1-m^2 fog collectors were used to collect fog water, and volumes collected were measured from tanks connected to the meshes (Figure 2). Due to the location of measuring stations, positioned in remote communities, data were taken with a frequency of 8 days by local population. An operator collected aggregated data and double-checked measurements every 20 days. The volume was always taken also at the end of each month. 2018 was reported as a regular year, with neither negative nor positive rainfall anomalies.

The fog collectors used were equipped with 50% half-shade Raschel mesh, which was the only one available on the Bolivian market at the time of the analysis. Such mesh was quite different standard SFC references, prescribing a 35% Raschel mesh in double layer (Schemenauer and Cereceda, 1994). However, a double-layered 35% Raschel mesh covers approximately the 60% of the area of the collector. Considering that the superposition of the two layers is always casual and that the 40% free space may have some variations in all applications (Schemenauer and Cereceda, 1994), we assumed that the 50% Raschel mesh could be considered quasi-equivalent to a standard SFC.

Fog-collected volumes were cumulated per each month, averaged, and expressed as l/m^2/d. A wind gauging station was installed next to the fog collectors, recording measurements with a frequency of 30 minutes, which were averaged per month. In addition to this meteorological information, a daily record of the presence or absence of fog was kept, and average rainfall volumes were retrieved from Vallegrande station, located in Vallegrande city at an altitude of 1998 m a.s.l. (data from World Weather Online, 2020). Rainfall amounts falling in area of the gutter collecting fog water, at the bottom of the meshes, were removed from the monthly averages.

3.2 *Designing a Fog water irrigation system*

The design strategy was based on the idea of irrigating crops during the dry period (from April to August), when crops are not grown due to water scarcity (FAO-GIEWS, 2020). Year 2018 was considered as design period, using as water supply the fog water that can be collected from one LFC during each month of analysis, in the most productive site, for a standard cropped area used to cultivate four crops (tomato, potato, maize and green beans in equal percentages). The main design variable for the system was the volume of a suitable storage tank.

The discharge entering in the system in month I, $Q_{in,i}$ (m^3/month) was calculated as:

$$Q_{in,i} = n \cdot S \cdot 0.88 \cdot Q_{fog,i} \cdot t_i / 1000 \qquad (1)$$

Where:

- n is the number of LFC considered, set to 1;
- S (m^2) is the design area of an LFC equal to 48 m^2;
- $Q_{fog,I}$ is the average daily volume of fog collected in the month i, from the previous paragraphs, referred to data collected with an 1-m^2 fog collector;
- t_i (day/month) is the number of days for month i;
- 0.88 is a scale parameter to consider that the fog collected by one SFC (of equivalent fog 1-m^2 fog collector) is usually more than the one which one LFC could collect in the same conditions (Bresci, 1998).

The discharge needed for irrigation at month i, $Q_{out,i}$ (m^3/month), was calculated as:

$$Q_{out,i} = d_{irr,i} / e_{irr} \cdot A \cdot t_i / 1000 \qquad (2)$$

Where:

- A (m^2) is the cropped area, assumed equal to 120 m^2 in the first trial;
- $d_{irr,I}$ (mm/d) is the daily average irrigation requirement for month i, calculated with CROPWAT 8.0®;
- e_{irr} is the irrigation efficiency, assumed 0.90 for drip irrigation.

CROPWAT 8.0 is a Windows-based software for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data (Martin, 1992). In addition, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns. Climate data input can accommodate daily, decadal, or monthly values, and are converted into a daily soil-water balance to develop optimal irrigation schedules, using various user-defined options for water supply and irrigation management conditions.

Climatic data for three years 2018 were gathered from ERA-5 (Copernicus Climate Change Service, 2017 -monthly maximum and minimum temperature (◦C), mean relative humidity (%), wind speed (km/day)), and CHIRPS rainfall dataset (Funk et al., 2015), which was found to have more accurate data (mm) for the area when considering very localized studies (Cantini et al., 2019). Sunshine hours (h) were taken from the Bolivian National Service of Meteorology and Hydrology (SENAMHI). The crop data for potato, maize, green beans, and tomatoes, such as rooting depth, crop coefficient, critical depletion, yield response factor, and length of plant growth stages, were obtained from the FAO Manual 56 (Allan et al., 1998). FAO Harmonized World Soil Database (HWSD) was used to obtain information, in this case a silty loam type.

The water balance equation used to simulate the storage system is as follows:

$$V_i = \begin{cases} V_{design} & if\ V_{i-1} + \left(Q_{in,i} - Q_{out,i} \right) > V_{design} \\ V_{i-1} + \left(Q_{in,i} - Q_{out,i} \right) & elsewhere \end{cases} \qquad (3)$$

Where:

- V_i is the actual volume of water in the storage tank at month i;
- V_{design} is the design volume of the tank to be realized.

The water balance model was computed for the water collected in 2018, by testing different V_{design} options, and identifying the minimum volume that allows to compute the balance of the tank with $V_i > 0$ for each timestep analyzed in each year (while $V_i < 0$ would represent a failure of the system). The water balance calculation was initialized with the tank filled by the fog collected in March, considering the initial volume for February equal to 0. The cropped area A was also adjusted (in a limit of ± 10%) for having a correct system functioning. After the initial design, the design process was repeated for potential situation with -5%, -10% and -20% for water amounts to check the sensitivity of the system to different climatic conditions.

4. Results

4.1. In-situ fog water collection for 2018

The average yearly values of daily fog water volumes ranged from 0.89 l/m²/d in Racetes (2131 m) to 6.01 l/m²/d in El Churo (3334 m) (Table 2). In Sivingalito (2091 m), El Pino (922 m) and Chapas (2608 m) annual averages were also considerable (3.66, 3.14 and 2.61 l/m²/d, respectively). While in many other case studies in increase in altitude was found to be linked to an increase in fog collection rates and volumes, in Valles Cruceños annual volumes were not significantly positively correlated with elevation. This could have been linked to the peculiar characteristics of the study site, with multiple valleys interspersed with relatively low reliefs.

In most sites, two peaks of fog water harvesting were observed, one in Feb-Mar and one in Oct-Dec (Table 2, Figure 3), with the first one generally largest than the second peak. Sites within the same mountain range displayed different amount and distribution of fog, highlighting that local topography represented an important factor (Figure A1 in Appendix). For example, El Churo is located in the windward side of the mountain range, facing the Amazon (which is most humid) while Manzanal, is located in the leeward site.

No significant relation was found between mean monthly values of wind speed (Table A1 in Appendix) and mean monthly volumes of water harvested (a linear model aimed to explain mean monthly volumes of fog collected as a function mean wind speed exhibited a value of $R^2 = 0.35$). Possibly, this is related to aggregating mean wind speed data, as fog events are sporadic.

4.3 Designing a Fog water irrigation system

Results indicate that using one LFC with a commercial tank size of 8 would allow the irrigation of the farm plot of 120 m^2 (potato, maize, green beans, and tomato in equal proportion) for one dry season (Mar-Aug). Our calculation, under the assumptions made in session 3.2, showed that the system is only limitedly sensitive to fog water reductions, highlighting the need of a larger tank (10 m^3) only for a 20% reduction. The water balance of the irrigation system is shown in table A2 in Appendix.

5. Discussion

5.1 Fog collection potential in Bolivian Valles Cruceños

The present study testifies a good potential for the use of fog as an unconventional water resource in the south-east Andean escarpment of Bolivia. In the best location (El Churo) yearly average fog collection values are up to 6.01 l/m^2/d, with peaks of 8.93 in the dry season. The very specific characteristic of the study site is to be an inland location, taking advantage of the fog formed on the Amazon forest and by orographic effect. While some fog collection projects can reach yearly average values over 10 l/m^2/d (Serra Malagueta in Cape Verde, Meija in Peru; Fessehaye et al., 2012), all these latter ones are based on advection fog, being thus limited to coastal areas. In terms of average fog volumes collected, the case study of Valles Cruceños can be set in an average position among the known fog collection experiments (Fessehaye et al., 2012, cfr. Figure 4). Among these, some similar analyses on orographic fog collection have been carried out in Nepal, but higher peak fog collection rates.

Like the Nepalese experiment (Pathivara Temple, Macquarrie et al., 2001), the study site of El Churo is at a relatively high altitude (3334 m a.s.l.) and represents one of the highest altitude experiments of fog collection known (Fessehaye et al., 2012, cfr. Figure 3). The characteristic of an elevated altitude may thus be one common feature of optimal inland fog collection sites.

Moreover, unlike many cases where fog occurrence and/or fog collection rates are heavily dependent on seasonality, with an actual “fog season” (Carvajal et al., 2022; Certini et al., 2019; Fessahaye et al, 2015), fog collection in Valles Cruceños is relatively stable along the year (figure 3). Furthermore, given the specificity, and the relatively clear identifiability of El Churo station as the best one for fog collection in Valles Cruceños (high elevation facing the Amazon basin on a north-east sloping area, taking advantage of fog moved easterly from the continent), it can be inferred that similar locations could represent potential optimal sites for fog collection in Bolivia, and more in general in Eastern Andes.

In the framework of an expansion of fog collection in the study area, it should be noticed that fog volumes analyzed in the present study were collected using the standard Raschel mesh. Such mesh has proven to be very efficient in fog collection for wind velocities below 1 m/s, while for velocities higher than 5 m/s other fog nets (such as the modern FogHa-Tin 3D mesh) have been proven to be more performant (Fernandez et al., 2018). Further analysis could be needed to identify the best mesh for the local condition of Bolivian East Andes, since average wind velocities stand in the middle of the range presented by Fernandez et al. (table 3). To further develop a rural development approach based on fog collection, ICO Bolivia and Zabalketa started a new project, funded by Munich ReFoundation, in 2019, aimed at testing the impact of novel "CouldFisher" fog collectors, produced by Aqualonis (http://www.munichre-foundation.org/en/Water/Fog_nets_in_Bolivia_Scouting_the_best_locations.html) which shows an overall better performance in terms of fog collection with reference to other type of meshes (Schunk et al., 2018). The results of the project, however, will have to be benchmarked with the highest costs of engineered and advanced fog collection meshes, such as the "CouldFisher" ones, that could undermine the economic sustainability of new interventions.

5.2 Fog-based irrigation system

Considering that 40 m^2 of crop can be sufficient for the basic need of a Bolivian family of four (FAO-TCP, 2006), one LFC with 8 m^3 of water storage tank can guarantee food security during dry periods to around three families. Vegetable gardens contribute significantly to food security, both as a supplementary source of food products or as a source of supply during the non-productive season or when there is no growth. In terms of economic costs one LFC cost may range from $ 1200 to $ 2400 with an expected lifespan on the fog collector system of an average of 10 years (Manzoor et al., 2018), while the purchase of the tank is considered at an indicative cost of $ 2000 and the drip irrigation system around $ 300 for the full plot. Therefore, the costs can be considered of $ 350 - $ 470 per year equal to $ 117 - $ 157 per family per year.

Since the austral winter is the season with lowest temperatures recorded, the limitation of this approach consists in the temperature requirements for selected crops. The worst example is the minimum temperature requirement for Tomato, equal to 15 °C, with an optimum range of temperature between 15 -25 °C (Witter and Aung, 1969), while the average temperature in El Churo during the austral winter is of 10 °C, reaching a minimum temperature of 2 °C.

In this framework, appropriate technologies such as mud-brick greenhouses could solve the problem. Greenhouse projects have already proven good results in El Alto (Bolivia), that has climatic conditions like Valles Cruceños, where FAO and El Alto's municipal government aimed at promoting the year-round production of vegetables in family gardens made of mud-brick greenhouses. The project showed that the temperature inside greenhouses was normally 10 °C higher than outside, and that El Alto familes could cultivate tomato, lettuce and paprika (FAO, 2014). Another project carried by Agence Française de Développement (AFD) can confirm the effectiveness of greenhouses in Bolivian Altiplano near La Paz (https://www.afd.fr/fr/actualites/grand-angle/la-serre-qui-libere-laltiplano?origin=/fr/actualites?field_date_value=&field_date_value_1=&field_type_target_id=All&field_region_country_target_id%5B%5D=177&field_theme_target_id=All&items_per_page=5). It should be noticed that crops cultivated in a greenhouse may have different crop water requirements with respect to those calculated for open cultivation. However, despite the increase of temperature, in a greenhouse wind is absent and air humidity is higher, resulting in a decrease of crop water requirements (Gong et al., 2020). Therefore, the implementation of greenhouses may further result in a decrease of water demand.

Fog collection has often been used for irrigation, mainly for reforestation projects (Certini et al., 2019), but also for agricultural production using drip irrigation (Fessaye et al., 2014). In these latter applications, fog water quality is often the main concern, often hampered by the passage of fog masses over areas with high air pollution given by anthropic activities (Sträter et al. 2010). The study area of Valles Cruceños should be tested for fog water quality. However, the issue could be limited by the fact that fog occurring in the area is generated and moves over the Amazon biota.

In any case, for successful fog-water based irrigation, it is fundamental to have a solid community-based management structure as in the case of the “El Tofo” system in Chile (Correggiari et al., 2017). Key elements of the fog system implementation should be: the full community involvement (since the beginning of the project), the establishment of a management committee, the training of such committee and appropriate economic and financial planning (Correggiari et al., 2017).

6. Conclusions

The present study highlights the practical feasibility of fog collection in Southern Bolivian region of Valles Cruceños, situated on the Eastern Andean escarpment. Rather than advection fog, orographic fog typically occurs in the region and can be collected, driven by easterly inland winds. The study sites thus represent a remarkable example of geographical setting allowing inland fog collection, like some case studies in Nepal, but with relatively lower fog collection rates.

Our experiment showed that at least 3-4 locations in Valles Cruceños could be suitable for fog collection, with a peak in El Churo station showing, on annual basis, an average of 6.01 $l/m^2/d$, with peaks up to 8.93 $l/m^2/d$. The ideal geographical locations for fog collection in the region are the ones situated at an elevation of around 3000 m a.s.l., but situated on north-east oriented slopes, facing the Amazon basin. Similar geographical settings could have the potential for fog collection implementation not only in Bolivia, but in the whole Eastern Andean escarpment. Fog occurrence, moreover, show a peak 3 to 4 months after the rainy season, allowing the collection of larger fog volumes in the dry season.

Starting from these values, our analysis shows that the development of a fog harvesting irrigation system in Valles Cruceños could promote food security and food sovereignty, allowing the families of small and medium producers to access means of sustainable life especially during the austral winter, a season characterized by low temperatures and scarce rainfall. The present study represents the first research on fog collection in Bolivia, and can be scaled up for analyzing new fog collection sites, for further testing water quality, or for have a larger planning of fog-based irrigation in the area of study, fostering food sovereignty and security. In the present paper suitable sites were pre-selected by a local NGO and the sole fog water collection potential was analyzed as suitability indicator, but further studies could also aim at integrating the agricultural cultivation potential of each site, besides fog productivity.

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References

Allen, R. G., Pereira L. S., Raes D., Smith M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.

Austin, M.P., 1987. Models for the analysis of species’ response to environmental gradients. In: Prentice I.C., van der Maarel E. (eds) Theory and models in vegetation science. Advances in vegetation science, vol 8. Springer, Dordrecht https://doi.org/10.1007/978-94-009-4061-1_4

Bresci, E., 1998. Fog collectors capturing spatial variability. 1st International Conference on Fog & Fog Collection. Vancouver, Canada, 19-24 July 1998. IDRC, pp. 465-468.

Cantini, F., Castelli, G., Foderi, C., Salazar Garcia, A., López de Armentia, T., Bresci, E., Salbitano, F., 2019. Evidence-Based Integrated Analysis of Environmental Hazards in Southern Bolivia. Int. J. Environ. Res. Public Health. https://doi.org/10.3390/ijerph16122107

Carvajal, D., Mora-Carreno, M., Sandoval, C., Espinoza, S., 2022. Assessing fog water collection in the coastal mountain range of Antofagasta, Chile. J. Arid Env. 198 (2022) 104679.

Castelli, G., Foderi, C., Guzman, B.H., Ossoli, L., Kempff, Y., Bresci, E., Salbitano, F., 2017. Planting waterscapes: Green infrastructures, landscape and hydrological modeling for the future of Santa Cruz de la Sierra, Bolivia. Forests 8. https://doi.org/10.3390/f8110437

Certini, G., Castelli, G., Bresci, E., Calamini, G., Pierguidi, A., Villegas Paredes, L.N., Salbitano, F., 2019. Fog collection as a strategy to sequester carbon in drylands. Sci. Total Environ. 657, 391–400. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.12.038

Cereceda, P., Osses, P., Larrain, H., Farías, M., Lagos, M., Pinto, R., Schemenauer, R.S., 2002. Advective, orographic and radiation fog in the Tarapacá region, Chile. Atmos. Res. 64, 261–271. https://doi.org/10.1016/S0169-8095(02)00097-2

Copernicus Climate Change Service (C3S), 2017. ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). https://cds.climate.copernicus.eu/cdsapp#!/home .

Cantini, F., Castelli, G., Foderi, C., Salazar Garcia, A., López de Armentia, T., Bresci, E., Salbitano, F., 2019. Evidence-Based Integrated Analysis of Environmental Hazards in Southern Bolivia. Int. J. Environ. Res. Public Health. 16(12), 2107 https://doi.org/10.3390/ijerph16122107

Estrela, M.J., Valiente, J.A., Corell, D., Millán, M.M., 2008. Fog collection in the western Mediterranean basin (Valencia region, Spain). Atmos. Res. 87, 324–337. https://doi.org/https://doi.org/10.1016/j.atmosres.2007.11.013

Estrela, M.J., Corell, D., Valiente, J.A., Azorin-Molina, C., Chen, D., 2019. Spatio-temporal variability of fog-water collection in the eastern Iberian Peninsula: 2003–2012. Atmos. Res. 226, 87–101. https://doi.org/10.1016/j.atmosres.2019.04.016 .

FAO, 2014. Growing greener cities in Latin America and the Caribbean. A FAO report on urban and peri-urban agriculture in the region. http://www.fao.org/3/a-i3696e.pdf

FAO, 2015. AQUASTAT Perfil de País - Bolivia (Estado Plurinacional de).

FAO - Technical Cooperation Programme (TCP), 2006. Project Promotion of home gardens for improved nutritional well-being TCP/LAO/2902 (A). http://www.fao.org/3/a-ag101e.pdf

FAO-GIEWS (Global Information and Early Warning System) 2020. Country Brief Bolivia http://www.fao.org/giews/countrybrief/country.jsp?code=BOL

Fernandez, D.M., Torregrosa, A., Weiss-Penzias, P.S., Zhang, B.J., Sorensen, D., Cohen, R.E., McKinley, G.H., Kleingartner, J., Oliphant, A., Bowman, M., 2018. Fog water collection effectiveness: Mesh intercomparisons. Aerosol Air Qual. Res. 18, 270–283. https://doi.org/10.4209/aaqr.2017.01.0040 .

Fessehaye, M., Abdul-Wahab, S.A., Savage, M.J., Kohler, T., Tesfay, S., 2015. The Potential for Scaling Up a Fog Collection System on the Eastern Escarpment of Eritrea. Mt. Res. Dev. 35(4), 365-373. https://doi.org/10.1659/mrd-journal-d-15-00013.1 .

Franceschetti G., 2000. The use of fog as a new water resource: possible applications. UNIPRESS, Padova, Italy.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066.

Garcia, M., Raes, D., Jacobsen, S.E., Michel, T., 2007. Agroclimatic constraints for rainfed agriculture in the Bolivian Altiplano. J. Arid Environ. 71, 109–121. https://doi.org/10.1016/j.jaridenv.2007.02.005 .

Garreaud, R., 1999. Multiscale Analysis of the Summertime Precipitation over the Central Andes. Mon. Wea. Rev., 127, 901–921. https://doi.org/10.1175/1520-0493(1999)127<0901:MAOTSP>2.0.CO;2 .

Garreaud, R., 2009. The Andes Climate and Weather. Adv. Geosci. 22. 3-11. https://doi.org/10.5194/adgeo-22-3-2009 .

Gobierno Departamental Autónomo de Santa Cruz, 2009. Plan de manejo area natural de manejo integradorio Rio Grande Valle Cruceños. Santa Cruz – Bolivia.

Gong, X., Wang, S., Xu, C., Zhang, H., Ge, J., 2020. Evaluation of several reference evapotranspiration models and determination of crop water requirement for tomato in a solar greenhouse. HortScience 55, 244–250. https://doi.org/10.21273/HORTSCI14514-19

Ibisch P.L., Mérida G., 2013. Biodiversidad: La Riqueza de Bolivia. Estada en Conocimiento y Conservación; Fundación Amigos de la Naturaleza, Ed. FAN (Fundación Amigos de la Naturaleza): Santa Cruz de la Sierra, Bolivia.

Instituto Nacional de Estadística (INE) 2012. Censo Población y Vivienda 2012 Bolivia. La Paz, Bolivia.

Instituto Nacional de Estadística (INE) 2013. Censo Agropecuario 2013 Bolivia. La Paz, Bolivia.

Kaseke, K.F., Wang, L., 2018. Fog and dew as potable water resources - maximizing harvesting potential and water quality concerns. GeoHealth 2, 327-332.

Klemm, O., Schemenauer, R.S., Lummerich, A., Cereceda, P., Marzol, V., Corell, D., Van Heerden, J., Reinhard, D., Gherezghiher, T., Olivier, J., Osses, P., Sarsour, J., Frost, E., Estrela, M.J., Valiente, J.A., Fessehaye, G.M., 2012. Fog as a fresh-water resource: Overview and perspectives. Ambio 41, 221–234. https://doi.org/10.1007/s13280-012-0247-8 .

Latrubesse, E.M., Stevaux, J.C., Cremon, E.H., May, J.-H., Tatumi, S.H., Hurtado, M.A., Bezada, M., Argollo, J.B., 2012. Late Quaternary megafans, fans and fluvio-aeolian interactions in the Bolivian Chaco, Tropical South America. Palaeogeogr. Palaeoclimatol. Palaeoecol. 356–357, 75–88. https://doi.org/https://doi.org/10.1016/j.palaeo.2012.04.003

Macquarrie K.I.A., Pokhrel A., Shrestha Y., Osses P., Schemenauer R.S., Vitez F., Kowalchuk, K., Taylor, R., 2001. Results from a high elevation fog-water supply project in Nepal. In: Proceedings of the 2nd international conference on fog and fog collection, pp. 227–229.

Manzoor, Q., Jiménez, G., Farnum, R., Dodson, L., Smakhtin, V., 2018. Fog Water Collection: Challenges beyond Technology. Water 2018, 10, 372. https://doi.org/10.3390/w10040372

Molina, J.M., Escobar, C.M., 2008. Fog collection variability in the Andean mountain range of southern Colombia. Die Erde 139, 127–140.

Rivera, J.D.D., Lopez-garcia, D., 2015. Mechanical characteristics of Raschel mesh and their application to the design of large fog collectors. Atmos. Res. 151, 250–258. https://doi.org/10.1016/j.atmosres.2014.06.011

Satgé, F., Hussain, Y., Xavier, A., Zolá, R.P., Salles, L., Timouk, F., Seyler, F., Garnier, J., Frappart, F., Bonnet, M.P., 2019. Unraveling the impacts of droughts and agricultural intensification on the Altiplano water resources. Agric. For. Meteorol. 279, 107710. https://doi.org/10.1016/j.agrformet.2019.107710 .

Schemenauer, R.S, Cereceda, P., 1991. Fog-water collection in arid coastal locations. Ambio, 20, 303–308.

Schemenauer R.S., Cereceda P., 1994. A proposed standard fog collector for use in high-elevation regions. J Appl Meteorol Climatol., 33, 1313–1322. https://doi.org/10.1175/15200450(1994)033<1313:APSFCF>2.0.CO;2 .

Schunk, C., Trautwein, P., Hruschka, H., Frost, E., Dodson, L., Derhem, A., Bargach, J., Menzel, A., 2018. Testing water yield, efficiency of different meshes and water quality with a novel fog collector for high wind speeds. Aerosol Air Qual. Res. 18, 240–253. https://doi.org/10.4209/aaqr.2016.12.0528

Smith, M. 1992. CROPWAT- A computer program for irrigation planning and management, FAO land and Water Development Division Food and Agriculture Organization of the United Nations, Rome, Italy.

Sträter, E., Westbeld, A., Klemm, O., 2010. Pollution in coastal fog at Alto Patache, Northern Chile. Environ. Sci. Pollut. Res. 17, 1563–1573. https://doi.org/10.1007/s11356-010-0343-x

UN, 2020. World Population Prospects 2019. https://population.un.org/wpp/

UN-Water, 2020: UN-Water Analytical Brief on Unconventional Water Resources. Geneva, Switzerland.

Vuille M. (1999) Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the southern oscillation. International journal of climatology, Int. J. Climatol. 19: 1579–1600

Witter S.H., Aung L.H., 1969. Lycopersicon esculentum Mill. In: L.T. Evans (Editor), the Induction of Flowering. Macmillan of Australia. https://doi.org/10.1016/0304-4238(77)90074-7 .

World Bank, 2008. Climate Change Aspects in Agriculture. Bolivia country note.

World Weather Online, 2020. https://www.worldweatheronline.com/vallegrande-weather-averages/santa-cruz/bo.aspx

Zabalketa, 2008. Establecimiento de reservas comunales para la conservación y gestión de fuentes de agua. Asociacion ZABALKETA de Cooperación y Desarrollo, Getxo – Bizkaia, Spain. https://zabalketa.org/archivos/publicaciones/libro-reservas-comunales-conservacion-gestion-fuentes-agua.pdf

Zabalketa, 2014. EXPERIENCIAS DE CAPTACIÓN DE AGUA DE NIEBLA PARA REFORESTACIÓN. Investigación de campo en territorios con escasez pluvial de Bolivia y Perú. Asociacion ZABALKETA de Cooperación y Desarrollo, Getxo – Bizkaia, Spain.

Zabalketa, 2016. Cuaderno ZABALKETA 01: Análisis del contexto y de la problemática del agua. Proyecto educativo “Derecho Humano al Agua y al Saneamiento, y Transformación Social en Bizkaia”. Asociacion ZABALKETA de Cooperación y Desarrollo, Getxo – Bizkaia, Spain.

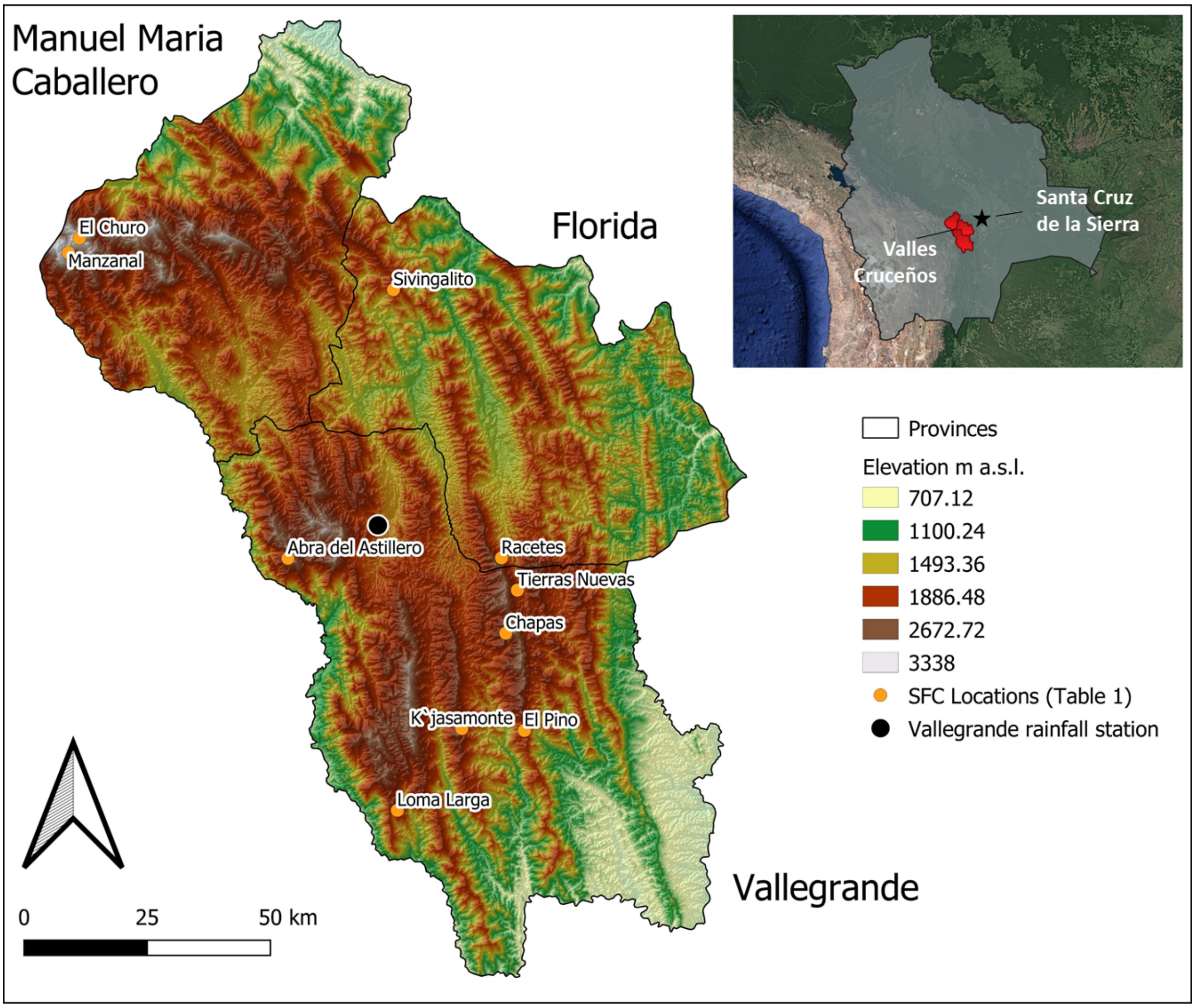

Figure 1. Study area and location of experimental sites

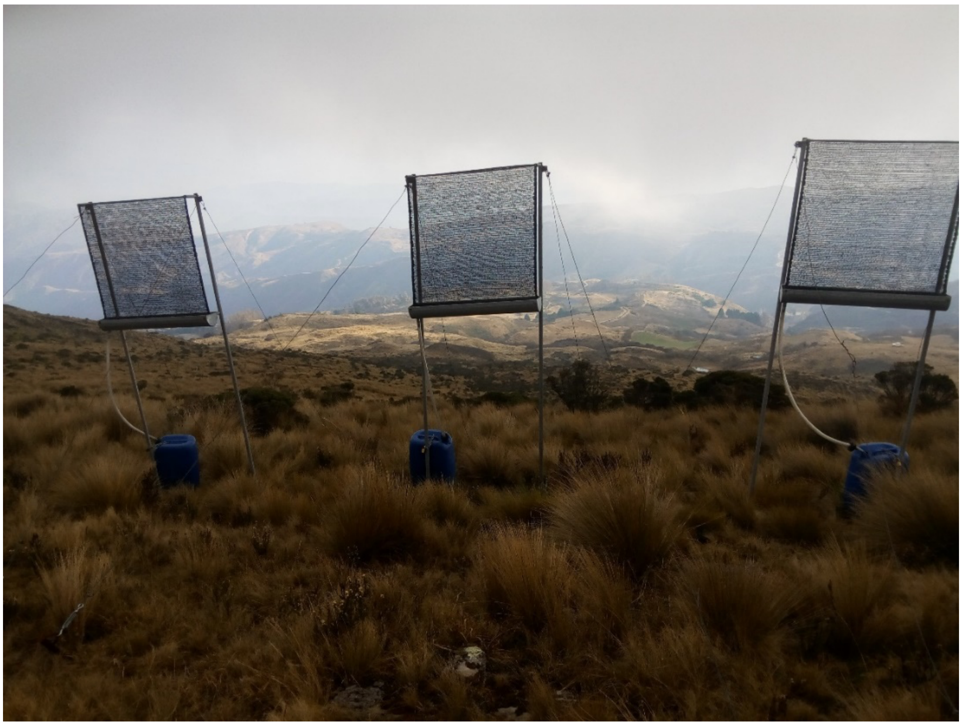

Figure 2. Experimental set up (fog collectors)

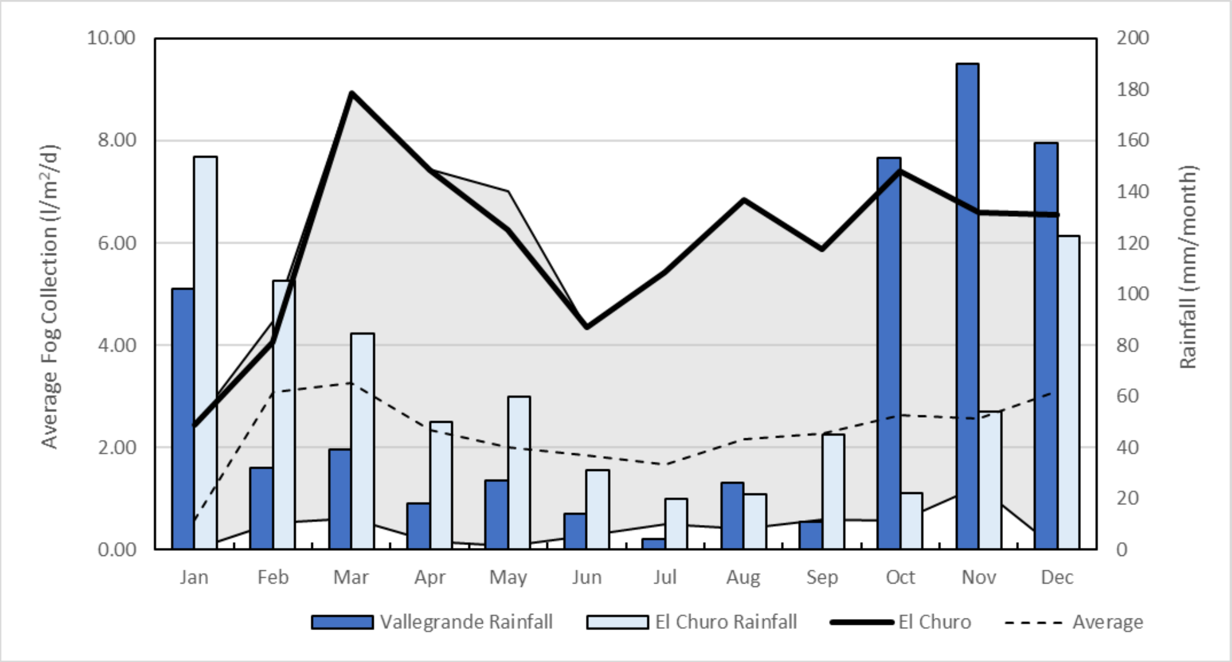

Figure 3. Fog water collection and rainfall data (2018). The graph includes the values for El Churo (3330 m a.s.l.), the fog collection average calculated across all stations, the span between the minimum and maximum value of fog collection observed across all the stations (grey area). Rainfall data were gathered from Vallegrande (World Weather Online, 2020) and El Churo (CHIRPS dataset, Funk et al., 2015).

Table 1. Location of experimental sites

N°	Locations	Latitude S	Longitude W	Elevation (m a.s.l.)
1	Abra del Astillero (Astillero)	18°24’	64°21’	2595
2	Chapas	18°32’	63°56’	2608
3	El Churo	17°48’	64°45’	3334
4	El Pino	18°72’	63°90’	922
5	K’jasamonte	17°26’	64°01’	420
6	Loma Larga	18°52’	64°09’	2234
7	Manzanal	17°50’	64°46’	3071
8	Racetes	18°24’	63°56’	2131
9	Sivingalito	17°54’	64°09’	2091
10	Tierras Nuevas	18°27’	63°55’	2133

Table 2. Monthly and annual average fog water collection in the study sites (l/m^2/d), for the year 2018. * indicates dry period in study area.

	Astillero	Chapas	El Churo	El Pino	K’jasamonte	Loma Larga	Manzanal	Racetes	Sivingalito	Tierras Nuevas	Max	Min
Jan	0.00	0.00	2.44	1.17	1.18	0.68	0.00	0.00	1.88	0.00	2.44	0.00
Feb	3.00	1.01	4.06	4.47	4.32	2.91	3.33	0.51	3.83	3.09	4.47	0.51
Mar	0.61	1.46	8.93	7.30	3.04	2.35	1.37	0.95	5.07	1.33	8.93	0.61
Apr*	0.30	5.31	7.43	3.79	1.42	1.05	0.99	0.16	2.65	0.18	7.43	0.16
May*	0.07	1.64	6.27	7.01	1.41	0.20	1.25	0.36	1.50	0.29	7.01	0.07
Jun*	0.42	3.20	4.34	3.19	1.48	0.85	1.20	0.36	3.03	0.27	4.34	0.27
Jul*	0.49	2.42	5.43	1.53	0.59	0.75	0.53	0.58	3.76	0.57	5.43	0.49
Aug*	0.42	3.32	6.84	1.51	1.01	0.94	0.48	0.80	5.46	0.75	6.84	0.42
Sep	0.60	3.20	5.86	2.83	0.88	1.18	0.73	1.43	3.34	2.67	5.86	0.60
Oct	0.65	2.50	7.40	2.04	0.76	3.92	0.56	2.69	4.20	1.99	7.40	0.56
Nov	2.83	3.09	6.59	2.89	1.29	1.59	1.24	2.06	2.87	1.54	6.59	1.24
Dec	1.97	4.21	6.55	0.00	3.22	1.39	1.30	0.76	6.33	2.23	6.55	0.00
Average (Standard deviation)	0.95 (1.00)	2.61 (1.38)	6.01 (1.67)	3.14 (2.14)	1.72 (1.11)	1.49 (1.02)	1.08 (0.79)	0.89 (0.77)	3.66 (1.38)	1.24 (1.01)		

Appendix

Figure A1. Relative position of El Churo and Manzanal stations (Google Earth)

Table A1. Average monthly wind velocity in the study sites (m/s) in 2018.

	Astillero	Chapas	El Churo	El Pino	K’jasamonte	Loma Larga	Manzanal	Racetes	Sivingalito	Tierras Nuevas
Jan	0.89	0.56		3.36	3.36	0.81			3.36	
Feb	0.85	1.12	1.67	1.17	1.17	0.64	1.67	1.12	3.60	1.12
Mar	1.20	1.48	2.56	2.39	2.39	0.88	2.56	0.72	2.10	0.72
Apr	0.76	1.15	3.14	2.61	2.62	0.62	3.14	0.70	2.27	0.70
May	1.24	1.39	2.91	1.95	1.95	0.71	2.91	1.33	3.30	1.33
Jun	1.24	1.65	2.97	2.84	2.84	0.73	2.97	0.39	3.00	0.39
Jul	1.48	1.41	3.05	2.78	2.78	0.85	3.06	1.09	2.98	1.09
Aug	1.41	1.40	3.07	2.92	2.92	1.10	3.07	1.05	2.98	1.05
Sep	1.32	1.45	3.18	1.41	1.41	0.92	3.18	1.07	2.62	1.07
Oct	1.06	1.26	2.18	2.10	2.10	0.83	3.27	0.87	2.88	0.87
Nov	1.21	1.19	3.15	2.07	2.07	0.75	3.15	0.97	2.46	0.97
Dec	1.17	1.11	2.64	1.82	1.82	1.02	2.64	0.86	2.93	0.86
Average (Standard Deviation)	1.15 (0.22)	1.28 (0.27)	2.79 (0.48)	2.33 (0.63)	2.33 (0.63)	0.80 (0.13)	2.90 (0.45)	0.93 (0.26)	2.87 (0.44)	0.93 (0.26)

Table A2. Irrigation system water balance

Month	$Q_{fog,I}$ ($l/m^2/d$)	$d_{irr,I}$ (mm/d)	$Q_{in,i}$ (m^3/month)	$Q_{out,i}$ (m^3/month)	V_i (m^3)
Original data					
Mar-18	8.93	0	11.7	0	8.0
Apr-18	7.43	0.6	9.4	2.4	8.0
May-18	6.27	1.5	8.2	6.2	8.0
Jun-18	4.34	2.6	5.5	10.4	3.1
Jul-18	5.43	2.1	7.1	8.7	1.5
Aug-18	6.84	0.7	9.0	2.9	7.6
Fog input -5%					
Mar-18	8.48	0	11.1	0	8.0
Apr-18	7.05	0.6	8.9	2.4	8.0
May-18	5.95	1.5	7.8	6.2	8.0
Jun-18	4.12	2.6	5.2	10.4	2.8
Jul-18	5.16	2.1	6.8	8.7	0.9
Aug-18	6.50	0.7	8.5	2.9	6.5
Fog input -10%					
Mar-18	8.04	0	10.5	0	8.0
Apr-18	6.68	0.6	8.5	2.4	8.0
May-18	5.64	1.5	7.4	6.2	8.0
Jun-18	3.91	2.6	5.0	10.4	2.6
Jul-18	4.89	2.1	6.4	8.7	0.3
Aug-18	6.16	0.7	8.1	2.9	5.4
Fog input -20%, Tank 10 m^3					
Mar-18	7.14	0	9.4	0	9.4
Apr-18	5.94	0.6	7.5	2.4	10.0
May-18	5.01	1.5	6.6	6.2	10.0
Jun-18	3.47	2.6	4.4	10.4	4.0
Jul-18	4.35	2.1	5.7	8.7	1.0
Aug-18	5.47	0.7	7.2	2.9	5.3