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Prospective use of collected fog water in the restoration of degraded burned areas under dry Mediterranean conditions

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ABSTRACT

A mountainous plot located in the interior of the Valencia region (east coast of the Iberian Peninsula) was identified for reforestation using the fog-water collection potential prevailing in the area. Fog data were obtained by means of an instrument ensemble consisting of a passive cylindrical fog-water collector, a rain gauge, a wind direction and velocity sensor and a temperature and humidity probe. Preliminary results gave rise to the additional deployment of a low-cost 18-m^2 flat-panel collector connected to three 1000-l tanks for larger scale fog-water collection and storage. The 2007 annual rate of fog water that could be derived from the instrument ensemble amounted to 3.3 l/m^2/day, which turn out to fill up the storage tanks completely in only 5 months, even though the flat-panel collector could not be operative 100% of the time. The study made use of the *in situ* stored water and a micro-irrigation network to irrigate a plot of reforestation seedlings through small water pulses localized deep in the planting hole during the summer dry period. Until the present, this forest location had always shown a difficult self-recovery due to the high level of land degradation resulting from recurrent forest fires in the past. Results indicate that survival rates and seedling performance of the two species planted, *Pinus pinaster* and *Quercus ilex*, improved with the use of small timely waterings and additional treatments with composted biosolid.

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1. Introduction

The Mediterranean basin, climatologically characterised by dry and hot summers followed by wet and mild winters, presents important problems in relation to water resources. Traditionally, water had been considered a practically unlimited natural resource, and many Mediterranean countries saw it as a permanently supplied product irrespective of season and/or drought variability. In recent years, however, this mentality has changed to the point of recognizing water resources as a valuable good. Population rise, coastal overcrowding, high human consumption, irrigated crop expansion, excessive exploitation of aquifers, among others, are the causes of water scarcity in most of the Spanish Mediterranean coastal regions. According to the Water Framework Directive (Kaika, 2003), i.e. Directive 2000/60/EC of the European Parliament and of the Council of 23rd October 2000, which establishes a framework for Community action in the field of water policy (DOCE L327/1 22.12.2000), excessive exploitation has led to water being considered rather like a heritage which must be protected, defended and treated as such. In Spain, temporary legal

restrictions on water consumption had to be adopted in the summer of 2003 in the regions of Valencia and Murcia and in the summer of 2005 in Andalusia. In fact, the water situation has reached the extreme of establishing a Drought National Observatory as a centre for the monitoring, knowledge, anticipation and mitigation of drought effects in Spain.

The Valencia region, where the study area is located, is situated in the centre of the Spanish Mediterranean coast (Fig. 1). Its annual pluviometric regime ranging from 400 to 600 mm, with a dependence on topography, results in typical conditions for a dry climate (Peñarrocha, 1994) and categorizes the region as belonging to the dry part of Spain. In addition, studies on rainfall modifications due to climate change (Quereda et al., 1996; Montón and Quereda, 1997; Millán et al., 2005a,b) predict a negative trend in precipitation in the southern part of the Iberian Peninsula, more accentuated towards the East and the South. Within this context of water scarcity, the quantification and assessment of any of the inputs in the hydrological system is basic for responsible water management in the framework of a sustainable environment and society. In this line, fog water harvesting has aroused scientific interest for its various applications in Mediterranean areas where water is limited. The coastal regions of eastern Spain meet most of the geographical conditions for fog occurrence and collection potential, as compiled by Schemenauer and Cereceda (1994b). The

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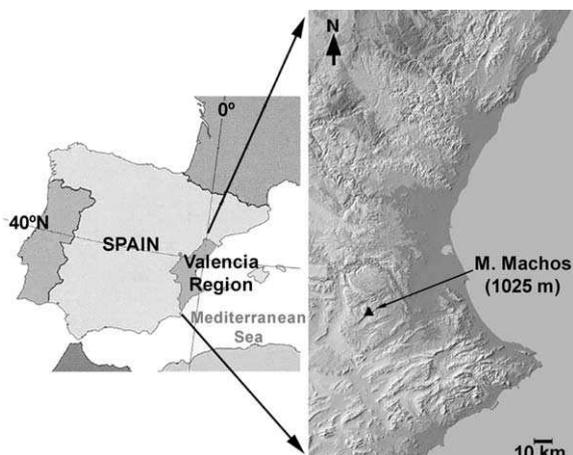 *E-mail address:* josean@ceam.es (J.A. Valiente).

Fig. 1. Geographical situation of the Valencia region and the experimental site.

region features mountain ranges in the proximity of the coastline which rise to altitudes exceeding 500 m and which lie perpendicular to the eastern maritime winds carrying clouds and wet air for the formation of coastal and advected fogs.

For a mountainous site, it is considered that fog collection takes place on a passive device when any type of ground-touching cloud renders either a fog-only or a fog in combination with rainfall episode. Passive fog collectors are not specific to fog in situations where fog and wind-driven rain in the form of drizzle are present simultaneously. This particular situation represents the so-called horizontal precipitation, i.e., the wind-driven horizontally transported component of precipitation together with the horizontally transported fog (Frumau et al., 2007). Vertical structures like passive fog collectors collect both fog-only, if presented alone, and horizontal precipitation when wind-driven drizzle and fog concur. Hereafter, the term "fog collection" will be used to refer to what a passive fog collector actually collects, i.e., it will include situations of horizontal precipitation as well as fog episodes alone. The collector used for the prospective studies features a protective cover on top as recommended by Juvik and Nullet (1995) in order to avoid major interferences caused by rain.

Previous studies in the Valencia region (Millán et al., 1998; Estrela et al., 2004, 2008; Valiente et al., 2007) have quantified the fog water potential at several specific mountain locations. They showed the important role that fog can play in the hydrological system. Fog collection in winter and summer came mostly from the fog contribution alone as the rainfall component is small in these two seasons (Estrela et al., 2008). Conversely, both types of precipitation were more alike in autumn and spring when frontal systems commonly generate a significant amount of both rainfall and fog. Annually, fog collection rates were 2–3 times higher than direct rainfall, which can be interpreted as the fog water potential for these coastal mountain areas.

This good potential for fog-water collection at certain mountain locations has led scientists to consider this new and easily available water as a resource for the reforestation of remote areas where land degradation has occurred after a long history of wildfires. In some areas, native forest vegetation cannot recover by itself and some human intervention is needed. However, reforestation actions carried out in Mediterranean dry or semiarid degraded lands usually show low percentages of seedling establishment and growth rates (Pausas et al., 2004). Water availability is considered the main factor constraining plant performance in these ecosystems (Di Castri et al., 1981; Blondel and Aronson, 1999). Furthermore, rainfall has decreased in the last decades (Maheras, 1988), and summer rainless periods have increased as a consequence (IPCC, 2007). Under these circumstances, the success

of restoration activities in degraded areas is expected to decrease. Vallejo et al. (2000) stated that periods of more than 120 days without significant precipitation (>5 mm) result in mortality rates above 80% in Mediterranean woody species seedlings during the first summer in the field. Shorter drought periods (70–80 days) also show high seedling mortality percentages. As a consequence, it is becoming more common to read about the application of emergency summer waterings in drylands (Rey-Benayas and Camacho, 2004) and various methods for collecting and channelling runoff water have also been shown as efficient techniques to increase survival and productivity (Bainbridge, 2002). Nevertheless, under dry Mediterranean climate, where the water deficit is less severe but the extent and irregularity of the drought periods may constrain the introduced vegetation, the use of these techniques is not so common.

In the reforestation of Mediterranean landscapes, pines and broad-leaved resprouting species (especially oaks) should be combined to take advantage of the complementary features of both groups of species, i.e., the faster growth of pines and the high post-disturbance resilience of oaks (Pausas et al., 2004). Also, improvements in the seedling nutrient status can enhance water use efficiency by reducing water stress and eventually raising seedling survival during extreme drought periods (Querejeta et al., 2008). The use of sewage sludge (biosolids) as a source of organic matter and nutrients in forestry is an old practice in productive systems around the world (Marx et al., 1995) but uncommon in the restoration of degraded lands (Loftin and Aguilar, 1994; Navas et al., 1997). However, several restoration research studies and pilot projects dealing with biosolid application have been carried out in the last decade in the Mediterranean Basin (Querejeta et al., 1998; Larchêvecque et al., 2006; Fuentes et al., 2007).

The present study aims to quantify the survival rates and seedling performance of two forest tree species (*Pinus pinaster* and *Quercus ilex*) planted on a degraded burned Mediterranean site and to see how the outcomes correlate with the application of composted biosolid combined with small timely water pulses localized deep in the planting hole during the summer dry period. Moreover, the irrigation water used is meant to be collected only by passive fog-water collection techniques and stored in high capacity water tanks for the whole length of the experimental campaign. Because the proper installation of the fog-water harvesting system requires some knowledge of the local winds and fog occurrence, complementary environmental sensors were deployed in advance.

2. Materials and methods

A location that fitted most of the above criteria (Mount Los Machos in Fig. 1) was selected in the interior of the Valencia region where appropriate topographic and degradation conditions as well as fog occurrence probability were met. The experimental site can be split into a fog-water catchment area with all the accoutrements necessary for collecting and storing water and a reforestation plot where the collected water is managed for irrigation, with the former being 40 m above the latter for gravitational flow (Fig. 2). The study covers a period of 1 year, 2007.

2.1. Restoration field plot and measurements

The experimental plot is located in an inland mountainous area of the region of Valencia (E Spain) at 60 km from the nearest coastline. It covers an area of about 2500 m^2 at 971 m a.s.l. with a SE-NE exposure and a gentle slope (<10%). The mean annual rainfall and temperature are 406 mm and 12 °C, respectively, and soils are clay-loam. In 1979 a large wildfire burned around 30,000 ha of mixed mature pine forest mainly dominated by
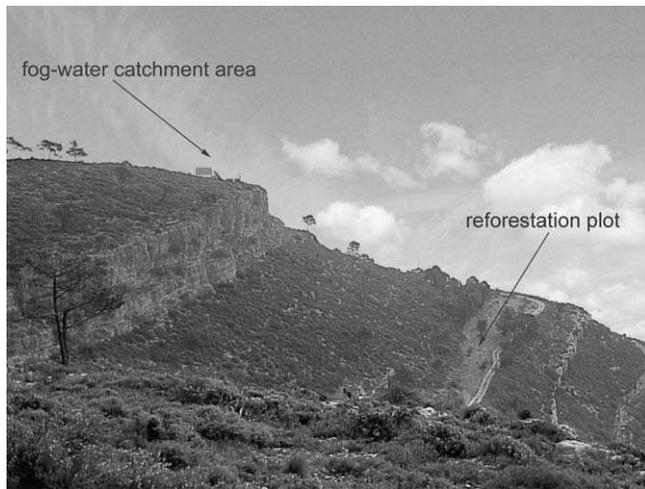
Fig. 2. Experimental site showing the fog-water catchment area at the top and the reforestation plot at the bottom-right of the image.
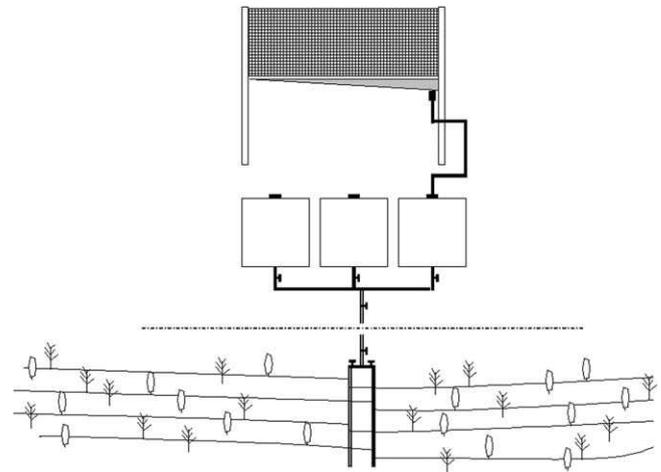

Fig. 3. Irrigation system layout implemented on the fog-water catchment site (top part) and on the reforestation plot (bottom part).

maritime pine (*P. pinaster*) and, to a lesser extent, Aleppo pine (*P. halepensis*). The vegetation recovered after the wildfire with an abrupt change in species dominance and community structure. According to Baeza et al. (2007), who analyzed the pattern of post-fire vegetation recovery in this same area, the community can now be classified as a shrubland with little regeneration of pines and a few adult trees that withstood the fire. Obligate seeder species (*Ulex parviflorus*, *Rosmarinus officinalis*, *Cistus albidus*) dominate the shrubland layer with an important accumulation of fine fuel components and necromass. This puts the area under a very high fire risk (Baeza et al., 2006).

Site preparation was conducted through selective clearing of seeder species using a scrub-clearing machine, leaving the scarce individuals of resprouter species as well as the regenerated pines standing. The slash was left on the surface of the soil as a mulch layer providing beneficial effects in terms of reducing the fire risk and increasing the ecosystem resilience (Valdecantos et al., 2009). The planting holes were mechanically opened with a backhoe excavator at a planting density of 2500 holes per hectare. A total of 620 1-year-old seedlings of *P. pinaster* and *Q. ilex* were planted interspersed in regular intervals within the experimental plot. Each of the seedlings was surrounded with a 40-cm high ventilated plastic treeshelter to avoid predation. The whole plot perimeter was fenced using cattle mesh since shepherding is a common activity in the area.

Water treatments consisted of natural precipitation (control), one or two water pulses of ca. 4.5 l hole^{-1} during summer (W1 and W2, respectively), and rainfall exclusion (W-). One main hose was deployed from the fog-water catchment area to the experimental plot and connected to a manual control head. The difference in elevation between both areas resulted in a water pressure of about 4 atm. Two sublines were then used to provide watering treatments W1 and W2 separately by means of alternating lateral lines along the planting holes (Fig. 3). One pressure compensating emitter of 2 l h^{-1} was placed in each planting hole, except for control and –W treatments, and water was injected to 20–25 cm deep by means of microtubing connected to each emitter. Watering treatments were easily conducted on July 3rd and August 3rd, 2007. A 0.45 m^2 waterproof plastic sheet was deployed over the soil surface of the planting hole in the rainfall exclusion treatment to reduce water input. The plastic sheets were deployed before a rainfall event was expected and retrieved once it finished. The centre of the sheet was slightly uplifted to allow aeration, divert rainfall water, and avoid soil surface overheating. This treatment did not intend to avoid all precipitation but rather to

reduce some of it to mimic future scenarios of climate change which are expected to be more water limited (IPCC, 2007). In half of the planting holes of each treatment, composted sewage sludge from a composting facility in Aspe (Alicante) was applied and mixed *in situ* with the soil at an application rate of 22 t dry weight ha^{-1} (360 g d.w per planting hole). The entire site preparation phase took place from December 2006 to January 2007.

Soil volumetric water content was monitored periodically by Time Domain Reflectometry (TDR Tektronik 1502C Cable Tester, Beaverton, OR, USA) using one vertical set of two probes (0–30 cm depth) in 10 planting holes per treatment. Soil water retention curves (drying path) of four replicates were quantified using a dewpoint hygrometer (WP4, Decagon Devices, Inc., Pullman, WA, USA), which was adjusted with an exponential model. Daily annual rainfall was recorded using a pluviometer (ECH$_2$ORain, Decagon Devices Inc., Pullman, WA, USA) located on the plot at 50 cm above the soil surface. Seedling morphology (total shoot length and basal diameter) of all seedlings was recorded 1 month after planting. Thereafter seedling survival and growth were recorded before and after the first summer after planting.

The estimated soil water potential (Ψ_s) was analyzed by one-way analysis of variance with one fixed factor (Water pulses). Differences between levels were compared by applying Student–Newman–Keuls test (SNK) at 0.05 significance level when ANOVA showed significant effects. Differences in seedling survival between Species, Fertilization and Water pulses were evaluated using log-linear models. Relative growth rates of each species were analyzed by two-way analysis of variance with two fixed factors (Fertilization and Water pulses). Data transformations were performed when necessary to ensure the validity of the assumptions of normality, linearity, and homoscedasticity. All analyses were performed using SPSS software (v. 13.0, SPSS Inc., Chicago, IL, USA).

2.2. Fog-water catchment set-up

Fog water was collected at an elevated site above the reforestation plot. Located over a SW-to-NE valley, the site is on a cliff that drops about 40 m to the reforestation plot and then another 300 m to the valley floor. This site is higher than the surrounding area and meets most of the conditions for fog collection potential. As a first step, a fog instrument ensemble (Estrela et al., 2008), consisting basically of a passive cylindrical fog-water collector, a rain gauge, a wind direction and velocity sensor and a temperature and humidity probe, was deployed in
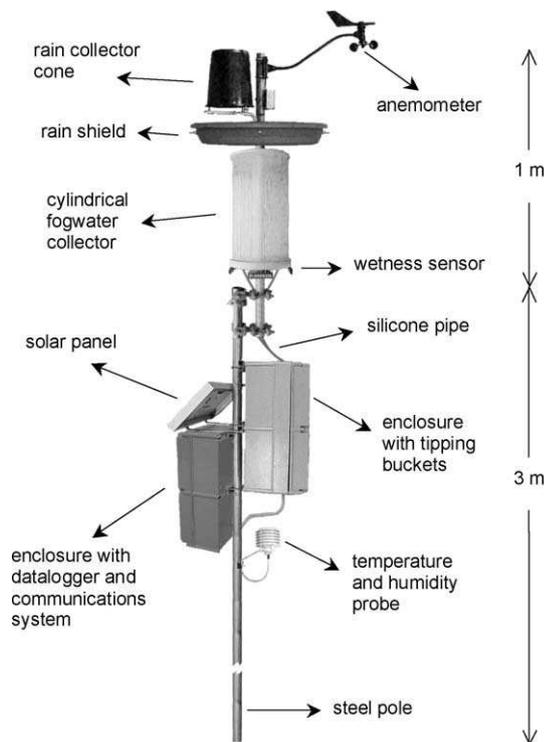
Fig. 4. Instrument ensemble for prospective studies on fog-water collection.

Fig. 5. Low-cost 18-m^2 flat-panel prototype being deployed in the fog-water catchment area.

November 2006 at the fog catchment site (Fig. 4). The rain gauge installed was a magnetic-reed-switch tipping bucket rain collector (Model 7856M of 0.2 mm resolution, Davis Instruments Corp., U.S.A.) which had previously been calibrated at the CEAM headquarters, the wind sensor was an integrated vane-anemometer (Model 7914, Davis Instruments Corp., U.S.A.), and the temperature and humidity sensor was a resistive platinum and capacitive film probe (Model 50Y, Vaisala Oyj, Finland). The fog-water collector is a handmade string array based on the ASRC (Atmospheric Science Research Center, State University of New York) collector which yields omnidirectional collection efficiency (Falconer and Falconer, 1980). Our collector consists of a cylinder, 26 cm in diameter and 46 cm in height, strung with five concentric rows of 0.8 mm thick nylon line. In all, 1000 vertically oriented and closely spaced strings are arranged on a cylindrical polyamide frame, resulting in an effective collection surface of 0.12 m^2 (diameter times height). Fog droplets carried by the wind are intercepted on the vertical nylon strings, form larger drops and then run down the strings. Once water accumulates, it can be conducted through the funnel-shaped collector base and silicon tubing into a magnetic-reed-switch tipping bucket rain collector (Model 7856M of 0.2 mm resolution, Davis Instruments Corp., U.S.A.) for fog-water volume measurements. This rain gauge is previously calibrated at the CEAM headquarters. The collected fog water volume per unit area (l/m^2) is calculated by dividing the collected volume by the effective collection surface of the collector. Additionally, a 60-cm diameter plastic tray carries out the function of a protective cover to avoid major rain interference, as indicated in Juvik and Nullet (1995) for the case of cylindrical collectors. Rain water intercepted by this cover is then drained out of the system, thus preventing the fog-water samples from being partly affected by rain. Apparently, this prevention of rain water reaching the fog samples is not perfect since rain drop trajectories are wind-driven and protection by the cover is limited. The higher the wind speed and/or the smaller the water droplets, the greater the likelihood that rain drops will enter the fog collector. As mentioned earlier, in addition to the fog-only episodes, the term "fog collection" also
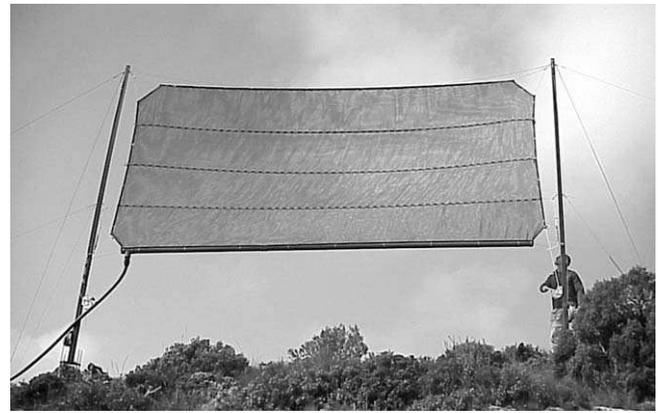
includes these cases of horizontal precipitation. Nevertheless, a rain shield is still necessary for cylindrical collectors to allow similar performance as a flat-panel collector but with the same collecting surface configuration regardless of the wind direction. Comparable ensembles have been employed by other authors, such as Burgess and Dawson (2004), who used a cylinder of louvered aluminium screen measuring 17.8 cm in diameter and 60 cm in height with a 60-cm diameter circular rain shield on top of the collector. The ensemble is to be left in the area to register the environmental conditions present at fog collection in order to obtain information for future activities.

A low-cost flat panel was also built to be installed on the fog-water catchment site in the vicinity of the above instrumental ensemble (Fig. 5). The panel is kept erect by two 5-m long anchored steel poles and is made of a mesh acquired at an agricultural materials store. This mesh is a UV-resistant Raschel woven netting in HD polyethylene monofilament. A double layer of the mesh reinforced with plastic-coated galvanized wire was used to build the net. Final panel dimensions were 6.4 m in width and 2.8 m in length, resulting in a collection surface of 18 m^2. Other hardware elements such as eye nuts, support cables, shackles, snaps, pulleys, braces and winches were purchased at local stores. Their arrangement when supporting the net was tested with a prototype following several models found in Heerden (2004) and Marzol (2005).

The fog-water collection process of the above flat panel is simple. Fog droplets borne by the wind are intercepted on the mesh strings, form larger drops and then flow downward under gravity. The water accumulates into a tilted gutter that has a hole at its lower end which in turn is connected to a hose. All the collected water flows by gravity through pipes to be finally stored in three interconnected 1000-l water tanks (see Fig. 3), with the same water level in each of the tanks. Both the accumulated water volume and the water flow in our experiment were then measured using a level pressure sensor (Model PDCR 1830 Series, GE Druck Limited, UK) which was firmly and permanently maintained at the bottom of one of the tanks. The flat panel was deployed in the field in April 2007 and fixed at an orientation of 55° from North according to the records obtained from the fog instrument ensemble. Maximum fog collection efficiency was then attained with the use of the previously recorded information on wind and fog. Unfortunately, within the deployment period, there were two very strong wind episodes causing a failure of the system for two periods during which fog water harvesting was not possible. The two periods when the flat-panel device became inoperative were: 14–24 May and 30 May–5 June.

The economic expenses at the experimental site, disregarding the fog collection instrumental ensemble and associated electronic

Table 1
Economic analysis of the experimental layout (not adequate at a management scale). Labour is expressed in terms of total amount of hours that one worker needed to manufacture and/or install an item (normally two or even three people were needed for some specific tasks).

Concept	Materials (€)	Labour (h)
Flat-panel collector	977	94
Three 1000-l tanks	720	6
Irrigation network	2832	32

equipment, are found in Table 1. The elements necessary to manufacture the flat panel were purchased at local stores and totalled 977€. Panel construction involved 90 h of labour distributed between two workers, while its field installation required three workers working 8 h each. The most costly aspect was the irrigation network which totalled 2832€ and covered a 2500-m² area, requiring the labour of two workers.

All the useful variables at the fog-water catchment area were automatically acquired by a data logger (Model CR10X, Campbell Scientific Ltd., UK) installed in a weather-proof box on the instrument ensemble. The stored data were transmitted by a GSM communication modem once a day. Sensor sampling was performed at 6-s intervals in the case of the wind sensor and the tipping buckets of the fog and rain sensors, and at 1-min intervals for the rest of the instruments. Data were recorded as 10-min averages of the sampling measurements and sent to a central receiving station where they were additionally converted into hourly values.

3. Results

3.1. Wind statistics and fog collection occurrence

Three different 2007 wind statistics, or wind roses, derived from the instrument ensemble data are given in Fig. 6. While the "all data" wind rose is a typical wind statistic based on the entire set of wind data, the other two wind roses, "fog occurrence" and "fog water volume", result from combining the wind data with either fog collection occurrence or collected fog water volumes. The "fog water volume" wind rose shows the percentage of fog water in the total accumulated volume collected at a certain wind direction and velocity.

The "all data" wind rose shows that the most frequent winds are distributed into two components: a wide component from SSW to NW peaking in the WNW direction, and a marked component peaking between the NE and ENE directions (Fig. 6). For the "fog occurrence" and "fog water volume" wind roses, a single large component that stretches between the NE and ENE directions is observed. Then, the most frequent wind directions in this area do not always coincide with the fog-bearing winds. Notice also how the percentages associated to stronger winds increase in the "fog water volume" wind rose, indicating the relevance of wind velocity in fog-water collection with passive devices. The NE-ENE direction is precisely the valley orientation and also the shortest way to the coastline. As the orientation of the large panel collector surface had to be consistent with the wind patterns found when fog collection occurs, it was set at an angle of 55° from North. This was done to obtain maximum fog water productivity and to lessen the harmful effects that the relatively frequent WNW winds, the strongest in the area, could cause in the flat-panel device.

The annual hourly frequency of fog collection occurrence for 2007, that is, the ratio of 1-h episodes delivering any amount of fog water to the total amount of hours in a year, was 15% according to the data obtained from the instrument ensemble. Similarly, hourly frequencies for 2007 can be defined for each of the 1-h periods of the day. Fig. 7 is a plot of the hourly frequencies for each hour of the
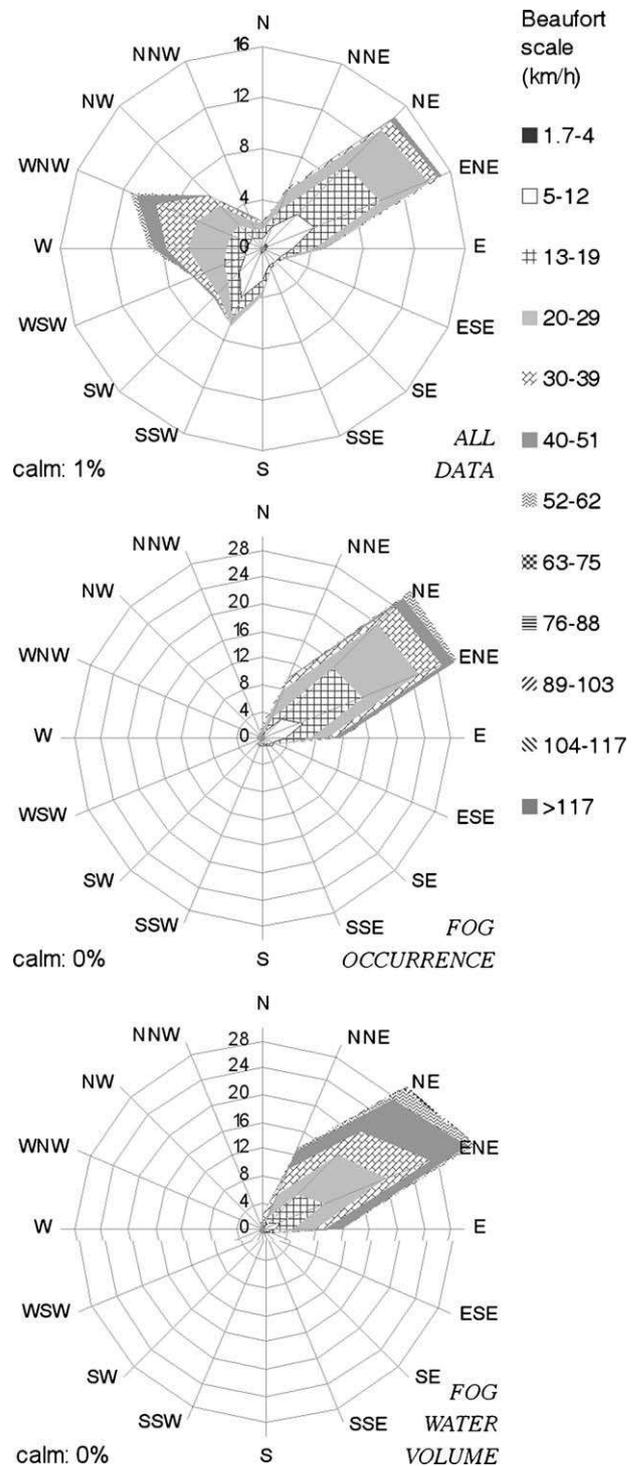

Fig. 6. Wind roses from data registered by the instrument ensemble in the fog-water catchment area for the year 2007. Data values are distributed into 16 wind direction bins and a Beaufort wind velocity scale. Concentric circles correspond to wind frequencies for the set of winds considered, except for the bottom wind rose which represent the percentages of fog water volumes over the annual total collected. The wind rose at the top is derived from the entire set of wind data, the one in the middle uses only wind data with simultaneous fog collection occurrence, and the one at the bottom weighs each wind value according to the water volume yielded at the cylindrical collector.

day and the relative contribution by each of the months. A regular daily cycle is clearly observed; it is slight or inexistent for the period from November to June, but prominent from July to October. For the summer months and the first half of autumn, fog
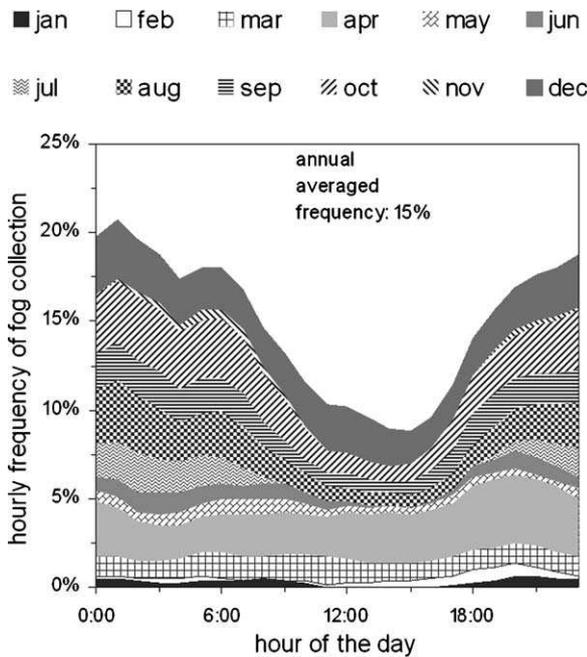
Fig. 7. Hourly frequency of fog collection occurrence for the 2007 data from the instrument ensemble. The total annual frequency of 1-h fog collection episodes is 15%. Each of the patterns represents the monthly contribution to the total annual occurrence.

maximum values develop most frequently during the early morning and are almost inhibited around midday.

3.2. Fog-water collection

Fig. 8 shows the monthly fog collection rates obtained as the ratio of water collected volumes to the length in days of available data for each month. The 2007 annual rate of fog collection, i.e., the average of the monthly values, is 3.3 l/m²/day. This represents a total amount of 1200 l/m² for 2007 in contrast to the annual precipitation amount of around 500 mm collected at the reforestation plot. During the first half of 2007, fog collection showed a steady increase, peaked in April, and then decreased smoothly. In the second half of the year, fog collection presented a greater monthly variability. At our experimental site, fog collection was found to be profitable and inexpensive. Another benefit is the possibility of collecting fog water even in the driest months.

From April to September 2007, the 18-m² flat-panel fog collector was deployed in the field in order to supply the three
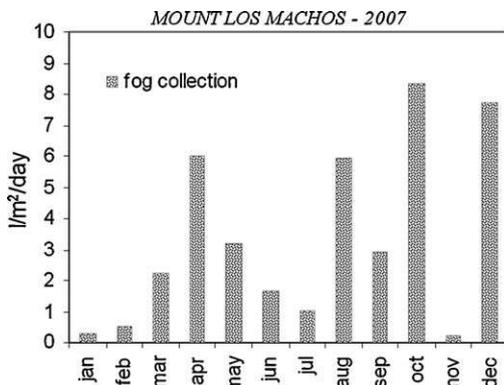

Fig. 8. 2007-monthly rates of fog collection, expressed in l/m²/day. Data from the instrument ensemble.
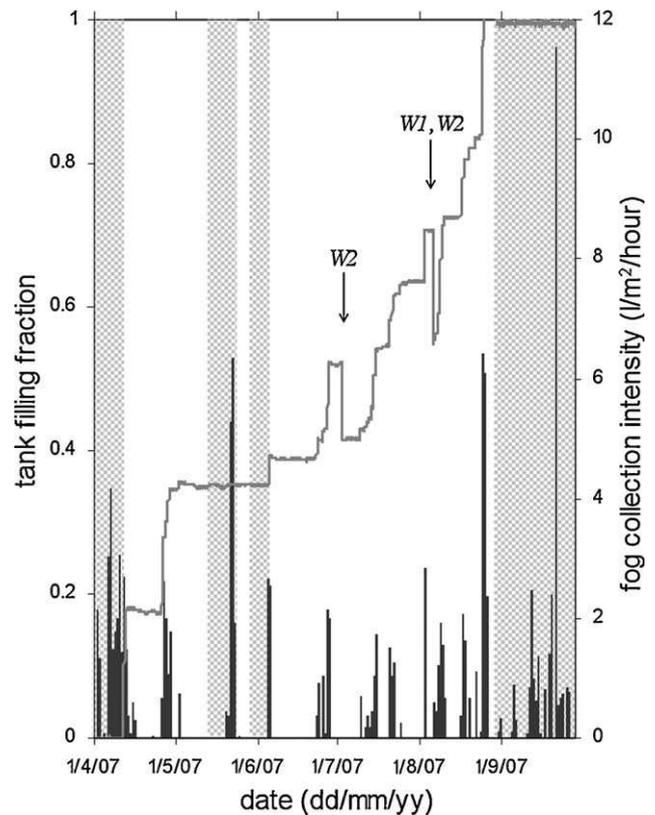

Fig. 9. Time series of tank filling fraction in comparison to fog water collected hourly at the cylindrical collector. Shadow bands correspond to periods when the flat-panel collector was not operative. The two down-facing arrows indicate seedling irrigation dates.

storage tanks with water. Being oriented in the fixed direction of 55° from North, the flat-panel collector attained maximum efficiency according to the initially available wind records from the instrument ensemble. The water level measurement in one of the tanks provided a time series for the tank filling fraction (Fig. 9). The two periods when no measurements were available due to technical problems resulted in a null fog water harvest although fog collection at the cylindrical collector was present (Fig. 9). By September 2007, the three storage tanks were already filled up, and the irrigation campaign had finished successfully. Notice how the fog collection pulses translate into an increase in the filling fraction, the more pronounced the input pulse the steeper the growth. Also, notice the depletion in water level caused by the two waterings.

3.3. Comparison between cylindrical and flat collectors

Tank water fluxes could also be recorded by means of the water level gradients registered on a level pressure sensor (Model PDCR 1830 Series, GE Druck Limited, UK). This flux is in turn the flat-panel fog-water collection rate, so a match-up to an equivalent flux in the cylindrical collector data is now possible for evaluation. Using the wind data and fog-water collection rates registered by the instrument ensemble, the equivalent flux is calculated for the angle direction at which the flat-panel collector is oriented, i.e., 55° from North. The calculation makes use of the projection of the unitary wind vector onto the fixed 55° direction, i.e., the cosine of the angle difference between the registered 10-min wind direction and the flat panel orientation. Equivalent hourly fluxes for the match-up evaluation were constructed using the expression in Eq. (1). The main purpose of the match-up is to evaluate to what degree a conversion of omnidirectional fog-water collection rates
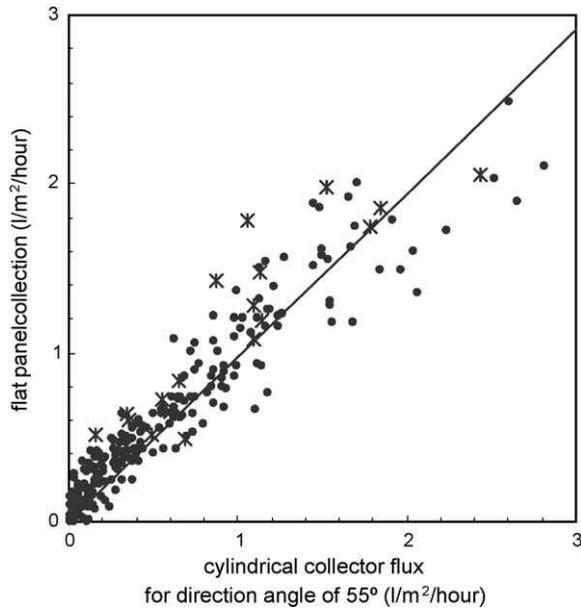
Fig. 10. Scatter plot showing the match-up between flat-panel and cylindrical hourly fog collections, the latter expressed as a flux at the direction of 55° from North. On the y-axis, flat panel fluxes are directly measured by the pressure level sensor. On the x-axis, fluxes are determined by means of Eq. (1) using data from both the cylindrical collector and the wind sensor. The straight line is the regression line fitted to the set of points (y = 0.97x). Asterisks represent the one-hour periods characterized by concurrent fog collection and rainfall detection. Ordinary dots are the one-hour episodes when only fog-water collection was measured.

into specific directional values is possible.

$$\phi_{\mathrm{h}} = \sum_{1\,\mathrm{h}} f_i |\cos(55° - \theta_i)| \qquad (1)$$

where θ_i is a 10-min wind direction expressed in degrees from North, f_i is the fog collection volume registered by the cylindrical collector in a 10-min period, and ϕ_{h} is the equivalent fog-water flux at the 55° direction in a 1-h period.

Fig. 10 contains the match-up that compares the two hourly fluxes during the time periods of flat panel operation. The scattering of flux points is concentrated near the origin of the axes and spreads towards higher values. Obviously, the number of events for which the hourly collection is low is greater than the number for which said collection is high. Nevertheless, a linear tendency can be established as shown by the fitted regression line in the figure. A least square fitting with null constant gave 0.97 for the regression coefficient, with 0.03 as its associated error, thus proving a 1:1 relation within the limits of the estimation error. Hence, if wind direction records in combination with omnidirectional collection rates are available at a temporal resolution of at least 10 min, it is possible to predict directional collection rates, such as those obtained by
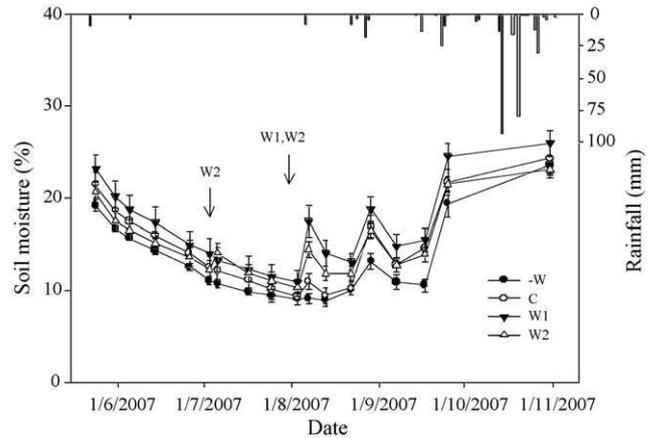

Fig. 11. Soil moisture dynamics (mean and standard error of $n = 10$) and precipitation records from June to November for the first year after planting. Arrows signify water pulses.

flat-panel devices. During the operational time period, the flat-panel collector managed to collect 154 l/m². Moreover, if the data registered by the cylindrical collector is used in Eq. (1), the equivalent collection totals 153 l/m² for the same period. The correspondence between both total amounts is very satisfactory, although a thorough analysis should employ a greater amount of data and several angle projections. Nevertheless, for common applications where the fog-water collection potential using low-cost flat panels needs to be estimated, the methodology presented here is perfectly valid.

3.4. Watering treatments and soil moisture dynamics

The rainfall exclusion conducted in late May and early June (12 mm) did not significantly change soil moisture. The first water pulse (W2) was applied on July 3rd when soil moisture fell below 13% (with an equivalent Ψ of −2.1 MPa). The second pulse (W1 and W2) took place on August 3rd, with a soil moisture of 11.7 and 11.1% (−3.15 and −3.70 MPa) in the W1 and W2 treatments, respectively. The periods without effective precipitation (>5 mm) were 40 and 71 days in the first and second water pulse, respectively. Soil water potential in the W1 and W2 planting holes increased immediately after the water pulses as compared with the −W and control treatments (Fig. 11 and Table 2). The first water pulse (W2) increased soil water content from 13.1 to 14.8%, equivalent to raising soil Ψ from −2.23 to −1.44 MPa (Table 2). Significant differences were found between the W2 and -W treatments, although they later vanished. The second water pulse produced a gradual and significant increase in soil moisture from -W to W1 and W2. These differences remained on all sampling dates, excepting August 22nd. Mean soil water content values for the complete period were 11.2 ± 0.7, 13.2 ± 0.9, 16.2 ± 1.2 and 14.7 ± 0.8% for -W, C, W1 and W2, respectively.

Table 2
Soil water potential (0–30 cm depth) before and after applying the two water pulses 40 (W1) and 71 (W1 and W2) days after no significant rain events (>5 mm) had occurred. We recorded a rain event (8 mm) on day 75, prevented in the rainfall exclusion treatment (-W). Different letters within the same row indicate significant differences ($p < 0.050$, SNK test) between treatments for this length of the dry period.

Length of the dry period (days)	Soil Ψ (MPa)[a]			
	−W	C	W1	W2
40	−2.48 ± 0.33	−2.06 ± 0.43	−1.69 ± 0.35	−2.23 ± 0.29
43	−2.63 ± 0.35 a	−2.20 ± 0.46 ab	−1.80 ± 0.36 ab	−1.44 ± 0.16 b
71	−4.72 ± 0.61	−4.47 ± 0.98	−3.15 ± 0.62	−3.70 ± 0.47
75	−4.39 ± 0.58 a	−2.72 ± 0.54b	−0.98 ± 0.20 c	−1.33 ± 0.15 c

[a] An exponential model was used to fit the relationship between ψ and soil moisture: $\psi = -74.2 + 73.8 * (1 - e^{(-0.32*H)})$
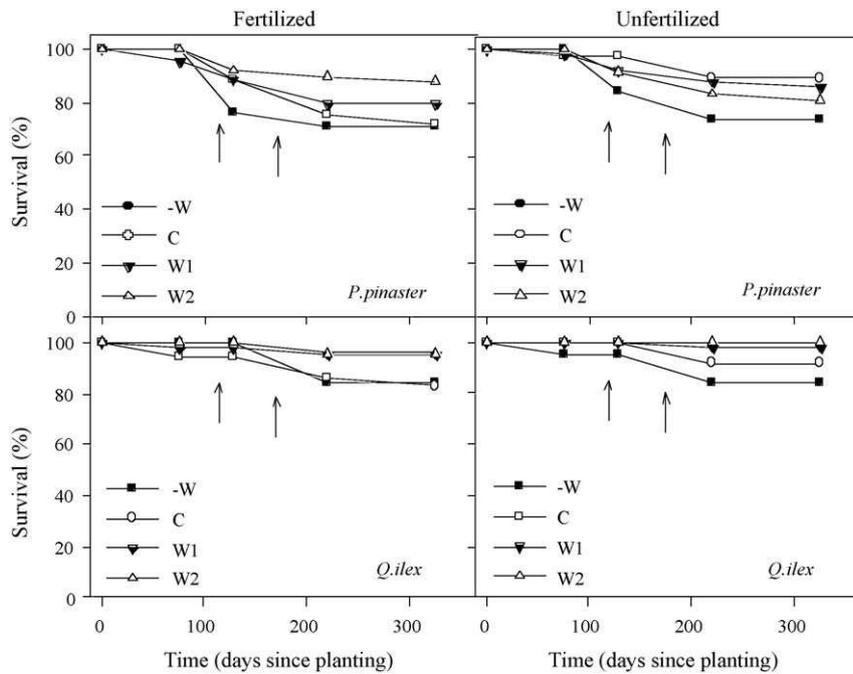
Fig. 12. Dynamics of survival in *Pinus pinaster* (top) and *Quercus ilex* (bottom) seedlings according to water pulses and fertilization treatments. Arrows signify water pulses (both in W2 and only the second one in W1).

Table 3
Summary of the log-linear analyses of 1 year seedling survival. Partitioned likelihood ratio statistic (G) and p values of the log-linear analysis.

Source of variation[†]	df	G	p
Sp	1	20.996	**<0.001**
F	1	3.843	**0.050**
W	1	10.485	**0.015**
Sp × F	3	0.520	0.471
Sp × W	3	4.440	0.218
F × W	3	3.026	0.388
Sp × F × W	3	3.516	0.319

[†] Sp = species, F = fertilization, and W = water pulses.

3.5. Seedling survival and growth

Seedling survival 1 year after planting was above 70 and 80% in maritime pine and holm oak, respectively (Fig. 12). The three factors included in the analysis resulted in significant differences in seedling survival (Table 3). Holm oak survival was significantly higher than maritime pine (93% vs. 81%), and survival with compost application was slightly but significantly higher than in unfertilized seedlings (85% vs. 89%). The water exclusion treatment (-W) showed the lowest survival in both species and fertilization treatments, even before the summer. One year after planting, the
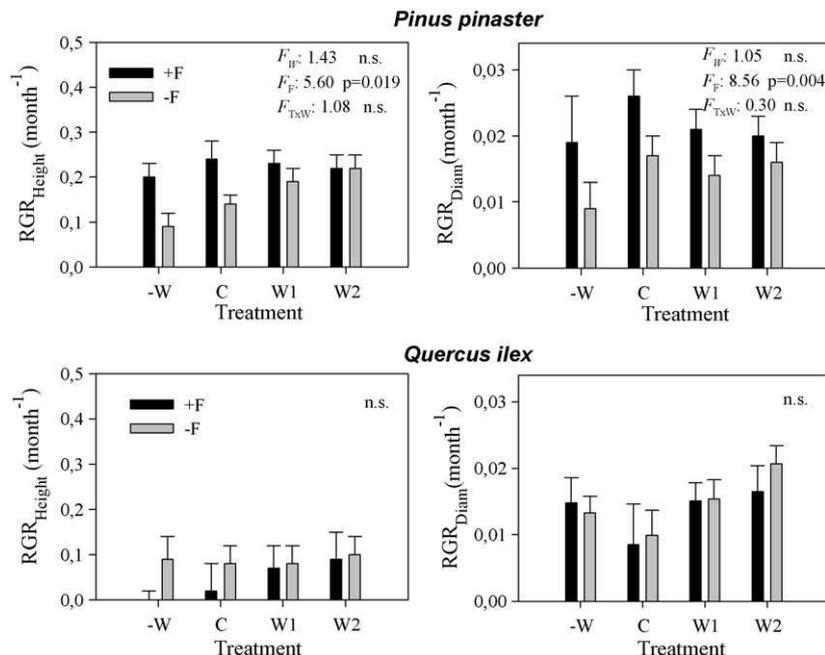

Fig. 13. Relative growth rate (mean and standard error of all surviving individuals) of *P. pinaster* (top) and *Q. ilex* (bottom) seedlings from late spring to winter in relation to Fertilization and Water pulses treatments. F values for the Water pulses (W) and Fertilization (F) factors are shown. n.s. = not significant (*p*-value > 0.05).

mean survival in -W was 78% while in W1 and W2, it was above 90%. Control seedlings showed intermediate values (84%). No interaction between factors was statistically significant (Table 3).

Seedling growth in *P. pinaster* was enhanced by the application of biosolids but not by the changes in water availability (Fig. 13). No interactive effect of water pulses and fertilization was observed but unfertilized pine seedlings showed a trend towards increasing seedling growth as water availability increased. Biosolid-amended seedlings showed no changes in growth patterns with the different watering treatments. *Q. ilex* growth was less sensitive to experimental factors than pine growth. No significant change in either height or basal diameter relative growth rate was recorded.

4. Discussion

Prior to the installation of large fog collectors, an evaluation of the combined wind direction and fog collection is essential to attain a satisfactory performance in bulk fog-water harvesting. The use of a cylindrical collector in prospective studies enables obtaining fog-water collection yields with the same efficiency in all directions. Moreover, the concurrent environmental data registered by the instrument ensemble significantly complement the fog-water collection yields. Thus, quantifying fog-water collection by wind direction with the use of an omnidirectional device makes it possible to determine what type of winds produce the maximum fog water yields. Once the most fog-productive wind direction has been derived, the large flat-panel collector must be installed to face to that direction. Additionally, the present study proposes in Eq. (1) a simple conversion of fog yields from the surveying cylindrical collector into fog water catches from the large flat-panel collector. Former studies (Schemenauer and Cereceda, 1994a) already stated that a linear relationship exists between their widely used flat standard fog collector (SFC) and a cylindrical collector similar to the ASRC one. The outputs from the two collectors were highly correlated for periods of fog, for periods with rainfall and for periods of mixed fog and precipitation. The correlation coefficient for the volumes of water collected by the two systems they encountered was as high as 0.84. However their comparison was made in a period with only slight variations in wind direction and with the flat panel oriented to the prevailing winds. No mechanisms were explicitly provided to transform the total volumes collected by one of the systems into the other. Obviously their SFC was in excellent agreement with the large flat-panel collectors, since both share similar planar geometry. In this present study, a simple methodology has been provided to estimate cumulative large flat-panel collector water catches from data registered at 10-min intervals with the use of a surveying cylindrical collector and an anemometer.

At the experimental site, winds carrying fog are predominantly from the NE-ENE direction. This direction, which coincides with the main valley orientation, is the shortest way to the coastline, 60 km away in a straight line. When fog collection occurs, which on average takes place at an annual hourly frequency of 15%, a daily pattern is observed with minimum collection values at midday and maximum values in the early morning. This behaviour is accentuated for summer and the first-half of autumn, and is slight or inexistent for the rest of the year. Daily fluctuations in the hourly frequency must be due to the development and dissipation of orographic fog since they are associated with the daily changes in air temperature. When the temperature decreases, the water vapour contained in the ascending air can condense and produce fog. These strong oscillations in air temperature are more regular during summer making the relative air humidity become frequently high at night but low during the daytime. Conversely, advected fogs normally caused by frontal systems render a non-dependent time pattern.

Summer fog-water collection is still present at a minimum rate of, at least, 1 l/m²/day. With an annual fog water rate of 3.3 l/m²/day for 2007, the experimental site can be classified as having a moderate-to-low potential for fog-water collection. High-ranking sites can yield as much as 9–10 l/m²/day depending on the characteristics of the year (Marzol, 2005; Estrela et al., 2008). Fog-water collection can be useful when a water source is needed in remote locations with clear fog water potential. In summer months with null rainfall, fog collection takes place during periods of fog alone. Nevertheless, maximum fog water deliveries are observed for months with periods of mixed fog and rainfall, as is the case of September and October. Although the annual rate may be classified as moderate-to-low, our 18-m² flat-panel collector still managed to fill up three 1000-l storage tanks in the first 5 months of our experimental campaign. For an uninterrupted year of operations and unlimited storage capacity, use of Eq. (1) on the whole 2007 data set yields a hypothetical total amount of 20,000 l of water that could be collected by means of one 18-m² flat-panel collector appropriately installed on the experimental site.

The time delay between collecting the fog water and applying it on the restoration plot made temporary storage necessary. On the other hand, drought periods can also occur outside of the summer season and stored water may be needed soon after planting.

Soil moisture in itself cannot be considered a definitive indicator of plant water status for optimizing the application of water pulses. Soil water potential, calculated by means of characteristic curves, is a more objective estimation of soil hydric properties. We applied the first water pulse for W2 in a conservative way: moderate water stress ($\Psi_s = -2.19$ MPa), a short rainless period (40 days), and a favourable microclimate within the treeshelters (Oliet and Jacobs, 2007). The second water pulse for W1 and W2 was applied under more stressful conditions ($\Psi_s > -3.0$ MPa), though reversible for *P. pinaster* (Schwanz and Polle, 2001). Plants of the *Quercus* genus maintain some physiological activity below these values (Valladares et al., 2000; Baldocchi et al., 2004). The lowest Ψ_s values we found in this study (-4.72 ± 0.61 MPa) may be associated both with the higher occurrence of early leaf loss in *Q. ilex* seedlings as a normal adaptation process to xeric areas (Sala and Tenhnunen, 1994) and the lower survival of *P. pinaster* seedlings (Martínez-Vilalta and Piñol, 2002). We estimated the soil water potential in the uppermost 30 cm of soil, but seedling roots may have reached soil horizons beyond 30 cm before the summer where Ψ_s is probably higher (Niu et al., 2005; Duursma et al., 2008). The high seedling survival may also be explained by the number of fog episodes that occurred at an averaged annual frequency of 15% (Fig. 7); these episodes were more recurrent during nocturnal hours and attained similar or even higher percentages in the summer months. Studies on fog deposition on forest vegetation conducted at selected locations have enhanced the importance of fog interception at many coastal and mountainous sites with climates from the tropical to Mediterranean and warm-temperate, emphasising the role of fog as another hydrologic input (Bruijnzeel et al., 2005). Corbin et al. (2005) used the isotopic composition of non-photosynthetic plant tissue to model fog water in Mediterranean areas along the California coast; they found that fog water oscillated between 28 and 66% of the total amount of water taken up by plants via roots during the summer drought.

Nevertheless, the seedling survival rate of both species was high in relation to other field experiments conducted in the same area (Pausas et al., 2004; Valdecantos et al., 2006). Holm oak responded to water pulses by increasing seedling survival both with and without biosolid application. Fuentes et al. (2004) observed that the implementation of simple structures for collecting runoff water significantly increased survival in holm oak seedlings. In maritime pine, only the fertilized seedlings tended to increase seedling survival with the water pulses. This interaction between

water and nutrient availability could be related to the release of salts from the compost which may increase soil electrical conductivity (Fuentes et al., 2007) and osmotic stress. The application of water pulses could alleviate this negative effect. Q. ilex usually has a more pronounced response to increased water availability than to nutrient supply (Valladares et al., 2000; Rey-Benayas and Camacho, 2004). P. pinaster and Q. ilex present different life traits and requirements and are characteristic of different successional stages. Pines are easily found in earlier successional phases while oaks dominate, if they do, in later ones. Although plant growth can be simultaneously limited by the availability of a number of different resources, it is important to assess which of these resources is the most limiting one under the given field conditions. Additionally, species with different features and life traits that share the same site may be limited by different resources. Growth of late-successional species is stimulated to higher extent by water than by nutrient availability while growth of early-successional species responds to increases in both resources (Canham et al., 1996), showing higher ecological plasticity. In our experiment, the growth pattern of Q. ilex did not change with either water or nutrient availability while P. pinaster showed enhanced growth rates with the application of composted biosolid. Nevertheless, holm oak seedlings may invest in belowground tissues and reach deeper soil horizons (Valde-cantos, 2001). It is likely that the climatic conditions in the planting year, including the number of fog episodes, were not stressful enough to generate a strong water limitation in the seedlings.

5. Conclusion

This study reveals how fog water collected on a mountainous site in a western Mediterranean region can be used for restoration applications in degraded areas where natural recovery is unlikely. Bulk fog water harvesting was achieved by means of large flat-panel collectors built at a low cost using simple materials. Before installing any large fog collectors, a preliminary omnidirectional evaluation of fog water yields at the prospective site must be made. In our case, the source of fog-bearing winds was found to coincide with the orientation of the main valley with respect to the coastline, which is about 60 km away in straight line. The experimental site can be classified as having a moderate-to-low potential for fog-water collection, with the annual fog water rate being 3.3 l/m^2/day for 2007. In only a 5-month period, including two failure episodes, one 18-m^2 flat-panel collector managed to fill up three 1000-l storage tanks for irrigation applications. Small water pulses during the first summer in the field promoted seedling survival and growth in Q. ilex and P. pinaster, respectively, in spite of the mild summer conditions recorded in 2007. Soil water potential is a good and relatively easy-to-measure indicator for scheduling water pulses to optimize this technique. The application of small water pulses to reduce the length of the drought period and split it into several less stressful intervals is an interesting option for restoring burned degraded areas more efficiently. It is expected that the more stressful the environmental conditions, the more efficient the water pulses. The continuous in situ collection of alternative water inputs throughout the year implies a diversification of the main objectives of restoration.

Acknowledgements

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