La precipitación oculta

y su papel en el balance hídrico de ecosistemas semiáridos

(Non-rainfall water input and its role in the water balance of semiarid ecosystems)

TESIS DOCTORAL

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LA PRECIPITACIÓN OCULTA Y SU PAPEL EN EL BALANCE HIDRICO DE ECOSISTEMAS SEMIÁRIDOS

Non-rainfall water input and its role in the water balance of semiarid ecosystems

Memoria de Tesis Doctoral presentada por Olga María Uclés Ramos para optar al Grado de Doctor en Ciencias Aplicadas y Medioambientales por la Universidad de Almería

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JUNTA DE ANDALUCIA

A mi familia.

A mis amigos.

A Sandro.

Al amor…

"I hear and I forget. I see and I remember. I do and I understand."

Confucius

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LA PRECIPITACIÓN OCULTA Y SU PAPEL EN EL BALANCE HIDRICO DE ECOSISTEMAS SEMIÁRIDOS

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INTRODUCCIÓN

El agua juega un papel muy importante como factor limitante en ecosistemas áridos y semiáridos, donde las precipitaciones son escasas y/o se acumulan en un corto periodo del año. El aporte de agua a la superficie del suelo de un ecosistema puede provenir, aparte de la lluvia, de tres fuentes diferenciadas (Garratt and Segal, 1988): i) el suelo (por circulación de agua desde las capas inferiores del perfil del suelo a las superiores); ii) las plantas (por exudación de agua por las raíces); iii) el aire. Esta tesis doctoral estudia este tercer punto; el aporte al ecosistema de agua atmosférica no proveniente de lluvia. El aporte de agua por esta fuente puede ser de gran importancia en ecosistemas áridos y semiáridos y se la conoce como "precipitación oculta". Ésta puede proceder del rocío, la adsorción de vapor de agua y la niebla:

- El **rocío** se forma cuando la temperatura de una superficie es menor o igual que la temperatura a la que el contenido de agua en el aire se vuelve saturante (punto de rocío) y por tanto el vapor de agua se condensa directamente sobre dicha superficie.
- La **adsorción** de vapor de agua se produce cuando la temperatura superficial es mayor que el punto de rocío y la humedad relativa del aire es mayor que la de los poros del suelo. Se crea un gradiente de vapor de agua mediante el cual dicho vapor se transfiere de la atmósfera al suelo y las moléculas de agua quedan retenidas en éste por fuerzas de Van der Waals.
- Finalmente, las **nieblas** consisten en un agregado visible de gotas de agua en suspensión en las proximidades de la superficie terrestre. Se produce por la condensación de pequeñas gotas en el aire cuando la concentración de vapor de agua de la atmósfera llega a saturación. Cuando estas gotas de agua entran en contacto con una superficie, se depositan en ésta por intercepción.

El rocío se ha estudiado en ecosistemas áridos y semiáridos ya que puede llegar a contribuir de manera importante en el balance hídrico del ecosistema (Jacobs et al., 1999; Kalthoff et al., 2006; Veste et al., 2008). También puede desempeñar un papel determinante como fuente hídrica para animales (Broza, 1979; Moffett, 1985; Steinberger et al., 1989), costras biológicas del suelo (del Prado and Sancho, 2007; Kidron et al., 2002; Lange et al., 1992; Pintado et al., 2005; Rao et al., 2009) y microorganismos (Lange et al., 1970). Algunos estudios también han confirmado el papel crucial que desempeña el rocío en la hidrología de plantas (Ben-Asher et al., 2010; Goldsmith, 2013). Además, la evaporación del rocío desde la superficie de las plantas a primeras horas de la mañana alivia el estrés hídrico de la vegetación, refrescando las hojas y reduciendo las pérdidas por transpiración (Sudmeyer et al., 1994). Por otra parte, la adsorción de vapor de agua del suelo puede proveer a las plantas de agua vital en periodos de déficit hídrico, provocando una estrecha relación entre la dinámica del agua del suelo y la respuesta de la vegetación y jugando un papel primordial en la conductancia estomática de las hojas y en la transpiración

(Ramirez et al., 2007). La adsorción también afecta a las propiedades del suelo y con ello al balance energético de un ecosistema (Verhoef et al., 2006). Por último, las nieblas pueden llegar a constituir un papel crucial en el ciclo hidrológico en algunos ecosistemas, como en el Desierto de Namibia (Hamilton and Seely, 1976) donde las nieblas están consideradas una fuente de agua vital para la flora y fauna (Seely, 1979). Además, algunos bosques son dependientes de la entrada de agua a través de las nieblas, como en la región semiárida de Chile (del-Val et al., 2006). Se han hecho esfuerzos en la cuantificación de la precipitación oculta, pero no hay ningún convenio internacional en cuanto al mejor método de medida. Las dificultades que supone su cuantificación, al requerir instrumentación de alta resolución y medición en continuo, han llevado al desarrollo de una gran cantidad de métodos de medida.

A continuación, en el Punto I, se realiza una pequeña revisión de los principales métodos de medida de la precipitación oculta utilizados en bibliografía. En el Punto II se desarrolla un apartado dedicado a los microlisímetros, método mayormente empleado en los últimos años y utilizado en el desarrollo de esta tesis doctoral. Como se ha mencionado anteriormente, la precipitación oculta, y principalmente el rocío, se han estudiado en muchos ecosistemas áridos y semiáridos, pero se han realizado pocos esfuerzos en el estudio de cómo la topografía puede afectar a su deposición. La falta de estudios comparativos en el aporte de la precipitación oculta entre laderas contrastadas es un ejemplo de ello. En el Punto III se aborda este tema de estudio y, finalmente, en el Punto IV se exponen y definen los objetivos de esta tesis doctoral.

I. Principales métodos de medición de la precipitación oculta

El rocío ha sido objeto de estudio a distintas escalas temporales y en ecosistemas diversos por múltiples motivos. Se ha estudiado tanto su duración, principalmente por su efecto en la proliferación de plagas en agricultura, como su cuantificación, por su efecto en el balance hídrico de ecosistemas áridos y semiáridos.

La duración del rocío (entendido como tiempo en el que una superficie permanece húmeda) ha sido ampliamente estudiada, principalmente por su importancia en el desarrollo de enfermedades y plagas en cultivos, ya que el período de humectación de las hojas puede determinar el desarrollo de patógenos y hongos. Pero esta duración es una variable difícil de medir o estimar, ya que varía considerablemente en función de la meteorología, del tipo de superficie o cultivo, así como de la posición de éste y del ángulo, geometría y localización de las hojas (Hughes and Brimblecombe, 1994; Madeira et al., 2002; Magarey et al., 2006). Se han usado algunos modelos matemáticos para predecir la duración de esta humectación (Madeira et al., 2002; Magarey et al., 2006; Monteith and Butler, 1979; Pedro Jr and Gillespie, 1981a; Pedro Jr and Gillespie, 1981b; Weiss et al., 1989) pero cuando las estimaciones con modelos físicos empíricos son muy complejas es necesario el uso de sensores in situ. Para ello, Gillespie and Kidd (1978) desarrollaron unos circuitos eléctricos que han evolucionado en los actuales sensores de humectación de hoja (en inglés: “leaf wetness sensors”). Estos sensores están formados por dos electrodos impresos sobre una placa de fibra de vidrio que reciben una señal eléctrica y miden la humedad superficial acumulada a través de la conductividad existente entre los electrodos.

También se han desarrollado varios métodos de cuantificación de rocío y tradicionalmente se han usado superficies artificiales para su cuantificación directa en campo, como el Duvdevani Dew Gauge (Duvdevani, 1947; Evenari et al., 1971; Subramaniam and Kesava Rao, 1983), el Cloth Plate Method (Kidron, 2000; Kidron et al., 2000) y el Hiltner Dew Balance (Zangvil, 1996). El Duvdevani Dew Gauge consiste en un bloque de madera rectangular (32 x 5 x 2.5 cm) pintado con un barniz y sobre el cual se condensa el rocío. La cantidad de éste se estima visualmente por la mañana comparando el tamaño y forma de las gotas con unas fotografías de referencia. El Cloth Plate Method consiste en un trozo de tela absorbente (6 x 6 cm) pegado a un vidrio (10 x 10 x 0.2 cm) y colocado sobre una placa de madera (10 x 10 x 0.5 cm) en el suelo. La tela se recoge por la mañana, poco antes del alba, y se calcula su contenido de agua gravimétricamente. Además, Beysens et al. (2005) usaron superficies de Plexiglas como recolectores de rocío y también se ha intentado medir el rocío en plantas usando palitos de madera o papel absorbente (Yan and Xu, 2010). Por último, el Hiltner Dew Balance consiste en un registro continuo del peso de un platillo de plástico colgado 2 cm sobre el suelo. Todos estos métodos de medida directos para la cuantificación del rocío son fáciles de reproducir y de aplicar y son útiles en trabajos de comparación pero no proporcionan valores reales, ya que las propiedades de sus superficies son diferentes de las naturales. Además, estas superficies también registran el aporte de agua proveniente de las nieblas por lo que es difícil discernir lo que aporta cada una de estas fuentes.

Se han llevado a cabo algunos estudios de deposición de rocío a largo plazo en varios ecosistemas áridos y semiáridos usando estas superficies artificiales para realizar las medidas. Evenari et al., (1971) y Zangvil (1996) estudiaron el rocío durante 4 y 6 años, respectivamente, en el Desierto del Negev, Israel. Subramanian and Kesava Rao (1983) y Beysens et al., (2005) hicieron lo mismo durante 3 años en el Desierto de Rajastán, India, y en Córcega, Francia, respectivamente. Y Kalthoff et al., (2006) midieron el rocío en el Desierto de Atacama, Chile, durante 2 años.

Otros esfuerzos en la medición del rocío han resultado en la aplicación de modelos matemáticos para determinar el flujo de vapor de agua desde y hacia los ecosistemas, como el Bowen ratio system (Kalthoff et al., 2006; Malek et al., 1999) y la ecuación de Penman Monteith (Jacobs et al., 1999). Estos métodos pueden cuantificar la cantidad y duración del rocío, pero requieren una ingente cantidad de datos ambientales y pueden ser difíciles de implementar.

La adsorción de vapor de agua también se ha intentado cuantificar usando modelos físicos, como la ecuación aerodinámica de difusión (Milly, 1984), pero ésta requiere una gran cantidad de variables meteorológicas y del suelo, por lo que no es de fácil aplicación (Verhoef et al., 2006). También se han usado ecuaciones empíricas basadas en factores meteorológicos como la amplitud diaria de la humedad relativa del aire (Kosmas et al., 1998) o la evaporación de agua desde el suelo del día anterior (Agam and

Berliner, 2004). Pero estas ecuaciones empíricas suelen proporcionar estimas poco fiables y/o erróneas cuando se aplican en otros lugares o en otras circunstancias meteorológicas diferentes de las existentes cuando se calcularon sus parámetros (estación del año y/o humedad de suelo) (Verhoef et al., 2006).

En cuanto a las nieblas, se pueden encontrar varios métodos de medición en la bibliografía, pero todos ellos están desarrollados para la cuantificación del agua interceptada por la vegetación o para su recolección para uso humano. Así, se han ideado diferentes estructuras, llamadas neblinómetros, para interceptar las gotas de agua en suspensión y medir la intensidad de las nieblas (Soto, 2000). Los neblinómetros de pantalla consisten en mallas que pueden ser de diferente composición (polipropileno, nylon…), forma (cilíndrica o rectangular) y tamaño (normalmente son de 0.5 o 1 m de altura). Se colocan a cierta altura del suelo o de la vegetación y las gotas de niebla impactan sobre ellas. Estas gotas se quedan retenidas en la malla y se agregan formando gotas mayores que se deslizan hasta caer a un canalón situado en la parte inferior de la malla. El agua recogida se canaliza luego a través de una manguera hasta un pluviómetro registrador de pulsos o hasta un recipiente de recolección. Otro tipo de neblinómetro, y que está inscrito en la Organización Meteorológica Mundial (OMM), es el Grunow, que consiste en un pluviógrafo con un pequeño cilindro de latón perforado sobre la boca.

Como se ha indicado anteriormente, también se puede medir la niebla a nivel de suelo con los métodos de medición de rocío indicados anteriormente (CPM, Duvdevani, Hiltner). Pero su diferenciación del rocío resulta difícil de discernir y, al igual que ocurre con el rocío, no se obtienen datos reales ya que no se utilizan superficies naturales.

II. Uso de microlisímetros

Existe otro método para la medición de la precipitación oculta y que actualmente está siendo más utilizado: los microlisímetros. Estos instrumentos permiten medir la variación del peso de una porción de suelo y han sido ampliamente usados para medir la evaporación de agua en suelo agrícola. Actualmente también se están utilizando en superficies naturales y para medir la precipitación oculta. Consiste en un recipiente de pequeño tamaño que contiene una porción reducida de suelo aislado del resto y en la que se mide la pérdida (evaporación) o ganancia (precipitación oculta) de agua. Éste parece ser el método más realista para la medición de la precipitación oculta ya que utiliza superficies naturales y detecta tanto rocío como adsorción de vapor de agua y niebla. En algunos estudios de rocío y adsorción se han usado microlisímetros manuales donde las muestras se retiran del suelo periódicamente para el registro de su peso (Jacobs et al., 2000; Jacobs et al., 2002; Rosenberg, 1969; Waggoner et al., 1969). Pero los métodos manuales presentan varios inconvenientes. En primer lugar, pueden subestimar la cantidad de precipitación oculta ya que el comienzo y final de las medidas están predeterminadas por el investigador y el período completo de aporte de agua puede verse reducido. Además, no permiten tomar medidas de modo continuo y la manipulación de las muestras puede provocar imprecisiones por aporte o pérdida de material en el traslado de éstas desde el suelo a la balanza y viceversa. Recientemente los microlisímetros automáticos están siendo más utilizados (Graf et al., 2004; Heusinkveld et al., 2006; Kaseke et al., 2012), ya que evitan la manipulación diaria de la muestra y proporcionan un registro continuo de su peso. Consisten en unos lisímetros colocados sobre unas balanzas y conectados a un almacenador de datos automático que registra el peso de las muestras de suelo en continuo.

Las dimensiones del microlisímetro están determinadas por las características de la célula de carga (parte esencial de una balanza) y cuanto mayor sea ésta, menor será su resolución. Heusinkveld et al. (2006) y Kaseke et al. (2012) midieron rocío en suelo desnudo y en costras biológicas usando una célula de carga de 1.5 kg de peso máximo. Los estudios realizados con microlisímetros se han centrado principalmente en la medida de rocío en suelo desnudo y en costras biológicas, ya que las dimensiones de las muestras son insuficientes para el desarrollo de experimentos con plantas. Así pues, se pueden encontrar algunos trabajos sobre diferencias entre suelo desnudo y costras biológicas (Liu et al., 2006; Maphangwa et al., 2012; Pan et al., 2010), o sobre arena y "mulching" de gravas para agricultura (Graf et al., 2004; Li, 2002) donde, además, no se diferencian las diferentes fuentes de la precipitación oculta (niebla, rocío y adsorción). La construcción de microlisímetros de mayor cabida permitiría el estudio de la precipitación oculta en plantas. De esta forma se podría desarrollar un estudio más completo donde se estudie como el aporte de agua por la precipitación oculta varía en función del tipo de cubierta de suelo (suelo desnudo, costras biológicas, piedras y plantas) y la influencia que cada una de las fuentes de la precipitación oculta tiene sobre éstas en ambientes naturales.

La instalación en campo de microlisímetros automáticos no es una tarea fácil. Tienen que estar enterrados, con la superficie de la muestra nivelada con la horizontal del suelo circundante para que las condiciones micrometeorológicas de su superficie sean reales. Además, los microlisímetros tienen que estar nivelados también con la vertical para evitar una posible excentricidad que podría afectar al correcto funcionamiento de la célula de carga. Otro problema es que el suelo tiende a moverse y, después de enterrados, los microlisímetros pueden inclinarse, girarse, desnivelarse e incluso romperse. Las lluvias también pueden provocar movimientos de tierras y, además, el agua puede entrar en el compartimento donde se encuentra la célula de carga y romperla. Así pues, solo se han llevado a cabo estudios durante cortos periodos de tiempo y con muy pocas réplicas (Graf et al., 2004; Heusinkveld et al., 2006; Kaseke et al., 2012). Por todo esto, es necesaria una mejora en la instalación en campo de los microlisímetros automáticos que permita el desarrollo de estudios con todas las réplicas necesarias y durante largos periodos de tiempo sin riesgo de roturas o desnivelaciones.

III. Influencia de la topografía en la precipitación oculta: estudio en laderas contrastadas

Como se ha mencionado anteriormente, se han realizado pocos esfuerzos en el estudio de cómo la topografía puede afectar a la precipitación oculta. En un ecosistema con una topografía heterogénea, las laderas de solana y umbría se encuentran expuestas a diferentes condiciones meteorológicas por lo que sus patrones de vegetación son diferentes, (Kutiel and Lavee, 1999). Normalmente la ladera de umbría presenta una mayor biomasa (Jacobs et al., 2000; Kappen et al., 1980; Kidron, 2005; Lázaro et al., 2008) como resultado de una menor insolación, lo que afecta a las propiedades del suelo y con ello también a la vegetación y fauna (Kutiel and Lavee, 1999). Solo unos pocos estudios se han centrado en las diferencias entre laderas y en muchos casos los resultados son contradictorios. Varios estudios han encontrado que la orientación de las laderas controlan la deposición de rocío en el desierto del Negev, pero unos encontraron mayores cantidades en las laderas de umbría (Noroeste) que en las de solana (Sureste) (Kidron, 2005; Kidron et al., 2000) y otros, por el contrario, registraron una mayor condensación de rocío en las laderas de solana que en las de umbría (Jacobs et al., 2000). Estos estudios se realizaron con diferentes métodos de medida y no se diferenciaron rocío y adsorción de vapor de agua, por lo que las cantidades de rocío medidas, y por tanto sus patrones, pueden no ser comparables y pueden no representar la realidad. Además, estos estudios suelen llevarse a cabo durante o después de la estación seca (verano u otoño), pero no hay datos sobre estas deposiciones en invierno o con suelo húmedo. El rocío y la adsorción son procesos diferentes y su relación con las variables micrometeorológicas y las propiedades del suelo deberían ser estudiadas separadamente y en diferentes estaciones del año. Además, es necesario un sistema eficiente de medida de la precipitación oculta que permita el estudio de su heterogeneidad entre laderas y que desvele a qué es debida.

IV. Objetivos y estructura de esta Tesis Doctoral

Como se ha desarrollado en la Introducción, uno de los principales retos es el desarrollo de un método de medida de la precipitación oculta que discrimine los tipos de precipitaciones y que sea fiable y fácil de aplicar. De todos los desarrollados hasta el momento, el uso de microlisímetros automáticos parece la opción más prometedora. El problema de éstos es que el pequeño tamaño de la muestra permite el estudio de la precipitación oculta solo en suelo desnudo o cubierto por biocostras, pero no permite su estudio en plantas. Además, por los riesgos a los que están sometidos en campo, estos estudios solo se han desarrollado durante cortos periodos de tiempo. Por todo esto, se hace imprescindible; i) la construcción de mayores microlisímetros que permitan estudiar el aporte de agua por la precipitación oculta en plantas y ii) el diseño de una instalación en campo que permita el desarrollo de estudios con todas las réplicas necesarias y durante largos periodos de tiempo. De esta forma se podrá estudiar la influencia de la precipitación oculta sobre los diferentes tipos de cubiertas en ambientes naturales (suelo desnudo, costras biológicas, piedras y plantas), diferenciando cada una de sus fuentes y durante las diferentes estaciones del año. Este sistema también hará posible el estudio de la precipitación oculta en laderas, de manera que se puedan clarificar los efectos que la umbría y solana producen en estos meso-hábitats, y en consiguiente, en la precipitación oculta.

Cabe destacar que de las tres fuentes de precipitación oculta, el rocío ha sido el más extensamente estudiado. Pero la mayoría de estos estudios se han desarrollado en ambientes áridos y utilizando superficies de condensación artificiales. Por ello, también se hacen necesarios el desarrollo de un modelo sencillo de estimación de rocío que analice este aporte de agua a lo largo del año y que se estudie dicho aporte en otro tipo de ecosistemas, como en ecosistemas costeros y esteparios, tan ampliamente distribuidos en el sur de la Península Ibérica. De este modo se podrá estudiar la variabilidad temporal del rocío, así como su contribución en el balance hídrico del ecosistema y los principales factores que gobiernan este proceso.

En resumen, el objetivo general de esta tesis es evaluar la influencia de la precipitación oculta en el balance de agua de ecosistemas áridos, así como su variabilidad estacional y la influencia del tipo de cubierta de suelo. Para esto se desarrollan dos metodologías de medición de la precipitación oculta; i) un microlisímetro automático para la medición directa en campo de los aportes (por la precipitación oculta) y pérdidas (por evaporación) de agua de muestras de suelo, y ii) un modelo teórico de estimación de rocío a partir de valores medidos de variables micrometeorológicas.

Para alcanzar estos objetivos, esta tesis doctoral se compone de 4 capítulos:

En el Capítulo I se desarrolla un microlisímetro automático para la medición continua de la evaporación y del aporte de agua por la precipitación oculta en muestras de suelo utilizando para ello diferentes tipos de cubiertas. También se desarrolla una estrategia de colocación de dichos microlisímetros en campo que permite el uso de tantas réplicas como sean necesarias y el desarrollo de estudios durante largos periodos de tiempo sin riesgo de roturas o desnivelaciones.

En el Capítulo II se realiza la medida y estudio de la precipitación oculta y las variables micrometeorológicas asociadas a cada tipo de entrada de agua (rocío, niebla y adsorción) y a cada tipo de cubierta de suelo (suelo desnudo, costras biológicas, piedras y plantas).

En el Capítulo III se estudia la precipitación oculta en un ambiente semiárido y se compara este aporte de agua entre dos semihábitats (laderas contrastadas).

Por último, en el Capítulo IV se desarrolla un modelo teórico de medición de rocío que permite la estimación de éste a partir de variables meteorológicas sencillas. Con este modelo se analiza el patrón de aporte de agua a través del rocío y su variabilidad estacional en un sistema semiárido, costero y estepario.

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Capítulo I

Microlysimeter station for long term non-rainfall water input and evaporation studies

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Capítulo I

MICROLYSIMETER STATION FOR LONG TERM NON-RAINFALL WATER INPUT AND EVAPORATION STUDIES

Abstract

Non rainfall atmospheric water input (NRWI), which is comprised of fog, dew and soil water vapour adsorption (WVA), has been proven to be an important water source in arid and semiarid environments. Its minor contribution to the water balance and the difficulty in measuring it have resulted in a wide variety of measurement methods (duration and quantification), especially for dew. Microlysimeters seem to be the most realistic method for dew measurement on natural surfaces and they can also detect WVA. This paper presents an automated microlysimeter that enables accurate studies of NRWI and evaporation on soil and small plants. Furthermore, we have developed a field strategy for their long term placement and installation which prevents damage from rainfall, soil movement or other field conditions, keeping the microlysimeters balanced and dry. This design allows the measurement of evaporation and NRWI on different cover types, including small plants. By monitoring the surface temperatures, dew and water vapour adsorption can be distinguished and the relative contribution of dew and WVA on the NRWI can also be found. Our automated microlysimeter design, construction and field installation have proven to be an useful and effective tool in a NRWI study.

Keywords: microlysimeter, dew, water vapour adsorption, non-rainfall water input, evaporation, semiarid

1. INTRODUCTION

Non rainfall atmospheric water input (NRWI) into an ecosystem can originate from fog, dew or water vapour adsorption (WVA). Fog occurs when the atmospheric water vapour concentration reaches saturation, a mass of condensed water droplets remains suspended in the air and is deposited on the surface by interception. Dew forms when the temperature of the surface where water will condense equals or falls below the dew point temperature of the surrounding air. WVA takes place when the relative humidity of the air is higher than the relative humidity in the pore space in the soil while the surface temperature is higher than the dew point temperature of the surrounding air (Agam and Berliner, 2006).

Non rainfall atmospheric water has been proven to be an important water source in arid and semiarid environments (Jacobs et al., 1999; Kalthoff et al., 2006; Uclés et al., 2013; Veste et al., 2008). Some studies have confirmed that summer soil WVA plays an important role in the stomatal conductance and vital transpiration in *Stipa tenacissima* in SE Spain (Ramirez et al., 2007), dew plays an important role in biomass production of plants at low water cost (Ben-Asher et al., 2010) and dew evaporation in the morning alleviates moisture stress in plants by cooling the leaves and reducing transpiration losses (Sudmeyer et al., 1994). Furthermore, several studies have stated that dew can play an important role in the development of biological soil crusts (del Prado and Sancho, 2007; Kidron et al., 2002; Pintado et al., 2005) and microorganisms (Lange et al., 1970). Dew and fog may also have a negative effect on plants promoting bacterial and fungal infections (Duvdevani, 1964), which may have an important impact on agriculture (Kidron, 1999). Some attempts have been made to study the duration and quantification of NRWI, but there is no international agreement on how this should be done. Its minor contribution to the water balance and the difficulty in measuring it, have resulted in a wide variety of measurement methods, especially for dew.

Dew duration has been long studied, mainly because of its importance in plant diseases, as leaf wetness duration can determine pathogen and fungus development. But leaf wetness duration is a difficult variable to measure or estimate, since wetness varies considerably with weather conditions, surface cover type or crop, as well as position, angle, geometry and location of the leaves (Hughes and Brimblecombe, 1994; Madeira et al., 2002; Magarey et al., 2006). Some micrometeorological data and mathematical models have been used to predict leaf surface wetness duration (Madeira et al., 2002; Magarey et al., 2006; Monteith and Butler, 1979; Pedro Jr and Gillespie, 1981a; Pedro Jr and Gillespie, 1981b; Weiss et al., 1989). However, the use of leaf wetness sensors is necessary when estimations by empirical or physical models are too complex. For this purpose, Gillespie and Kidd (1978) developed an electrical impedance grid that has evolved on actual commercial leaf wetness sensors. These sensors consist of a wire grid that a current can flow through when free water bridges the gap between two trace wires. The wires are energized by a potential difference from a datalogger's excitation circuitry. When dew or rain is deposited on the sensor surface, the datalogger senses the current due to the presence of water on the grid.

As dew may have an important role in the water budget in arid and semiarid ecosystems (Jacobs et al., 1999; Kalthoff et al., 2006; Uclés et al., 2013; Veste et al., 2008), its quantification becomes an important issue. Some theoretical and modelling methods, such as the Bowen ratio technique (Kalthoff et al., 2006; Malek et al., 1999), the Penman Monteith equation (Jacobs et al., 2002; Moro et al., 2007) and, more recently, the Combined Dewfall Estimation Method (CDEM) (Uclés et al., 2013) may be found in the literature. These techniques can quantify the amount and duration of dew, but require an enormous amount of atmospheric variable data. Furthermore, they can be difficult to implement and do not measure fog or WVA, or do not differentiate between these two phenomena and dew.

Other efforts at estimating dew have resulted in the development of direct measurement methods using artificial surfaces, such as the Duvdevani dew gauge (Duvdevani, 1947; Evenari et al., 1971; Subramaniam and

Kesava Rao, 1983), the cloth plate method (Kidron, 2000; Kidron et al., 2000) and the Hiltner dew balance (Zangvil, 1996). The Duvdevani dew gauge consists of a rectangular wooden block (32 x 5 x 2.5 cm) coated with a special paint where dew condenses. Using reference dew photographs, the dew amount can be stated visually in the early morning. The cloth plate method consists of an absorbent cloth (6 x 6 cm) attached to a glass plate (10 x 10 x 0.2 cm) and placed on a wooden plate (10 x 10 x 0.5 cm). The cloth is collected in the early morning and it is weighed and dried to calculate its water content. Beysens et al. (2005) used plexiglas surfaces as dew collectors and some attempts have also been made to measure dew on plants using artificial collecting surfaces such as poplar wood stick, sunflower stick and filter paper (Yan and Xu, 2010). These methods are unable to record the dew duration but the Hiltner dew balance does. This method consists of a continuous registration of the weight of an artificial condensation plate hanging 2 cm above the ground. All these direct measurement methods are easy to implement but under or overestimate dew, since their surface properties are different from natural surfaces. Hence, these dew measurement methods are useful for intersite comparisons but do not provide real values and are unable to measure WVA.

Microlysimeters are an effective method for measuring NRWI on natural surfaces, as they can detect dew and WVA with accuracy (Uclés et al., 2013). Several NRWI studies have been done with manual microlysimeters (Jacobs et al., 2000; Jacobs et al., 2002; Ninari and Berliner, 2002; Rosenberg, 1969; Sudmeyer et al., 1994; Waggoner et al., 1969). However, manual methods usually underestimate NRWI, because the beginning and end of the measurement period are predetermined by the researcher and the entire water input period may be reduced. Recently, automated weighing microlysimeters are being more used (Graf et al., 2004; Heusinkveld et al., 2006; Kaseke et al., 2012; Uclés et al., 2013), because this method avoids daily manipulation of the sample and records continuously anywhere. Sample dimensions in automated microlysimeters are determined by the load cell characteristics, since the larger the sample or the load cell are, the lower the resolution. Heusinkveld et al. (2006) and Kaseke et al. (2012) used a 1.5 kg rated capacity single point aluminium load cell for measuring dewfall on bare soil and on biological soil crusts (BSCs). Indeed, microlysimeter studies have focused on bare soil and BSCs monitoring, as sampling cup dimensions are insufficient for plants. However, Uclés et al. (2013) successfully used a larger load cell (3 kg rated capacity) to measure NRWI on small plants.

The accuracy of the automated microlysimeter measurements depends on their field installation as they must be buried with the surface of the soil samples flush with the surrounding soil. Furthermore, they have to be mounted with the balance of the load cells perpendicular to avoid eccentricity. After burial, the soil tends to move and the microlysimeter may tip, twist, be thrown out of the balance and break. Another common problem is damage from soil movements caused by rain and water entering the load cell case. Therefore, only short automated microlysimeter studies have been done with a small number of replicates. The study of Kaseke et al. (2012), for example, had to be stopped because of an imminent rainstorm storm which could have flooded and damaged the load cell. Microlysimeters must be improved and a suitable field installation method must be developed to be able to deal with all these drawbacks and carry out long term studies with all the replicates needed.

This paper presents an automated microlysimeter (MLs) which may be used for the accurate study of NRWI and evaporation on soils and small plants. We have also developed a long term MLs field installation and placement strategy which avoids damage from rain, soil movement or other field conditions, keeping the MLs balanced and dry. In this study, twelve MLs were installed in a Mediterranean semiarid steppe ecosystem (Balsa Blanca, Almería, SE Spain) with different cover types in the sampling cups (plants, BSCs, stones and bare soil). The MLs and the field installation were tested for: 1) input signal; 2) sample dimensions with two different soil types; 3) load cell temperature dependence; and 4) effectiveness of the field installation strategy. MLs data for 49 days (May - June 2012) were analyzed and their daily signal and the possibility of differentiating between WVA and dew were verified. Furthermore, the sensitivity of the MLs in differentiating NRWI and evaporation on different cover types was also studied.

2. MATERIAL AND METHODS

2.1. Study site

Most of the measurements were conducted at Balsa Blanca, but El Cautivo field site was also used for Test_2.

Balsa Blanca is a Mediterranean coastal steppe ecosystem in Almería, SE Spain (36º56’30”N, 2º1’58”W, 208 m a.s.l.). This site, which is one of the driest ecosystems in Europe, is located in the Cabo de Gata-Níjar Natural Park. Balsa Blanca is in the Níjar Valley catchment, 6.3 km away from the Mediterranean Sea. Vegetation is sparse and dominated by *Stipa tenacissima*. The mean annual air temperature is 18 ºC and the long-term average rainfall is 220 mm [historical data recorded by the Spanish Meteorological Agency (1971 – 2000); www.aemet.es]. The predominant soils are thin, with varying depths (about 30 cm at most, average 10 cm), alkaline, saturated in carbonates, with moderate stone content, frequent rock outcrops (Rey et al., 2011) and with a sandy loam texture. For further information of the study site, see Uclés et al. (2013).

The study site at El Cautivo was used for testing our second hypothesis (Test_2). El Cautivo field site is a badlands ecosystem located in the Sorbas-Tabernas basin in Almería, SE Spain (N37º00’37’’, W2º26’30’’). Soils are silty loam, affected by surface crusting processes (Cantón et al., 2003), and in general soil is less developed and organic matter content is lower than in Balsa Blanca soils.

2.2. Automated microlysimeter design and field installation

We have designed an automated microlysimeter (MLs) using a single point aluminium load cell based on Heusinkveld et al. (2006). A load cell is a transducer that converts a force into a measurable electrical signal by the deformation of strain gauges. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load. The load cell gives a Mv signal that is a function of the electricity applied. Hence, the voltage input must be supplied by a stable energy source. The final data is given by the ratio of the load cell Mv signal to the input voltage (Mv V^{-1}). In our case, the load cells were connected to a datalogger (CR1000, Campbell Scientific, Logan, UT, USA) and were excited with 12 volts directly from the input plug. The system energy was supplied by a solar photovoltaic installation composed by a solar panel (Suntech, STP050D-12/MFA), a battery (12V, 90Ah) to store energy for nocturnal measurements and a solar charge controller (Solarix PRS 1010, Steca).

One of the purposes of this study is not only to measure dew on bare soil, but also on small plants. Hence, the sampling cup must allow the development of roots inside it, or allow the plant to survive long enough for the experiment. Therefore, a 3 kg rated capacity single point aluminium load cell (model 1022, 0.013 x 0.0026 x 0.0022 m, Vishay Tedea-Huntleigh, Switzerland) was selected. We used a 0.152 m diameter and 0.09 m deep PVC sampling cup with this load cell. This size is large enough for small dwarf bushes, grasses and annuals to survive long enough to carry out an experiment. We hypothesized that this sample depth would provide a good temperature gradient within the soil profile without significantly affecting the soil heat balance. Soil cores were extracted by excavating plastic tubes that had been hammered into the soil. A cap was fitted to the bottom of the tube to retain the soil and prevent drainage.

Once the sample dimensions were established, the MLs (Fig. 1a) were designed in two parts; a mobile weighing part (Fig. 1b) and a fixed protection part (Fig. 1c). The mobile part is made up of the load cell, which is connected to a PVC plate (0.10 m diameter) by a rod (0.022 m long and 0.006 m diameter). The sample is located over the PVC plate. The load cell has four mounting holes, two in the loading end and two in the attached end. An aluminium connecting piece (0.025 x 0.025 x 0.001 m) with three screw holes in it is used for mounting. Two holes are for screwing the aluminium piece to the loading end of the load cell and the third is for screwing it to the rod. The load cell is held by an aluminium plug (0.074 x 0.026 x 0.017 m) attached to an aluminium base plate (0.18 x 0.10 x 0.01 m) inside a protective PVC housing (0.18 x 0.23 x 0.09 m). The rod is inside a protective PVC tube (0.15 m long, 0.043 m diameter and 0.004 m thick). A circular aluminium case (0.017 m diameter, 0.011 m deep and 0.001 m thick) at the top of the tube protects the PVC plate and the sample. The bottom of the circular aluminium case is riddled with holes, so rainwater can drain out (Fig. 2d), and to maximize drainage, the PVC plate also has a protruding ridge around the bottom, and an

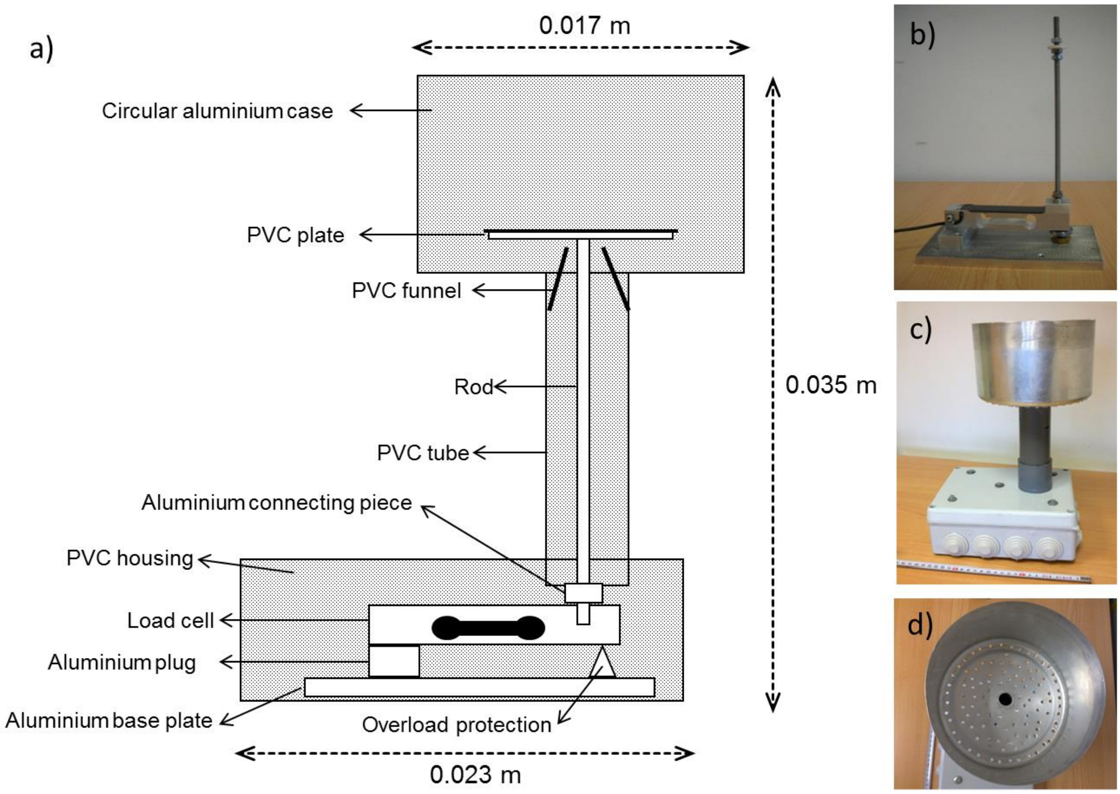

Figure 1. *Automated microlysimeter design and photographs*

inverted PVC funnel is inserted in the top of the tube. Finally, a piece of aluminium is placed under the loading end of the load cell for overload protection.

According to the manufacturer, the total error found was 0.02 % of the rated output with internal temperature range compensation. To minimize the remaining temperature dependence and water exposure, the MLs was made of aluminium, and the PVC box was placed inside a 0.015-m-thick polyspan box with a waterproof cover.

Finally, two calibration tests were performed in the laboratory: one for general calibration to check the whole measurement range of the load cell and another for specific calibration by adding small loads to 2 kg fixed weight to simulate the soil sample weight.

This set-up methodology was based on experience from an unsuccessful earlier attempt where the load cells were buried directly in the soil. This first attempt ended with a flooding of the system and failure of the load cells during a strong rain event. A new set-up was performed where the MLs were placed inside wooden boxes in groups of three (Fig. 2). They were buried in the field with the surface of the sampling cup flush with the surrounding surface (Fig. 2a, 2b). These boxes were anchored and levelled in the soil with steel rods. A total of four boxes were buried, each with its own drainage tube connected to a pit (Fig. 2a, 2c). A pipe connected the pit to the surface so that pit conditions could be checked after each rainfall event (Fig. 2d). The boxes were filled with polystyrene to stabilize the temperature. The surface of the boxes can be covered with material from the surroundings to avoid changing the albedo near the samples.

The MLs design and the field installation were checked with several tests:

Test_1: This test checked the input signal. The system energy was supplied by a solar photovoltaic installation and even if we used a solar charge controller the input voltage varied from 12 to 14 volts, depending on the input from the solar panel. We checked whether this variation in the input voltage would affect the load cell function or not, and if so, look for a solution.

Test_2: Sample dimensions were studied in this test. Surface temperatures were monitored in the sample and in the surroundings to check whether they could be affected by the sampling cup dimensions. Thermocouples buried 2-3 mm deep (Type T, Thermocouples, Omega Engineering, Broughton Astley, UK) were used to monitor the temperature recorded at 15-second intervals and averaged every 15 min by a datalogger (CR1000, Campbell Scientific, Logan, UT, USA). This study was done in Balsa Blanca and in El Cautivo sites to check the sample dimensions in two different soil types.

Test_3: This test checked the influence of the temperature on the load cell signal. Once the MLs were placed in the field, and before the placement of the soil samples, they were covered for one month (April 2012) to avoid

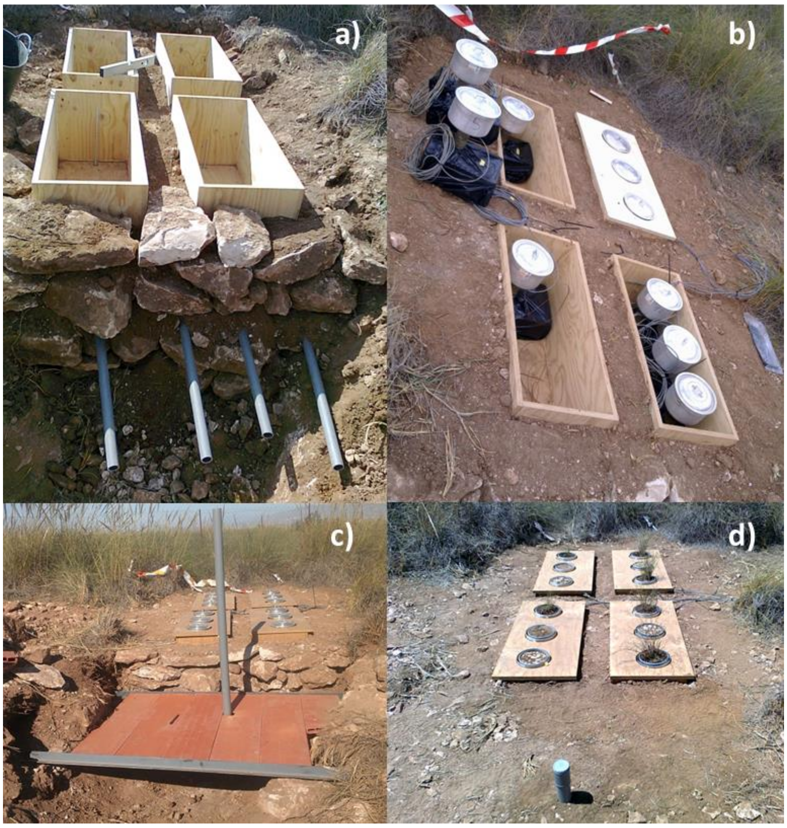

Figure 2. *Field installation*

water exchange with the environment and their signals were recorded. Thermocouples (TCRT 10, Campbell Scientific, Logan, UT, USA) were installed inside the PVC load cell boxes to monitor their temperatures.

Test_4: Specific calibrations were done once a month in the field to adjust the calibration range over time. These calibrations were done by adding small weights to the MLs samples. Furthermore, the field installation strategy was tested by checking the MLs conditions over time (dryness and balance).

2.3. Non rainfall water input measurements

Twelve MLs in four boxes were installed in the field. Six of the sampling cups contained *Stipa tenacissima* and the others contained undisturbed bare soil, stones and biological soil crust samples (BSCs) (Fig. 2d). Plants had an LAI of around 0.4 m^2 m^{-2}, and were 0.3 m wide and 0.2 m high. Stones were embedded in the soil and covered 70 % of the sample surface. BSCs consisted of cyanobacteria and lichens and covered almost 100 % of the sample surface. For the MLs data analysis and interpretation, some meteorological variables were measured on site. Ground-level air temperature and humidity were monitored by a thermo-hygrometer (HMP45C, Campbell Scientific, Logan, UT, USA). Rainfall was measured by a tipping bucket rain gauge (ARG 100, Campbell Scientific, Logan, UT, USA) and wind speed was measured at a height of 3.5 m (CSAT-3, Campbell Scientific, Logan, UT, USA). Data were sampled at 15-second intervals and averaged every 15 min by dataloggers (Campbell Scientific, Logan, UT, USA).

Daily changes in the water content of the uppermost soil layer were analysed: evaporation during the day and NRWI during the night. Negative changes in mass in the MLs corresponded to evaporation and positive changes to NRWI. Hence, evaporation was calculated as the difference between the daytime maximum and minimum, and NRWI was calculated as the difference in weight between the night-time maximum and the minimum of the day before. We studied the daily MLs signal and its relationship with the meteorological variables involved in a NRWI event, specially the surface temperature. The dew point temperature can be used to differentiate between dew and water vapour adsorption (WVA). The bare soil surface temperature was monitored by thermocouples (Type TT-T-24S, Thermocouples, Omega Engineering, Broughton Astley, UK) buried 0.002-0.003 m deep and this temperature was compared to the dew point temperature to differentiate between dew and WVA. The real soil surface temperature is difficult to measure with *in situ* sensors, but we assume our thermocouples provide a good estimation. Dew was considered when positive changes in mass in the MLs matched with the surface temperature below the dew point temperature and the rest of water input was assumed to be WVA. Furthermore, the sensitivity of the MLs in recording differences in evaporation and NRWI among the different cover types was also checked.

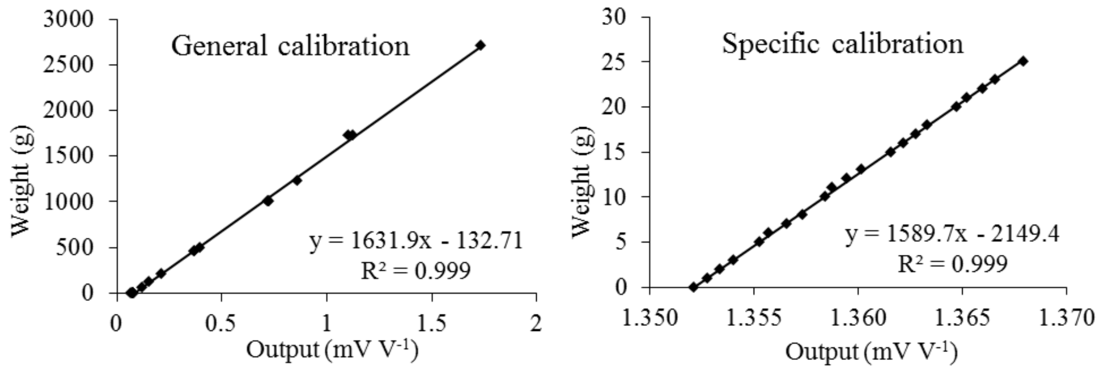

Figure 3. *Calibration tests in the laboratory*

3. RESULTS AND DISCUSSION

3.1. Microlysimeters and field installation tests

Calibration tests in the laboratory were successful (Fig. 3) and had a satisfactory resolution of 0.01 g (0.00055 mm).

The system was powered by a solar photovoltaic installation with a solar charge controller, but the input voltage was unstable. Since the load cells need a constant excitation voltage, this volts variation caused strong noise in the load cell signal that made the data analysis impossible, especially in determining the beginning and end of evaporation and NRWI. We solved this problem during Test_1 by installing a voltage stabilizer that maintained the input at 12 volts (LB-10, Cebek) (Fig. 4).

Regarding the sampling cup dimensions, Ninari and Berliner (2002) stated that for measuring dew, the minimum depth of a sample should exceed the depth at which the diurnal temperature is constant (0.5 m in the Negev). However, Jacobs et al. (1999) carried out several tests in the Negev with sampling cups having a 0.06 m diameter and three different heights (0.01, 0.035 and 0.075 m), and found consistent results with the 0.035 and 0.07 m-high sampling cups, reporting that the daily moisture cycle is confined to the upper 0.02-0.03 m of the soil profile. In fact, several studies have been carried out successfully using small sampling cups (Table 1).

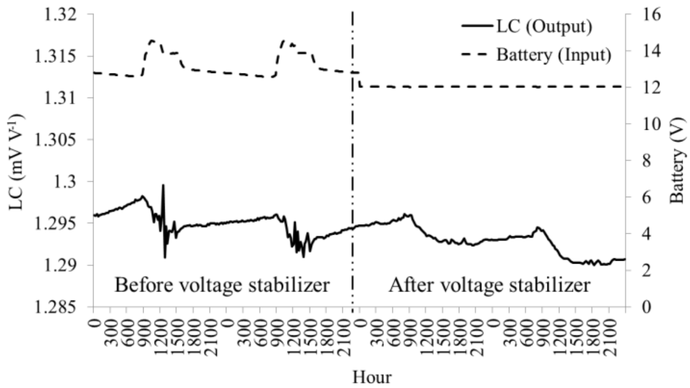

Figure 4. *Voltage stabilizer effect on the load cell output signal and on the battery*

We assessed the representativeness of our sampling cup and its dimensions by finding the effect of changes in soil surface temperature in the sample at two sites with markedly different soil characteristics: Balsa Blanca and El Cautivo (Test_2). Results confirmed that there were no significant differences between night-time soil surface temperatures measured in the sample and in the surroundings (Fig. 5). But this representativeness is temporary and MLs

Table 1. *Microlysimeters sampling cup sizes in bibliography.*

REFERENCE	PLACE	SAMPLES SIZE	
		Diameter (m)	Depth (m)
Jacobs et al. 1999	Negev Desert, Israel	0.060	0.035
Graf et al. 2004	Canary Islands, Spain	0.290	0.060
Heusinkveld et al. 2006	Negev Desert, Israel	0.140	0.035
Pan et al. 2010	Shapotou Desert, China	0.100	0.030
Kaseke et al. 2012	Stellenbosch, South Africa	0.140	0.035
Uclés et al. 2013	Almería, Spain	0.150	0.090

samples must be replaced with time, since the soil characteristics inside the sampling cup change differently from the surroundings (Boast and Robertson, 1982). The longer the sample is isolated from the soil matrix, the greater the differences will be. However, under extremely dry conditions, water movement in the liquid phase becomes negligible, and the change of water content at any given depth will thus be the result of water vapour movement and physical adsorption or desorption (Scanlon and Milly, 1994). Since these processes are mostly confined to the uppermost soil layer, samples operation time will be longer during dry periods and must be replaced more often during the wetting season, especially after a strong rainfall event.

When the surface temperatures of the sample and the surroundings are similar, it can be assumed that they both have similar temperature profiles, and therefore the latent heat flux in the sample is representative of the surrounding soil (Ninari and Berliner, 2002). Hence, it can be stated that these sample dimensions are adequate for the study of NRWI. But the duration of this representativeness depends on the weather conditions, so continuous surface monitoring is necessary to confirm sample validity over time.

In the load cell temperature dependence analysis, the temperature test (Test_3) did not show any direct or significant temperature effect on the load cell signal (R^2=0.03; N=3200; 15-min data). Neither was any temperature effect found when these data were analysed daily, and the daily temperature differences were compared to the load cell signal (R^2=0.20; N=30 days).

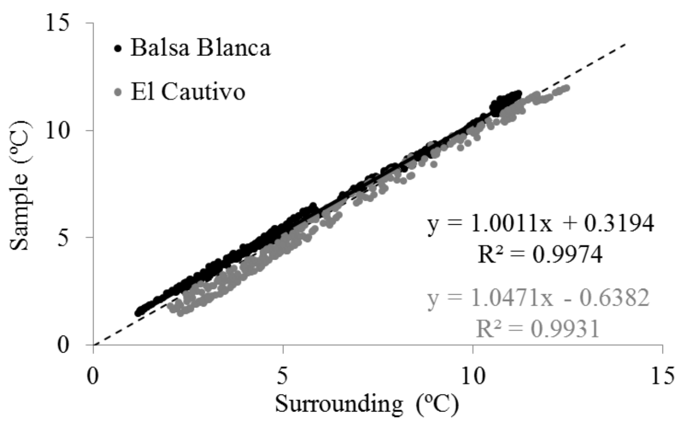

Figure 5. *Night soil surface temperature in the sample and in the surroundings in Balsa Blanca and El Cautivo field sites. (15-min data, N=400). In all analysis p-value<0.0001.*

The monthly MLs field calibrations were successful (Test_4) and only small variations were found after rainfall events and during the following evaporation. These variations were higher after strong rainfall events, so samples were replaced and the MLs were recalibrated after the evaporation period. These periodic specific calibrations allowed us to use the calibration line with the best fit each time. Furthermore, the MLs were checked after the rainfall events, and one year after their placement at the site. The field installation did not allow water to get inside the PVC boxes, the load cells remained dry and the MLs remained balanced.

3.2. Non rainfall water input measurements

One of the advantages of the proposed method is the capability to non-manually measure NRWI. This is emphasized in light of former measurements that were carried out manually, such as in different regions of Israel aiming to study the effect of dew on plants (Ashbel, 1949; Duvdevani, 1964; Kidron, 1999) or aiming to quantify dew amounts (Jacobs et al., 2000; Jacobs et al., 2002; Ninari and Berliner, 2002).

When the MLs and their field installation were assessed and found to be adequate, the daily MLs signal was analysed. Daily evaporation and NRWI on three nights in a bare soil sample may be clearly observed in Figure 6. During the first and second nights, the surface temperature (*Ts*) dropped below the dew point temperature (*Td*), the wind speed was low and the relative humidity (*RH*) was over 90 %. Until *Td* was reached, the positive change in the MLs mass was due to WVA, and when *Td* was reached, dew condensation took place in the sample. On the third night, *RH* was under 70 % and *Td* was not reached, so, only WVA was responsible for the water uptake by the sample.

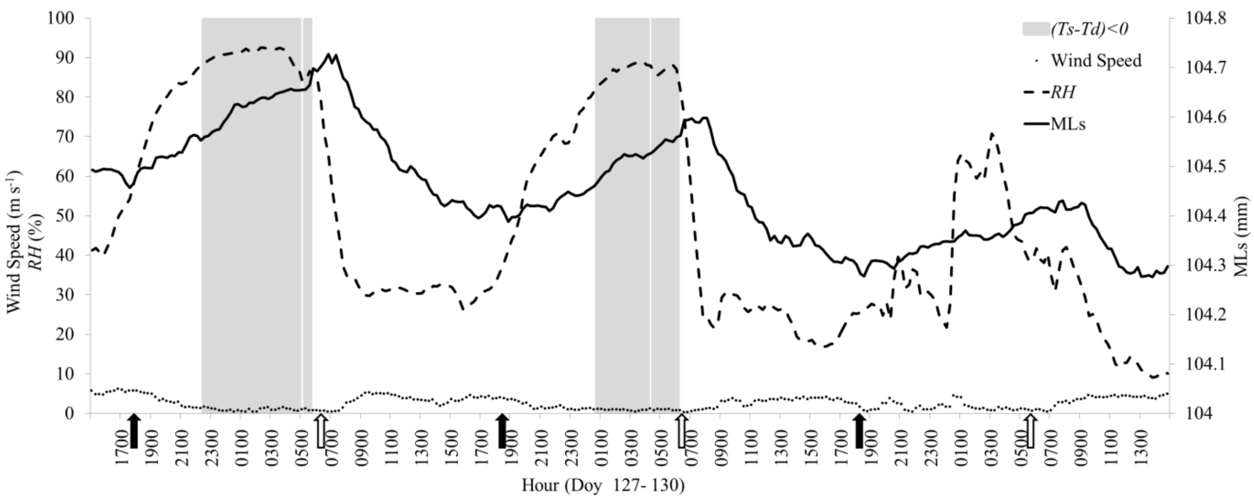

Figure 6. *Bare soil daily evaporation and water input during Doy 127-130. RH: relative humidity. MLs: automated microlysimeter signal in mm. Grey bars indicate the period of time while the surface temperature (Ts) is below the dew point temperature (Td). Black arrows: sunset. White arrows: sunrise. Hours refer to solar time.*

The MLs signal was not a smooth line, but jagged, since the output was not perfectly stable, and a 0.01 mm background noise was found. This error agrees with the error found by Heusinkveld et al. (2006) in their MLs. Furthermore, it has been shown that there can be small evaporation episodes during a dewfall event (Uclés et al., 2013) as shown in Figure 6. The MLs signal rose during the night because of NRWI and small descents also occurred as consequence of evaporation events. The same trend can be found during the day, as the MLs signal went down because of evaporation and small WVA events occurred. But these small increases can also be produced by the wind moving the sampling cups or transporting small soil particles. It is worth mentioning that during a NRWI event the wind is very low and there is less possibility of noise from wind in the signal.

Kaseke et al. (2012) calculated the NRWI as the sum of all inputs excluding any evaporation that may take place. We think this calculation overestimates the input because it includes all the MLs background noise. They used the same procedure for calculating evaporation and the noise generated by wind during the day may also have been added in. However, we used the differences between daytime minimums and night-time maximums to calculate NRWI and evaporation, so the daily error, i.e., background and wind noise, should be negligible.

Our MLs were able to find differences in NRWI and evaporation in the uppermost soil layer between different cover types. These differences were analysed during a study period of 49 days with no fog or rainfall events (Doy 121-169, year: 2012) (Table 2). Maximum NRWI was recorded for plants followed by BSCs, bare soil, and finally, stones. The same pattern was found for evaporation. Our daily NRWI for BSCs and bare soil is in agreement with the bibliography (Agam and Berliner, 2004; Heusinkveld et al., 2006; Jacobs et al., 1999; Pan et al., 2010).

Table 2. *NRWI and evaporation on different surface cover types during the study period. Averages are provided with their standard deviations.*

	NRWI		Evaporation	
	Total (mm)	**Average (mm night^{-1})**	**Total (mm)**	**Average (mm day^{-1})**
Plants	13.63	0.32±0.14	33.84	0.54±0.16
BSCs	13.03	0.28±0.07	15.91	0.38±0.08
Bare soil	11.13	0.24±0.06	13.09	0.33±0.08
Stones	9.50	0.16±0.08	9.85	0.23±0.06

A more accurate study on bare soil was made to distinguish dew from WVA based on the bare soil surface temperature and the dew point temperature (Figure 6). During the study period, WVA represented 66 % of the NRWI on bare soil, while dew contributed only 34 %. Several studies have shown that WVA is the predominant NRWI input vector on bare soil in arid and semiarid environments (Agam and Berliner, 2004; Kaseke et al., 2012; Pan et al., 2010). But the role of WVA and dew on the other surface cover types has not been studied. These MLs and the field installation strategy seem to be a good tool for further studies assessing the contribution of WVA and dew to the NRWI, and, consequently, to the water budget of a given site.

4. CONCLUSIONS

Our automated microlysimeter design, construction and field installation have proven to be a useful and effective tool in a non-rainfall water input study. The automated microlysimeter design enables the measurement of evaporation and water input on different cover types and the sample size makes the study of small plants possible. The different heat capacities of each cover affects the surface temperatures, and therefore, the beginning of the dew deposition. Hence, if the surface temperatures are monitored, dew and water vapour adsorption can be distinguished, and the relative contributions of dew and water vapour adsorption to the non-rainfall water input and, thereby, to the water budget, can be found. This system is an economical and easy method for a non-rainfall water input study.

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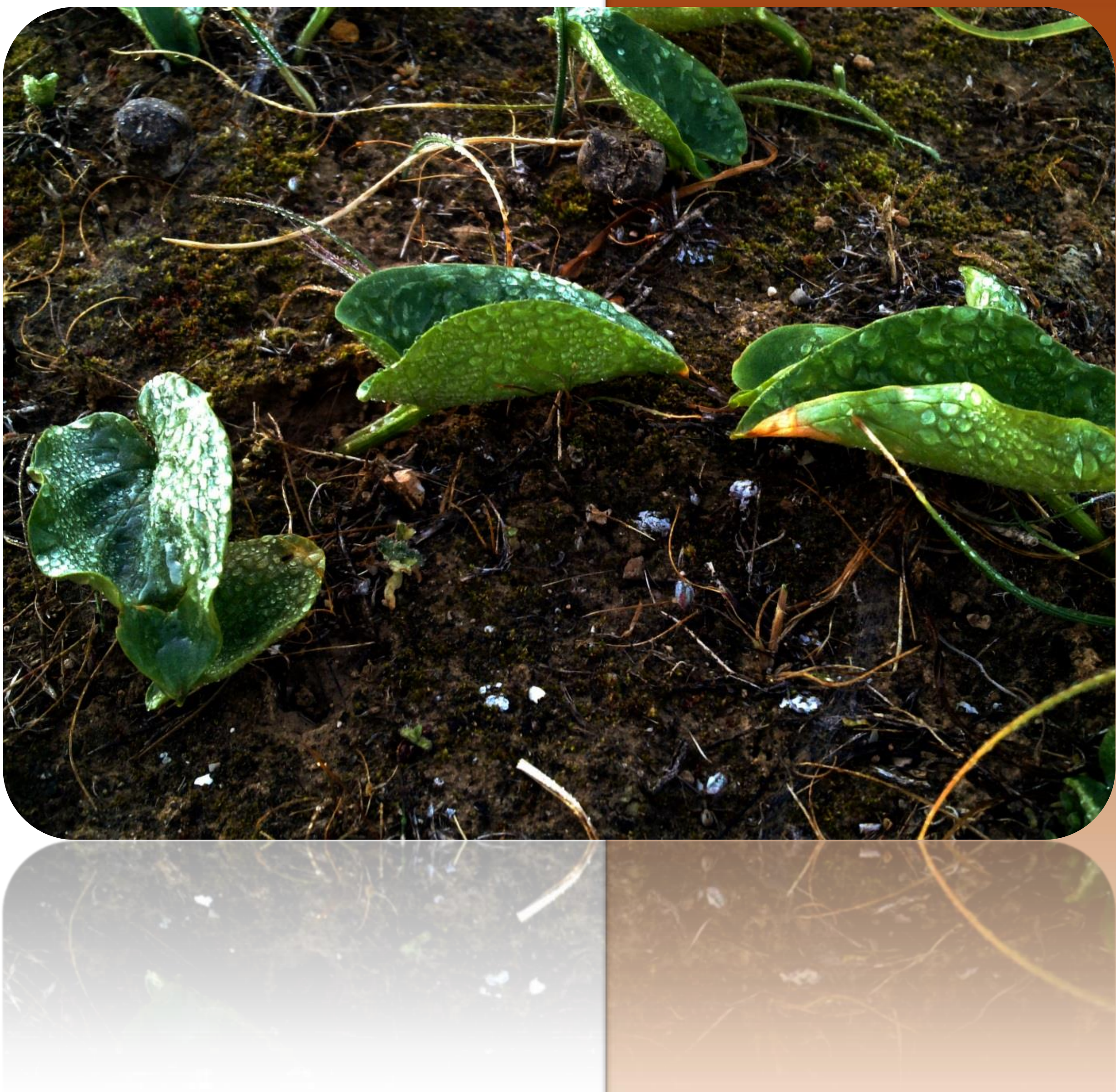
Capítulo II

Partitioning of non-rainfall water input regulated by soil cover type



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Capítulo II

PARTITIONING OF NON-RAINFALL WATER INPUT REGULATED BY SOIL COVER TYPE

Abstract

In arid and semiarid environments, where precipitation is scarce and mainly limited to the wet season of the year, the water contribution by non-rainfall water inputs (NRWI) may play a significant role in the water balance. Natural ecosystems are heterogeneous with a great variety of surface covers, such as stones, biological soil crusts (BSC), bare soil, trees, shrubs and other plants. To be able to understand the role that NRWI may have in a system, all the surface types involved and all the NRWI sources (fog, dew and water vapour adsorption) should be differentiated, analyzed and studied separately. This manuscript study NRWI on different cover surfaces of the soil in a natural coastal-steppe ecosystem. Automated microlysimeters were located in the field containing small *Macrochloa tenacissima* plants, bare soil, stones and biological soil crusts. Daily changes in the water content of the samples were registered. The different sources of NRWI were differentiated and their partial contributions to the total NRWI and to the daily evaporation were analyzed.

Each cover type showed a different response in the presence of NRWI and these responses were also dependent on the NRWI source. In turn, the surface cover influenced the subsequent evaporation the day after. The number of dew events varied with the surface cover type and water vapour adsorption occurred all days in all the covers, alone or preceding a fog or a dew event. Dew represented the main NRWI source in plants and stones, while water vapour adsorption was the main input in bare soil and BSC. Fog was a minor component of the NRWI during the study period and its partial contribution to the total input was similar for all the cover types. NRWI satisfied a great part of the evaporation demand, especially in plants and stones.

Keywords: non-rainfall water input, dew, water vapour adsorption, surface temperature, semiarid, water balance.

1. INTRODUCTION

Free liquid water on the Earth's surface can come from the soil (dew rise), the plants (guttation) and the air (fog, dew, and soil water vapour adsorption) (Garratt and Segal, 1988).

This last source has been called non-rainfall atmospheric water input (NRWI) and has been studied because of its role in the water budget of arid and semiarid ecosystems. Fog occurs when the atmospheric water vapour concentration reaches saturation and a mass of condensed water droplets remains suspended in the air. These droplets can be later intercepted by a surface. Dew forms when the temperature of a surface is lower or equal to the dew point temperature and water directly condenses on it. When this temperature condition is not satisfied and the relative humidity of the air is higher than the relative humidity of the pores in the soil, a water vapour gradient from the atmosphere to the soil is created and water is added to the soil by water vapour adsorption (WVA).

Dew can play a significant role in arid and semiarid regions because of its influence in the water balance (Hao et al., 2012; Jacobs et al., 1999; Moro et al., 2007; Uclés et al., 2013b; Veste et al., 2008). Dew may alleviate water stress on plant leaves in the early morning (Sudmeyer et al., 1994) and some desert plants can use dew as a water source (Ben-Asher et al., 2010; Evenari et al., 1971). It has been reported the influence that dew has on some desert animal communities (Broza, 1979; Moffett, 1985; Steinberger et al., 1989), and in the development of soil microorganisms (Lange et al., 1970) and biological soil crusts (del Prado and Sancho, 2007; Kidron et al., 2002; Lange et al., 1992; Pintado et al., 2005; Rao et al., 2009). WVA contributes a significant amount of water to the soil, affecting its properties and hence the radiation and energy balance (Verhoef et al., 2006) and it can supply plants with water vital to its survival in seasons with a severe water deficit (Ramirez et al., 2007). Fog may play an important role in the hydrological cycle of some ecosystems (del-Val et al., 2006; Hamilton and Seely, 1976) and can be considered a vital water source for endemic flora and fauna (Seely, 1979).

Natural ecosystems are heterogeneous with a great variety of surface covers, such as stones, biological soil crusts (BSC), bare soil, trees, shrubs and other plants. Some studies can be found in the bibliography about NRWI deposition in different surfaces using microlysimeters but they do not differentiate between dew, fog and WVA. Furthermore, because of the difficulty on measuring NRWI on plants, they mainly focus on BSC and bare soil (Liu et al., 2006; Maphangwa et al., 2012; Pan et al., 2010) or in bare soil and mulching (Graf et al., 2004; Li, 2002). Only a few studies can be found regarding the vegetation contribution to the NRWI of a system (Uclés et al., 2013a; Uclés et al., 2013b) and they stated that plants and shrubs can play a significant role in the NRWI. Indeed, Uclés et al. (2013b) found a dew contribution by plants of 64% in a semiarid ecosystem, pointing out the significant role that vegetation may have in dew deposition. Different scenario occurs in bare soils, since several studies found that dew is a rare occurrence on them, and that WVA is the main NRWI in this surface cover (Agam et al., 2004; Kaseke et al., 2012; Pan et al., 2010; Uclés et al., 2013a). On the contrary, dew deposition can be a significant water source in BSC compared with bare soils (Maphangwa et al., 2012; Zhang et al., 2009) and some lichen species have proven to intercept sufficient water from fog and dew to sustain positive net photosynthesis for a considerable portion of the day (Lange et al., 2006). Hence, each cover type shows a different response in the presence of NRWI and these responses are also dependent on the NRWI source; dew, fog or WVA. Therefore, to be able to really understand the role that NRWI may have in an ecosystem, all the surface types involved and all the NRWI sources should be differentiated, analyzed and studied separately. But no bibliography can be found about these responses in the different cover types and over dew, fog and WVA conditions.

In this manuscript we aim to evaluate the differences in NRWI on different cover surfaces of the soil (plants, stones, BSC and bare soil) in a natural ecosystem using automated microlysimeters. We hypothesize that the different sources of NRWI (fog, dew and WVA) contribute differently to the total NRWI and to the daily evaporation (ET) of the surface cover. In turn, the surface cover may also influence the NRWI at night and the subsequent ET the day after. Hence, the different sources of NRWI (fog, dew and WVA) are differentiated and their partial contributions to the total NRWI and to the daily ET are analyzed.

2. MATERIAL AND METHODS

2.1. Study site

The Balsa Blanca experimental field site is a coastal-steppe ecosystem and it is one of the driest areas in Europe. It is located only 6.3 km away from the Mediterranean Sea, in the Cabo de Gata-Níjar Natural Park in Almería, Spain (36º56'30"N, 2º1'58"W, 208 m a.s.l.). Vegetation is sparse and dominated by *Macrochloa tenacissima* (= *Stipa tenacissima*, alpha grass) combined with bare soil, stones and biological soil crusts in the open areas. Its mean annual air temperature is of 18ºC and its long-term average rainfall is 220 mm, mainly in winter [historical data recorded by the Spanish Meteorological Agency (1971-2000); www.aemet.es]. The predominant soils are thin, with varying depths (about 30 cm at most, average 10 cm), alkaline, saturated in carbonates, with moderate stone content and frequent rock outcrops (Rey et al., 2011).

For further information about the site, see Uclés et al., (2013b) and Rey et al. (2011).

2.2. Non-rainfall water input measurement method and data analysis

There is not a standard method or instrument internationally accepted for measuring NRWI, but there has been an increased use of microlysimeters in the last years since they are able to register the different NRWI sources (fog, dew and WVA) in an undisturbed natural surface. In this study, the NRWI amounts were measured by automated microlysimeters (MLs) and their construction, field installation and sample dimensions were done following Uclés et al., (2013a). The MLs were constructed using a single-point aluminium load cell (model 1022, 0.013 x 0.0026 x 0.0022 m, Vishay Tedea-Huntleigh, Switzerland), and the PVC sampling cups were 0.15 m diameter and 0.09 m deep. Field calibrations were successfully made twice a month using standard loads and they had a satisfactory resolution of 0.1 g (0.0055 mm).

Nine automated microlysimeters (MLs) were located in the field. Three microlysimeters contained small *Macrochloa tenacissima* plants, and the other six microlysimeters contained undisturbed soil samples with different surface covers: 2 MLs with bare soil, 2 MLs with stones and other 2 MLs with biological soil crusts (BSC). Plants had a Leaf Area Index (LAI) of around 0.4 m^2 m^{-2}, and were 0.2 m wide and 0.3 m high. Stones were embedded in the soil and covered the 40% of the sample surface. BSCs consisted of cyanobacteria and lichens (mainly *Diploschistes diacapsis and Squamarina lentigera*) and covered the 100% of the sample. Daily changes in the water content of the samples were analysed. Negative changes in mass in the MLs corresponded to ET and positive changes to NRWI, which was calculated as the difference in weight between the night-time maximum and the minimum of the day before. Since the plant and stones samples did not covered the 100% of the surface, some bare soil was directly exposed to the atmosphere and the MLs registered also its NRWI. Hence, in the NRWI calculations of the plant and stones samples, the water amount from bare soil was removed proportionally to its surface cover in the sample using the information provided by the bare soil samples. Hence, the NRWI was referred by the real surface cover of each cover type. It is worthy to mention that the *Macrochloa tenacissima* plants in the area were bigger than the plants used in these samples. No bigger plants could be selected because of the limitation in the capacity rate of the load cell. Nevertheless, this study raises interesting results in the comparison of NRWI between plant and no plant surfaces.

The different NRWI sources for each cover type were also differentiated (dew, fog and WVA). The surface temperature of each of the cover types was compared with the dew point temperature of the air to differentiate between dew and WVA. The surface temperatures were monitored with thermocouples. They were buried 2 - 3 mm in the soil for the monitoring of the BSC and bare soil temperatures (0.2 mm wire core diameter; Thermocouples Type TT-TI-24-SLE, Omega Engineering, Broughton Astley, UK). In the case of stones, thermocouples were inserted into thin fissures of the rock and covered with isolated adhesive tape to avoid the direct insolation from the sun. In the plants, a thinner thermocouple was used (0.13 mm wire core diameter; Thermocouples Type TT-T-36-SLE, Omega Engineering, Broughton Astley, UK) and it was located inside the fold the *Macrochloa tenacissima* leaf has to avoid the direct insolation from the sun and to minimize the air temperature influence. Finally, a fog event was determined when the relative humidity of the air (*RH*) was over 99% and the beginning of a fog event was also corroborated by wetness sensors (model 237, Campbell Scientific, Logan, UT, USA).

Air temperature and *RH* were monitored at a height of 0.5 m by a thermo-hygrometer (HMP45C, Campbell Scientific, Logan, UT, USA) with an accuracy of ±3%*RH* (90 to 100 % *RH*) and rainfall was measured by a tipping bucket rain gauge (ARG 100, Campbell Scientific, Logan, UT, USA). MLs and meteorological data were recorded at 15-second intervals and averaged every 15 min by dataloggers (CR1000, Campbell Scientific, Logan, UT, USA). The study was developed during 74 days (Doy 121-195, year 2012) and only one small rainfall event occurred during this period (Doy 170, 1.2 mm).

An estimation of the contribution of each cover type to the total NRWI in the ecosystem was done as follows. The specific amounts calculated with the MLs samples for each cover type were extrapolated to the total ecosystem using their ecosystem coverage in the case of bare soil (2.3%), BSCs (20.8%) and stones (12.2%). As referred before, the plants used in this study were smaller than the plants presented in the area. For this reason, the NRWI in these plants was calculated in terms of liters of water in m^2 of leaves using the LAI of each plant. After that, the contribution of plants to the entire ecosystem was estimated using the ecosystem LAI (0.46, 0.32, 0.19 and 0.14 in April, May, June and July, respectively) which was calculated from the extrapolation of the canopy LAI to the vegetation cover using the linear relation of the Macrochloa tenacissima Normalized Difference Vegetation Index (NDVI) (Unpublished results).

3. RESULTS

3.1. Analysis of surface temperatures

As represented on a typical dew night in Figure 1, surface temperatures varied with the cover type. The stones temperature (*Tstones*) during the day was the highest one, followed by the bare soil (*Tsoil*) and BSC (*Tbsc*). The plant temperature (*Tplant*) was the lowest one and it was slightly higher than the air temperature (*Tair*). During the night, *Tstones* was the lowest temperature, followed by *Tplant*, *Tair*, *Tbsc* and *Tsoil*. When the temperatures descended during the evening, *Tstones* reached firstly the dew point temperature (*Tdew*) followed by *Tplant* and *Tair*. Later in the night, *Tbsc* reached *Tdew* and, finally, *Tsoil* did it. Hence, dew condensation took place in all the covers during this night. In the morning, *Tsoil* exceeded *Tdew* in the first place and it was followed by *Tbsc*, *Tair*, *Tplant* and *Tstones*. So, surface temperatures raised *Tdew* following the contrary order than they did in the evening.

The averaged (± Standard deviation) period of time the surface temperatures were under *Tdew* for all the period analyzed was similar for plants and stones, with 7.0±2.9 hours $night^{-1}$ and 7.8±2.0 hours $night^{-1}$, respectively. Bare soil registered the lowest values with 2.0±2.0 hours $night^{-1}$ and BSC registered 3.6±2.1 hours $night^{-1}$.

3.2. Non-rainfall water input results

Maximum water input values occurred at 6:00±1 hours (1-2 hours after sunrise) regardless the surface cover type. This maximum water input at dawn was also found by other researchers (Brown et al., 2008; Kaseke et al., 2012) who stated that the daytime after sunrise plays an important role in the NRWI since the early sunbeams cause a slight turbulence that increases the humidity of the air overlaying the soil surface and allows a continuous dew condensation during the early morning (Kidron, 2000a; Kidron et al., 2000; Pan et al., 2010; Zhang et al., 2009).

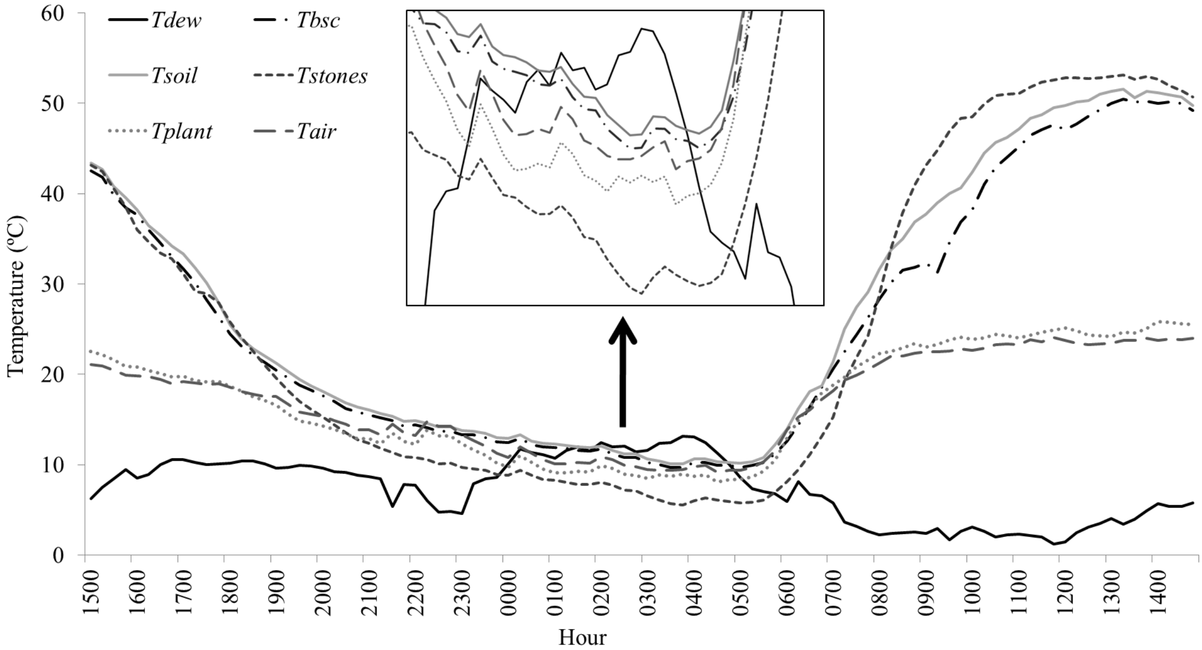

Figure 1. *Surface temperatures, air temperature and dew point temperature (Doy 142-143, year 2012).*

The total water incorporated in the ecosystem by NRWI during the study period varied with the surface cover type, with maximum values on plants (Fig. 2). WVA occurred all days in all the cover types, alone or preceding a fog or a dew event. Six fog events were registered and the number of dew events varied with the surface cover type (Fig. 2). Dew represented the main NRWI source in plants and stones, while WVA was the main input in bare soil and BSC. Fog was a minor component of the NRWI during the study period and its partial contribution to the total input was similar for all the covers.

Mean daily rates were calculated for each NRWI source separately (Fig. 4). Since the purpose of this figure is to analyze the rate differences between the different events, these rates are expressed in mm of water input (dew, fog or WVA) per night and no zeroes were added in the average when no input occurred at any of the surface covers. Fog rates were similar in all the cover types and only a higher fog rate was found in plants. Fog rates represented the largest rate, except for stones, where dew rates were the highest ones. WVA rates were significantly lower than fog and dew rates in plants and stones. On the contrary, dew rates were the lowest ones in bare soil and BSC.

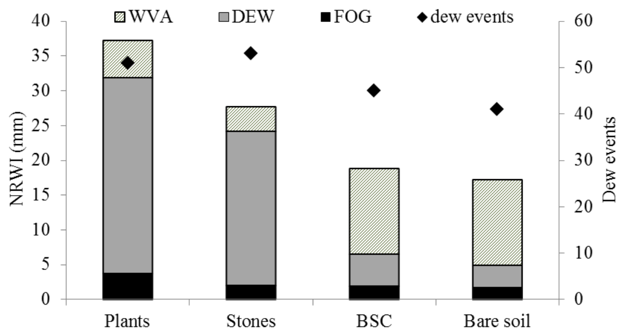

Figure 2. *Total non-rainfall water input (NRWI) and partial contributions of fog, dew and WVA to the total NRWI in the different cover types (histogram) and number of dew events (diamonds) during all the study period (Doy 121-195, year 2012).*

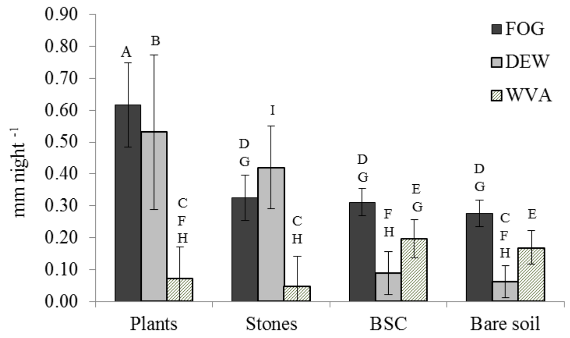

Figure 3. *Mean daily rates for fog, dew and water vapour adsorption (WVA) events in the different cover types. Standard deviation in bars. Fisher's least significant difference (LSD) post hoc test. Different letters denote statistical significance at* $p < 0.05$. *(Doy 121 195, year 2012).*

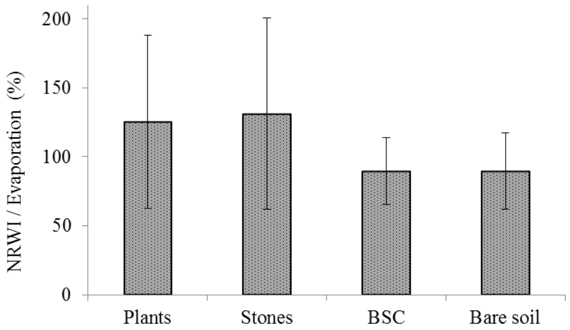

Figure 4. *Ratio between evaporation and the non-rainfall water input (NRWI) of the night before. (Doy 121-195, year 2012).*

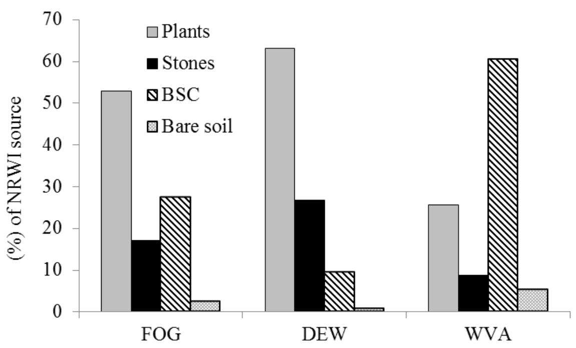

Figure 5. *The relative contribution of each cover type to dew, fog and water vapour adsorption (WVA) in the total ecosystem for all the study period. (Doy 121-195, year 2012).*

Finally, taking into account that nocturnal NRWI usually evaporates the following morning, the daily evaporation was compared to the NRWI of the night before in each of the cover types to clarify the importance of NRWI in the site (Fig. 4). NRWI satisfied a great part of the evaporation demand, especially in plants and stones where NRWI exceed the evaporation.

Total NRWI values in the different cover types during the study period were extrapolated to the entire ecosystem to elucidate the total ecosystem NRWI amount and the contribution of each cover in the total fog, dew and WVA of the site (Fig. 5). A great contribution of BSC in the WVA input was found while dew was mainly incorporated in the ecosystem by plants and stones.

4. DISCUSSION

The representativeness of the sources of NRWI (fog, dew and WVA) was dependent on the surface cover type. Since dew played a significant role in the water input of plants and stones, WVA was the dominant NRWI source in BSC and bare soil. At ecosystem level, dew was mainly incorporated in the ecosystem by plants and stones and it is worthy to mention that besides its reduced coverage proportion, BSC contributed with about the 70% of the WVA input in the ecosystem. Bare soil did not play a significant role in the NRWI, mainly justified by its minor ecosystem coverage (2.1%). However, in desert ecosystems, where bare soil is the predominant surface cover, the NRWI in this surface may play a major role in the water balance of the system (Agam and Berliner, 2004; Verhoef et al., 2006).

This dew preference on plants and stones may be explained by their lower surface temperature at night which entails a higher dew occurrence and a longer duration of these events. Indeed, daily dew rates differences between covers shall be mainly explained by these two factors. Regarding the surface temperature, the higher the differences in nocturnal surface temperatures of two surfaces with the dew point temperature, the higher the difference in the dew amounts (Kidron, 2010). Stones registered the highest temperatures during the day and, contrary to what may be expected with large-volume stones that may store their heat for long (Kidron, 2010), they registered the lowest temperatures during the night, attesting an efficient longwave radiational cooling and registering the highest dew rates, followed by plants, BSC and bare soil. On the other hand, dew deposition is highly dependent on dew duration (Beysens et al., 2005; Kidron, 2000b; Uclés et al., 2013b; Zangvil, 1996). Since plants and stones registered the longest durations of their surface temperatures below the dew point temperature, their daily dew rates were significantly higher than BSC and bare soils rates.

WVA occurred all days in all the cover types during the study period, alone or preceding a fog or a dew event. Our results are in accordance with other studies in arid and semiarid environments which found WVA to be the highest NRWI source in BSC (Maphangwa et al., 2012) and in bare soils (Agam and Berliner, 2004; Kaseke et al., 2012; Maphangwa et al., 2012; Ninari and Berliner, 2002). The daily fog rates were similar in all the cover types since the surface temperatures do not interfere in the fog interception. The higher fog rate found in plants may be explained by their higher surface in contact with the mass of droplets suspended in the air. Furthermore, plants with rosette growth forms and flexible narrow leaves (as *Macrochloa tenacissima*, used in this study) have proven to be particularly efficient as fog interceptors (Martorell and Ezcurra, 2007).

It is worthy to mention the effect that stones and BSC have in the bare soil surface. In accordance with other authors (Danalatos et al., 1995; van Wesemael et al., 1995), WVA was drastically reduced by the presence of stones embedded in the soil surface because they have a negative effect on the WVA by reducing the soil-atmosphere interface (Kosmas et al., 1998). However, some WVA was recorded in the stones surface samples, explained by the adsorption of water molecules in the porosity of the stones or by the soil underneath. NRWI satisfied a great part of the evaporation demand in all the cover types but a great reduction in the water evaporation rate in samples with embedded stones in their soil surface was found, effect also registered by Danalatos et al. (1995) and Wesemail et al. (1995). Hence, although the presence of stones in the soil surface reduces the amount of WVA during the night, their overall effect in soil moisture conservation, as compared to the bare soil, is positive by protecting the transmitted water vapour under the stones from the evaporative losses during the day (Kosmas et al., 1998) and by increasing the dew condensation.

Finally, the higher dew and WVA rates in BSC compared with bare soil are in agreement with other studies (Pan et al., 2010; Zhang et al., 2009) and may be explained by the presence of exopolysaccharides (EPS) in the biocrust surface. It has been proven that EPS are involved in the mechanisms of dew deposition (Fischer et al., 2012) and that they play a significant role in giving a spongy structure to BSC that increases WVA (Rossi et al., 2012). EPS enhance the capability of BSC to trap water molecules and have been referred as the responsible of the NRWI uptake by BSC (Colica et al., 2014). The occurrence of dew is an important factor in the growth and development of BSC in extremely harsh environments (Zangvil, 1996). Since net photosynthesis on cyanobacterial crust necessitates liquid water above 0.1 mm (Lange et al., 1992), our results highlights the role that dew and fog may play in the BSCs activity. Indeed, some lichen species have proven to intercept sufficient water from fog and dew to sustain positive net photosynthesis for a considerable portion of the day (Lange et al., 2006). The influence the water uptake by WVA has on BSC has not been studied, and our results indicate that this water input may also have an interesting effect in the BSC development.

Several studies can be found about the positive effect NRWI have on vegetation. Plant canopies are ideal dew and fog interceptors (Vogel and Müller-Doblies, 2011) and the excess of water harvested over the canopy-storage capacity is transferred to the soil surface via stem flow or leaf drip where it is absorbed by the plant root system (Hutley et al., 1997). Also the adsorption of atmospheric water vapour by soils and its uptake by the superficial roots of plants are vital in sustaining their growth and survival and in determining their distributions and relative abundance in arid zones (Matimati et al., 2013). Similarly, our results point out a significant water supply by NRWI on plants, providing water on their surface and in the soil underneath.

5. CONCLUSIONS

The differences in the surface temperatures of each cover type affect the duration of the dew deposition, which, in turn, is directly related to the dew deposition amount. Stones and plants showed the highest number of dew events, dew durations and dew rates, since bare soils registered the lowest values. WVA occurred all days in all the cover types and bare soil and BSC registered the highest rates and amounts. Since the surface temperature does not interfere in the fog interception, fog rates were similar in all the cover types.

The total amount of NRWI during the study period highlighted a minor contribution of bare soil in the total input and a significant participation of plants, BSC and stones. Furthermore, the representativeness of the sources of NRWI (fog, dew and WVA) was dependent of the surface cover type. Water vapour adsorption comprised the largest component of NRWI intercepted by soil and lichens, while dew represented the main NRWI source in plants and stones. NRWI satisfied a great part of the evaporation demand in all the cover types during the study period and may represent an important water source for the ecosystem.

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Capítulo III

Non-rainfall water inputs are controlled by aspect in a semiarid ecosystem

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Capítulo III

NON-RAINFALL WATER INPUTS ARE CONTROLLED BY ASPECT IN A SEMIARID ECOSYSTEM

Abstract

Differences in vegetation pattern between slope aspects in semiarid environments are well known, with shaded aspects presenting a higher biomass. The micrometeorological and soil conditions involved in non rainfall water inputs (NRWI), comprising dew and water vapour adsorption (WVA) were compared between two contrasted slopes and different environmental conditions (wet and dry periods). Changes in natural soil surfaces were measured using automated microlysimeters, and the partial contributions of dew and WVA to the total NRWI were clarified. Dew amounts were higher on the northeast facing slope and were directly related to dew durations. Differences in dew deposition between slopes were mainly driven by insolation patterns, which controlled the surface temperatures, the soil water content and, in turn, dew duration. Apart from spatial variation in microclimate, WVA deposition was higher in the southwest facing slope due to its higher clay content and electric conductivity and because of its lower soil water content. Water vapour adsorption was directly governed by the relative humidity amplitude in summer (with dry soil) but not in winter. A significant amount of water evaporation was satisfied by NRWI, reaching 100% in dry periods and being WVA the main input.

Keywords: slope, aspect, microlysimeter, dew, water vapour adsorption, insolation

1. INTRODUCTION

The non-rainfall water input (NRWI) composed of fog, dew and water vapour adsorption (WVA) may play a significant role in the water balance of arid and semiarid environments, where water availability is an important limiting factor. Fog consists of the condensation of water droplets in the air because of saturation of the water vapour concentration. Dew forms when vapour water is directly condensed on a surface because of its lower surface temperature compared with the dew point temperature of the air. Finally, WVA occurs when this temperature condition is not achieved and the water uptake by the soil is governed by a gradient in the water vapour pressure between the soil and the free atmosphere.

Dew has been studied in arid and semiarid environments because of its significant role in the water budget (Jacobs et al., 1999; Uclés et al., 2013b). It is also an important water source for animals (Steinberger et al., 1989), plants (Ben-Asher et al., 2010) and biological soil crusts (del Prado and Sancho, 2007; Lange et al., 1997; Pintado et al., 2005). Consequently, many attempts have been made to quantify dew in arid and semiarid environments. Its low amount and the difficulty in measuring it have resulted in the use of a great variety of methods, not always comparable, such as theoretical models (Kalthoff et al., 2006; Uclés et al., 2013b) or artificial condensing surfaces (Duvdevani, 1947; Kidron, 2000; Zangvil, 1996). Theoretical methods are often difficult to implement and require a great amount of data input, while artificial surfaces are easier to implement but under- or over-estimate dew, because their surface properties are different from natural ones. In the past few years, manual (Jacobs et al., 2000; Ninari and Berliner, 2002) and automated microlysimeters (Heusinkveld et al., 2006; Kaseke et al., 2012; Uclés et al., 2013a; Uclés et al., 2013b) have been used more frequently in dew studies, which is advantageous, because measurements are made over natural surfaces. In addition, microlysimeters not only register dew but also WVA, which contributes a significant amount of water to the soil (Kosmas et al., 1998), affecting its surface properties and hence the radiation and energy balance (Verhoef et al., 2006). Water vapour adsorption may also supply water to vegetation that can be vital to its survival in seasons with a severe water deficit, giving rise to a close relationship between soil water dynamics and plant water response, and playing a significant role in the stomata conductance and transpiration of vegetation (Ramirez et al., 2007). Its theoretical quantification, e.g. by use of the aerodynamic diffusion equation (Milly, 1984), requires a great amount of meteorological and soil data, which can be difficult to obtain. Some attempts have also been made using empirical equations based on meteorological factors, such as the daily relative humidity amplitude (Kosmas et al., 1998) or the soil evaporation of the day before (Agam and Berliner, 2004), but these equations may lead to inaccurate estimates of WVA when used for a site or season different from the one for which the equation parameters were derived (Verhoef et al., 2006). Microlysimeters have become the most used WVA quantification method and some studies have reported WVA as the predominant input vector in bare soils in arid and semiarid environments (Agam and Berliner, 2004; Kaseke et al., 2012; Pan et al., 2010).

NRWI (mainly dew) have been measured in several arid and semiarid environments, but few efforts have already been made to study its variability among habitats, such as different slope aspects. There are differences in the vegetation pattern between sun-facing and shaded slopes in semiarid environments because they are exposed to different micrometeorological conditions. Normally, the shaded slopes present a higher biomass (Jacobs et al., 2000; Kappen et al., 1980; Kidron, 2005; Lázaro et al., 2008) as a result of the differences in solar radiation, which affects soil properties and, in turn, vegetation and fauna (Kutiel and Lavee, 1999). A few authors have examined differences in the deposition of dew between aspects, but unfortunately, none of them has studied WVA, and in many cases their results were contradictory. Studies using the cloth plate method (CPM) have reported that aspect controls dew precipitation in the Negev with higher dew depositions in the shaded (northwest) than in the sun-facing (southeast) aspects (Kidron, 2005; Kidron et al., 2000) and with the lowest dew amounts in the wadi bed (Kidron et al., 2000). Other studies in the Negev, however, using microlysimeters have shown a different pattern, with higher dew depositions in the sunny slopes (Jacobs et al., 2000) and with the highest dew amounts in the wadi bed (Heusinkveld et al., 2006). Furthermore, these studies were developed during or after the dry season (summer or autumn) but no data in the wet season or with wet soil are available in the literature. Dew and WVA are different processes to study, and their relationship with the micrometeorological variables and soil properties should be examined separately and in different seasons.

We hypothesized that WVA would play an important role in the NRWI and could account for the observations of differences in NRWI amounts between different aspects. We present a study of the water uptake by soil using natural surfaces in a badland ecosystem (El Cautivo, Southeast Spain) characterized by contrasting vegetated (dwarf shrubs, biocrusts, annual plants and grasses) north- to east-facing slopes and bare and eroded south- to west-facing slopes. Non-rainfall water input sources (dew and WVA) and their partial contributions to the total NRWI are differentiated and compared between these two contrasted aspects using automated microlysimeters in a wet and a dry periods.

2. MATERIAL AND METHODS

2.1. Study site

The El Cautivo field site is a badland ecosystem located in the Neogene–Quaternary Sorbas-Tabernas basin in Almería, Southeast Spain (N37º00'37'', W2º26'30''; Fig.1). The site is surrounded by several ranges that are around 2000 m a.s.l.: Sierra de Gádor, Sierra Nevada, Sierra de Filabres and Sierra Alhamilla. Altitude in the study site varies from 247.5 to

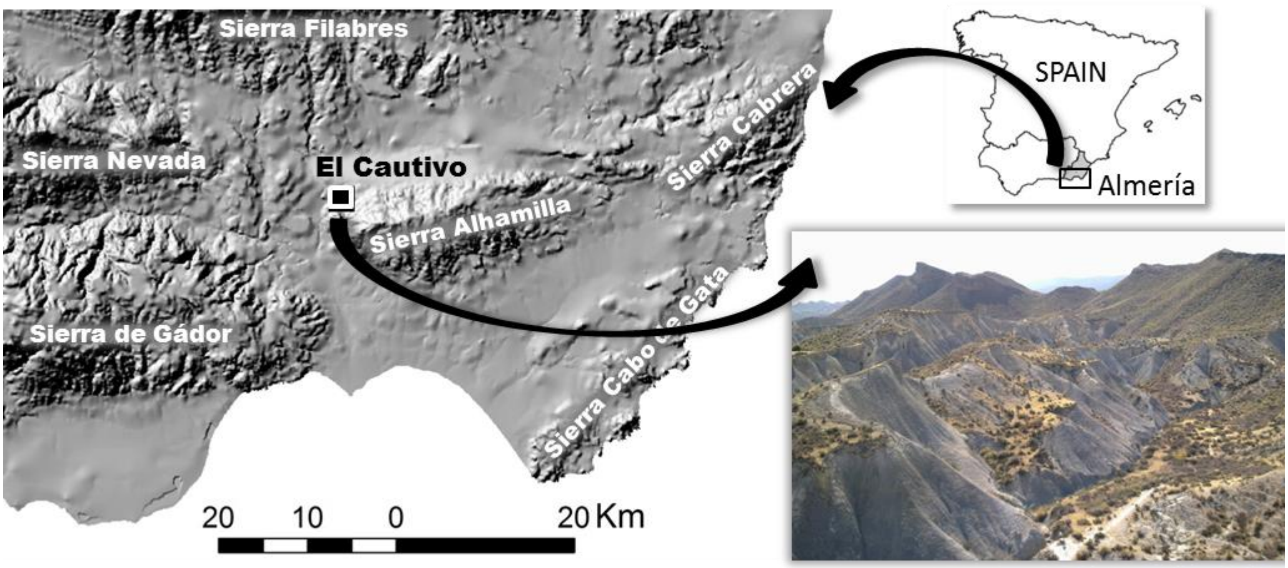

Figure 1. *Study site location.*

382.5 m a.s.l. Several studies related to its geomorphological, hydrological and erosion properties have been carried out at the site (Cantón et al., 2004; Lázaro et al., 2008). The climate is semiarid thermo-Mediterranean, with a mean annual temperature of 17.8 ºC and a mean annual rainfall of 235 mm, mostly in winter, as recorded over a 30 years period (1967–1997) in Tabernas (5 km from the site) (Lázaro et al., 2001). The predominant wind directions in the site are northwest in winter and southeast in summer (Lázaro et al., 2004). The most obvious features of these badlands are their vegetation pattern: northeast-facing slopes (*NEF*) are covered by vegetation: grasses, dwarf shrubs, annuals and an important cover of biological soil crusts (BSC) including many species of terricolous lichens (*Diploschistes diacapsis, Squamarina lentigera, Lepraria isidiata)* and often patches dominated by cyanobacteria, while southwest facing slopes (*SWF*) have a less developed soil, a minor vegetation and BSC cover *(Diploschistes diacapsis*, *Fulgensia desertorum*, *Endocarpon pusillum)* and were formerly bare and eroded (Lázaro et al., 2008). The average cover is 38% plants and 55% BSC in the *NEF slopes* and 2% plants and 18% BSC in the *SWF* slopes. Soils on both slopes have a silty loam texture but their composition and electric conductivity vary: 20.9% clay, 60.8% silt, 15.9% fine sand, 2.4% coarse sand and 0.029 dS m^{-1} in the *NEF* slopes; and 24.0% clay, 63.8% silt, 12.0% fine sand, 0.2% coarse sand and 0.061 dS m^{-1} in the *SWF* slopes (Cantón et al., 2003).

2.2. Meteorological measurements

The micrometeorological and soil conditions involved in dew and WVA depositions are studied and compared between the two contrasted slopes. The mean micrometeorological variables that were monitored were: insolation, relative humidity, wind velocity, soil water content, dew point temperature and air and soil surface temperatures. Both slopes in the experimental area were equipped with two micrometeorological stations. Each of them was composed by:

Soil thermocouples (TCAV, Campbell Scientific, Logan, UT, USA) which averaged temperature was used to correct the soil water content (CS616, Campbell Campbell Scientific, Logan, UT, USA). Air temperature and relative humidity (*RH*) were monitored at a height of 0.5 m by a thermo-hygrometer (HMP45C, Campbell Scientific, Logan, UT, USA). Rainfall was measured by a tipping bucket rain gauge (ARG 100, Campbell Scientific, Logan, UT, USA) and wind speed was measured at a height of 0.5 m (A100L2, Campbell Scientific, Logan, UT, USA). Soil surface temperature (*Ts*) in both slopes was monitored by thermocouples buried 0.002-0.003 m deep (Type T, Thermocouples, Omega Engineering, Broughton Astley, UK). Total monthly potential insolation as well as the monthly duration of direct incoming solar radiation were calculated for each slope under clear sky conditions using the Solar Radiation tool in ESRI ® ArcMap 10.1 and based on a 1 m resolution Digital Elevation Model obtained from an airborne light detection and ranging (LiDAR) survey with a resolution of 4 height points per square metre.

2.3. Microlysimeters measurements

Two automated microlysimeters (ML) were located at each aspect to register the water changes in the uppermost soil layer. The undisturbed soil samples were taken from the respective slopes. The samples surfaces were largely covered by biocrusts (mainly lichens) and by some cyanobacteria and bare soil. The selected soil samples had a similar biocrust cover to minimise the influence of the variability of their cover or composition in the study. It was assumed that differences in the crust cover or composition were negligible and that differences in NRWI in the ML between slopes were mainly driven by the topography, hence by exposure and the composition of the soil matrix. To include the season variability, the study was developed during one month in winter [day of the year (doy) 19-49] and one month in summer (doy 141-169). A total of 29 nights were analysed per period. The last rainfall event before the winter period took place the doy 15 with 13.8 mm and two small rainfall events occurred during the study period: 4 mm the doy 27 and 0.5 mm the doy 32 (negligible).

The ML were constructed using a single-point aluminium load cell (model 1022, 0.013 x 0.0026 x 0.0022 m, Vishay Tedea-Huntleigh, Switzerland), following Uclés et al. (2013a). PVC sampling cups were 0.152 m diameter and 0.09 m deep, because a previous research (Uclés et al., 2013a) confirmed its adequacy on a NRWI study. The ML and meteorological data were recorded at 15-second intervals and averaged every 30 min by data loggers (CR1000, Campbell Scientific, Logan, UT, USA). The ML calibration probes were satisfactory in the laboratory and in the field, where a basal noise of 0.001 mm was found, in agreement with Uclés et al. (2013a). Daily changes in the water content of the uppermost soil layer were analysed. Negative changes in the mass of the ML corresponded to evaporation and positive changes to NRWI, which were calculated as the difference in weight between the night-time maximum and the minimum from the previous day. Since the conditions conducive for WVA preclude dew from occurring concurrently and vice versa (Brown et al., 2008), *Ts* was compared with the dew point temperature to differentiate between dew and WVA. Dew was considered when positive changes in mass in the ML matched with *Ts* below the dew point temperature and the rest of water input was assumed to be WVA.

3. RESULTS

There was no significant differences in air temperature (P=0.80), or relative humidity (*RH)* (P=0.79) between slopes (Kruskal Wallis non-parametric ANOVA). Mean wind speed difference between aspects was 0.15 m s^{-1} which was in the range of the anemometer accuracy (1% 0.1 m s^{-1}); hence no significant differences between slopes were found either.

RH fluctuated during the day, with a daily average amplitude of 46% (Fig. 2). Furthermore, maximum and minimum *RH* values were slightly lower in summer.

The soil water content (SWC) at 0.04 m depth was higher in winter and was significantly lower (Oneway ANOVA, P<0.0001) in the *SWF*

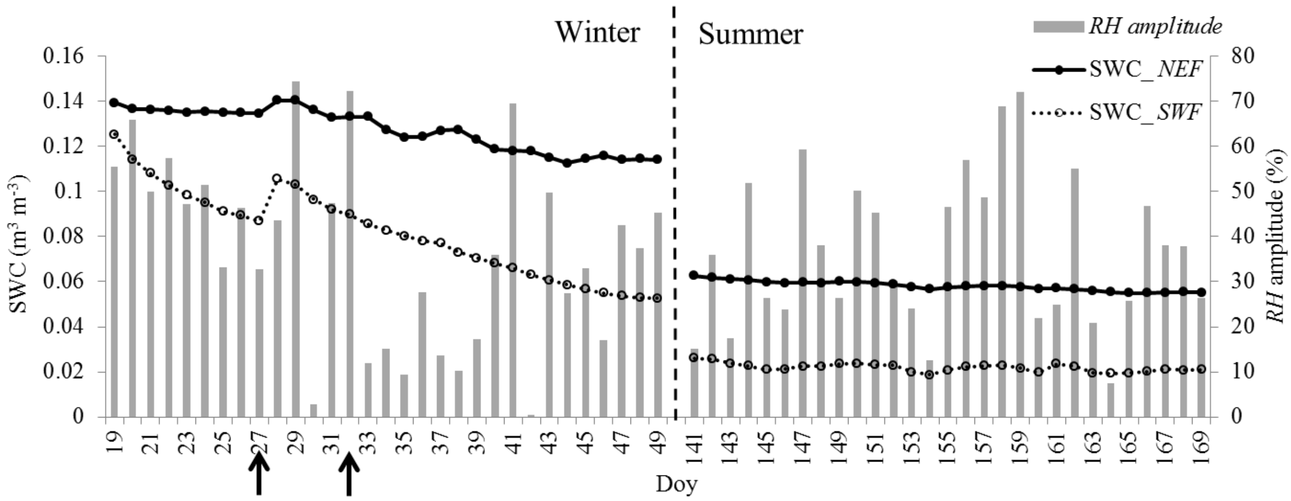

Figure 2. *Soil water content (SWC) in the Northeast (NEF) and in the Southwest (SWF) facing slopes and relative humidity (RH) amplitude during the study periods. Rainfall events occurred on doy 15 (13.8mm), 27 (4 mm) and 32 (0.5, negligible) (rainfalls during the study period are indicated by arrows).*

slope during all the study periods (Fig. 2). It is worthy to mention that the SWC during the winter period was continuously decreasing from the previous rainfall and the *SWF* slope loses its moisture faster than the *NEF* slope.

The total monthly potential insolation and duration showed a season-dependent pattern, with higher values in summer. Its pattern also differed among slopes (Fig. 3), with higher potential insolation values in the *SWF* slope. Insolation duration was longer in the *SWF* slope in winter but in the *NEF* slope in summer.

Insolation occurred earlier in the morning in the *SWF* slope in winter, but the opposite in summer. Furthermore, shading in the evening occurred earlier in the *NEF* slope in summer and at the same time in both aspects in winter. The soil surface temperature (*Ts*) patterns were different between seasons and aspects and agreed with the insolation patterns (Fig. 4). In winter, maximum *Ts* was 18.5 ± 4.3 ºC higher in the *SWF* slope. In the evening *Ts* started to decrease in both slopes at the same time and it first reached its minimum value in the *NEF* slope. For dew events, *Ts* in the *NEF* slope was below the dew point temperature for 4.5 ± 2.5 hours longer than in the *SWF* slope and more dew events occurred in the *NEF* slope (Fig. 4).

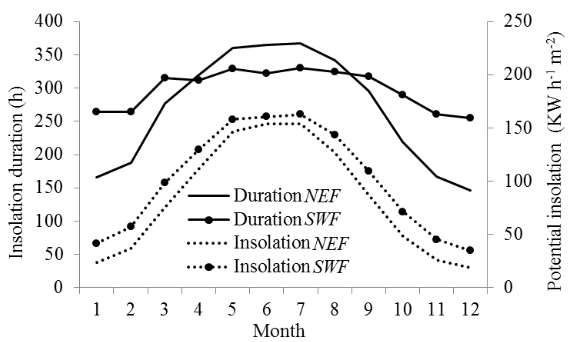

Figure 3. *Monthly potential insolation and duration in the Northeast (NEF) and in the Southwest (SWF) facing slopes during the year.*

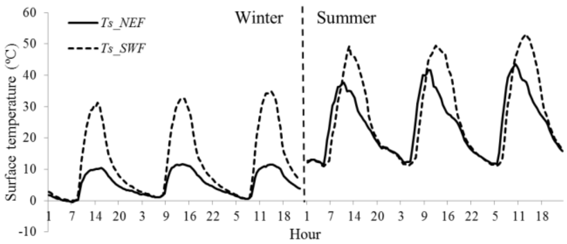

Figure 4. *Surface temperature (Ts) comparisons between the Northeast (NEF) and the Southwest (SWF) facing slopes in winter (doy 20-22) and summer (doy 142-144).*

In the early morning, sun insolation started slightly earlier in the *SWF* slope and its *Ts* started to rise earlier than in the *NEF* slope. In the dry season, differences in *Ts* between aspects diminished. Maximum *Ts* was 11.6 ± 2.3 ºC higher in the *SWF* slope while in the evening the shading effect and the decrease of *Ts* started earlier in the *NEF* slope (Fig. 4). The amount of time *Ts* remained at the minimum values was reduced compared to the wet season. The duration that *Ts* was under the dew point temperature was 1.5 ± 1.4 hours longer in the *NEF* slope where more dew events occurred. Dew frequency in summer was lower than in winter (Fig. 5). During the early morning hours, insolation and the rising of *Ts* took place earlier in the *NEF* slope.

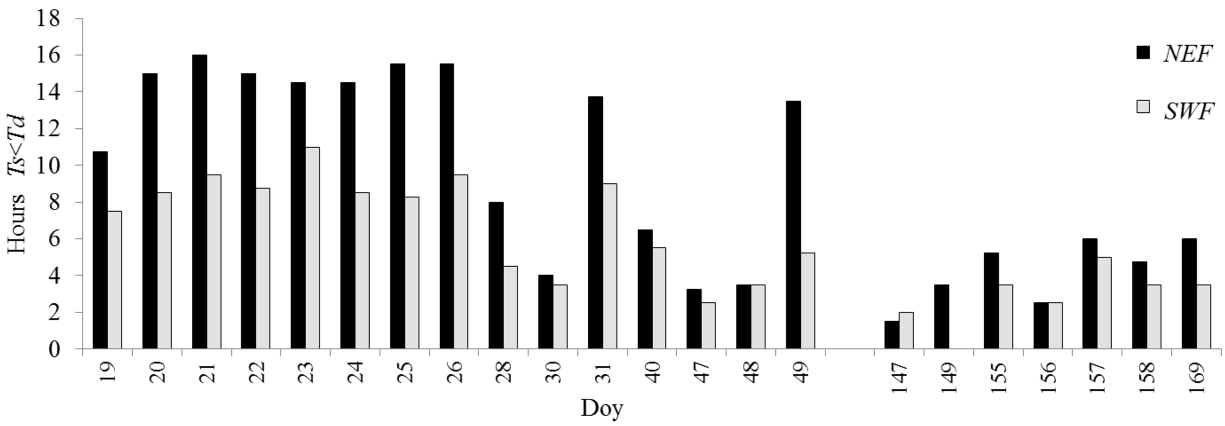

Figure 5. *Length of time during which surface temperature (Ts) was lower than the dew point temperature (Td) in the Northeast (NEF) and in the Southwest (SWF) facing slopes during the study periods (only dewy days are represented in the graph).*

The insolation and *Ts* patterns agreed with the ML data (Fig. 6). In winter, the ML maximum values were recorded later in the *NEF* slope because of a continuation of the input phase while the sun insolation started the evaporation process in the *SWF* slope. In summer, maximum ML values occurred at the same time in both slopes, but evaporation started later in the *SWF* slope. Dew only occurred with *RH* over 80% and the ML signals followed the same trend than *RH*, especially in summer (Fig. 6). This figure also shows a sharp *RH* increase during the afternoon.

Daily dew amounts were higher in the *NEF* slope than in the *SWF* slope (Table 1). Hourly dew rates were similar in both slopes in winter and rates were slightly higher in the *NEF* slope in summer. When daily dew amounts were compared with the dew duration of the events, a good linear relationship was found in both slopes (Fig. 7). The opposite pattern was found with WVA, with higher rates and daily depositions in summer and in the *SWF* slope. WVA began at 18:00 hours in winter and around 16:00 hours in summer and was dependent on the daily amplitude of RH, especially in summer (Fig. 8).

Total NRWI was higher in summer than in winter. No significant differences between quantities and durations of NRWI between aspects were found, and only a slightly higher amount in the *SWF slope* because of its intense WVA deposition was found (Table 1). Finally, the evaporation during the day was compared with the NRWI during the evening and the previous night. The NRWI provided one third of the evaporation in the *NEF* slope and almost half of the evaporation in the *SWF* slope during winter and represented the entire evaporation amount in summer. Furthermore, in winter, WVA represented the 30 % of the NRWI in the *NEF* slope and the 60% in the *SWF* slope and it was the main water input in summer.

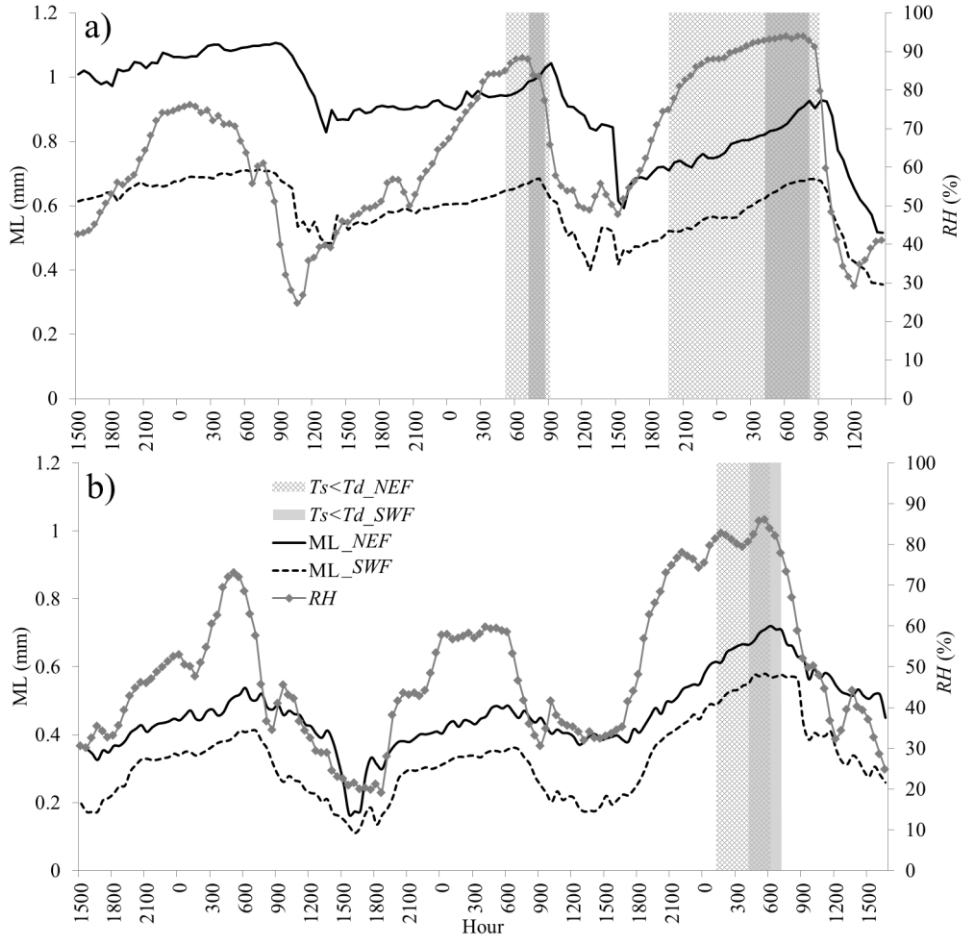

Figure 6. *Microlysimeter data in the Northeast (MLs_NEF) and the Southwest (MLs_SWF) facing slopes and relative humidity (RH). Bars indicate the amount of time the surface temperature was below the dew point temperature in the Northeast (Ts<Td_NEF, ragged bars) and in the Southwest (Ts<Td_SWF, grey bars) facing slopes. a) Winter, doy 46-48; sunrise: 7.50h; dusk: 19.00h. b) Summer, doy 167-169; sunrise: 6.45h; dusk: 21.30h. Hours refer to solar time.*

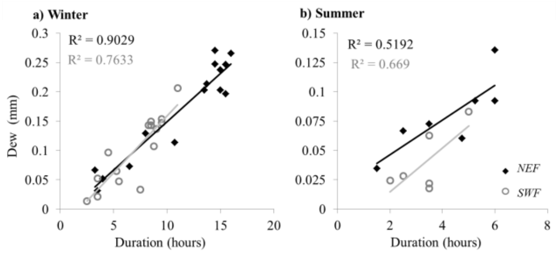

***Figure 7**. Relationship between daily dew duration and dew amounts during the study periods.*

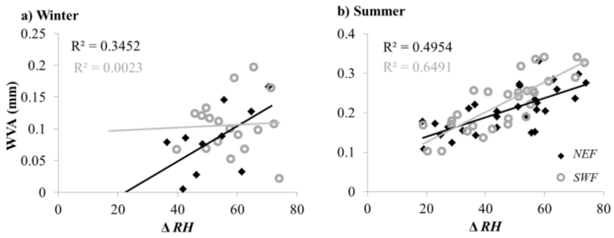

***Figure 8.** Relationship between daily water vapour adsorption amount (WVA) and the amplitude of the relative humidity (ΔRH).*

***Table 1.** Total non-rainfall water input (NRWI), dew and water vapour adsorption (WVA) on the Northeast (NEF) and Southwest (SWF) facing slopes.*

		Winter		Summer	
		NEF	***SWF***	***NEF***	***SWF***
NRWI	total mm (*)	3.22	3.47	6.17	7.40
DEW	events	15	14	8	6
	mm day^{-1} (**)	0.159±0.082	0.107±0.060	0.086±0.037	0.040±0.026
	mm hour^{-1}	0.014±0.003	0.014±0.005	0.011±0.003	0.006±0.003
WVA	events	10	18	29	29
	mm day^{-1} (**)	0.079±0.051	0.109±0.054	0.190±0.057	0.247±0.071
	mm hour^{-1}	0.009±0.005	0.014±0.005	0.017±0.007	0.020±0.007
WVA/NRWI	daily (%)	32.98	61.13	91.96	97.76
NRWI/EVAP	daily (%)	32.64	45.52	104.6	98.42

(*) Total mm refers to the accumulated NRWI during the entire study period

(**) Days with no input were excluded from the averages

4. DISCUSSION

4.1. Non-rainfall water input and related meteorological variables

Dew deposition was dependent on the duration of the dew event, as seen in the Negev, Israel (Kidron, 2000; Kidron et al., 2000; Zangvil, 1996) in Corsica, France (Beysens et al., 2005) and in Almería, Spain (Uclés et al., 2013b). In winter, dew condensation took place after dawn (8:00 hours), may be influenced by the slight turbulence triggered by the early sunlight, as demonstrated in other sites near the sea, such as the Negev Desert, Israel (Jacobs et al., 2000; Kidron et al., 2000) or Stellenbosch, South Africa (Kaseke et al., 2012). But no evidence of dew condensation after dawn was found in summer because the temperatures were higher and the dew phase finished before dawn, a phenomenon also reported in the Negev (Veste and Littman, 2006). Dew events and daily dew condensation amounts and rates in summer were lower than in winter, because the dew durations were greatly reduced because of a longer insolation, higher *Ts* and lower *RH* at night.

Because hourly dew rates in both aspects were very similar, dew duration was the responsible of the dew amounts differences between aspects. Indeed, dew condensation was higher in the *NEF* slope because of a higher dew occurrence and longer dew events. Besides the differences in the soil particle size distribution, the lower potential insolation and duration in the *NEF* slope caused a lower water evaporation from the soil. Further, the higher SWC in the *NEF* slope resulted in lower *Ts* values during the day than in the *SWF* slope. In the evening, *Ts* in the *NEF* slope reached the dew point temperature earlier and remained at low values for longer than *Ts* in the *SWF* slope. Furthermore, in winter, insolation occurred earlier in the *SWF* slope in the morning and the evaporation phase began in this slope, while the shading effect in the *NEF* slope resulted in the continuation of the input phase and provoked a longer persistence of dew. This phenomenon was also reported by other authors in the Negev (Kappen et al., 1980; Kidron, 2005; Veste and Littman, 2006). This longer early morning dew condensation, together with the earlier beginning of the dew event at night in the *NEF* slope, produced high differences in dew duration between aspects. In summer, insolation lasted longer in the *NEF* slope and evaporation phase started earlier, nevertheless shade arrived sooner in the evening and the dew duration was still longer than in the *SWF* slope.

Hence, differences in daily dew accumulations between aspects were mainly dependent on dew duration which, in turn, was dependent on the insolation length, which was also seen in the Negev (Kidron, 2000). Indeed, only potential insolation (out of all meteorological variables studied) showed a different pattern between aspects. This is explained by the thermal valley winds, which are parallel to the valley axis and create the channelling effect (Weigel and Rotach, 2004). It consists in a re-direction of the wind, which is forced to blow along the valley and therefore similar wind velocity, air temperature and relative humidity are found in both aspects (Kidron et al., 2011; Weigel and Rotach, 2004).

The decrease of air and soil temperatures in the evening, together with a sudden increase in *RH*, probably as a result of afternoon winds transferring moist air from the Mediterranean Sea, increased the vapour pressure gradient from the soil to the atmosphere, resulting in a water gain in the soil by WVA. Water vapour adsorption increases with the clay composition of the soil (Kosmas et al., 1998) as well as with the electric conductivity (Heusinkveld et al., 2006), but, on the contrary, WVA is greatly restricted under wet soil conditions (Kosmas et al., 1998) and under high surface temperatures (Verhoef et al., 2006). The higher WVA values found in the *SWF* slope are justified because of its higher clay content, higher electric conductivity and lower SWC. In turn, the higher SWC in winter explained the lower WVA in this period, as well as the delayed commencement of the process and the lower hourly and daily rates. The diurnal fluctuations of WVA by the soil in summer followed the fluctuations of the *RH* as was previously seen by other authors (Kosmas et al., 1998; Ramirez et al., 2007) and its diurnal amplitude was related with the total WVA deposition. However, this direct relationship between WVA and *RH* amplitude was not evident in winter, because the SWC was higher and the water vapour gradient between the soil and the atmosphere was not influenced as much by small daily variations in *RH*.

4.2 Comparison of the non-rainfall water input values measured at El Cautivo with other studies

Our dew results are in agreement with a previous study in this site, that found a dependence of dew with the aspect exposure and higher dew amounts in the shaded slope (del Prado and Sancho, 2007). Aspect was previously reported to control dew precipitation also in the Negev (Kappen et al., 1980) where greater dew deposition was found in the shaded aspects (northwest) than on the sun exposed ones (southeast) using the CPM method (Kidron, 2005; Kidron et al., 2000). However, these results seem to be in contrast with Jacobs et al. (2000) who found higher dew amounts in the *SWF* slope using microlysimeters (ML). These studies have been developed with different measurement methods and with their own limitations. The CPM consists of an absorbent cloth attached to a glass plate over a wooden plate. The cloth is collected in the early morning and it is weighed and dried to calculate its water content. Because the collection surface is a cloth over a glass material, the properties of the soil are mainly missing and the surface temperature is greatly changed from the natural surface. In the case of ML study, it did not differentiate between dew and WVA, hence the dew amounts and its pattern may be mistaken and misleading. Hence a possible explanation for this apparent contradiction is that Jacobs et al. (2000) did not differentiate WVA from dew and all the NRWI measured with their ML was assumed to be dew. Jacobs et al. (2000) carried out their experiments at the end of the dry season with a very dry soil and registered higher NRWI in the *SWF* slope probably because the insolation was higher and the soil was drier and exposed to a higher WVA and not because of a higher dew condensation. Nevertheless, the differences between aspects found by Jacobs et al. (2000) were small (maximum of 0.02 mm) and the observed pattern was not constant. The inclusion of WVA into dew amounts is often done in the bibliography when working with ML (Graf et al., 2004; Heusinkveld et al., 2006; Jacobs et al., 2000; Pan et al., 2010), which leads in an overestimation of dew amounts and in a misleading reporting of its trend. Graf et al. (2004), for example, found a large amount of dew of 0.17 mm with a maximum of 0.33 mm in bare soil using ML in June in the Canary Islands. They did not see that *Ts* dropped below the dew point temperature, or at least, not during the entire input phase, and therefore WVA was also responsible for this water gain, not only dew. Finally, our dew amounts were in the range of amounts reported in other semiarid ecosystems exposed to extremely high temperatures and insolation such as the Negev Desert, Israel (Zangvil, 1996), the Rajasthan Desert, India (Subramaniam and Kesava Rao, 1983) or the Atacama Desert, Chile (Kalthoff et al., 2006).

Our WVA daily values, 0.079 – 0.247 mm

day^{-1} (Table 1), are lower from those found in other studies. Agam and Berliner (2004) found 0.18 – 0.33 mm day^{-1} in a bare sandy loam in the Negev (13% clay, 15% silt, 72% sand), lower than those of Verhoef et al. (2006) who found 0.2 - 0.5 mm day^{-1} in a sandy loam soil in Spain (14.8% clay, 7% silt, 78.2% sand), and Kosmas et al. (2001) who found WVA values of 0.05 – 3.7 mm day^{-1} in a medium texture soil in Greece (16.8% clay, 24% silt, 59.2% sand). The lower values of Agam and Berliner (2004) compared with the other studies may be due to the lower clay composition of their soil. The larger WVA amount of Kosmas et al. (2001) was previously attributed by Verhoef et al. (2006) to the clay type, since they hypothesized that it was montmorillonite, which has a high water adsorption potential. High WVA amounts were also reported in South Spain by Ramirez et al. (2007) that found an average of 1.42 mm day^{-1} in a silty loam soil (17.7% clay, 50.9% silt, 31.4% sand). The higher clay composition and proximity to the ocean were the reason for the high WVA amounts in that study. Therefore, the factors that could explain our lower WVA deposition compared with the above studies are related not only to soil composition, but with the meteorological variables: (i) our main clay type was illite, with lower water adsorption potential than montmorillonite in Kosmas et al. (2001); (ii) our site is not directly exposed to the Mediterranean Sea as it was in Ramirez et al. (2007) as several ranges close the direct input of moisture from the sea and the *RH* rising in the evening was probably lower; (iii) the daytime temperature in our site was surely higher than the temperatures in the other sites, suppressing WVA (Verhoef et al., 2006) except for the Negev Desert, that surely was also affected by high surface temperatures; (iv) our soil structure was very fine with a larger proportion of silt and clay than in the other studies (silt and clay represent the 80-90% of the soil) and this soil composition probably affected the porosity of the soil, decreasing vapour diffusivity and vapour sorptivity (Rose, 1968). The aforementioned studies were developed using different measurement methods or microlysimeters dimensions, hence, their comparisons should be interpreted cautiously.

4.3 Total non-rainfall water input and its ecological influence

The amount of NRWI represented the ≈40% of the loss of water through evaporation during winter and the 100% during summer. Total NRWI deposition was higher in summer because of a very intense WVA process that compensated and exceeded the reductions in dew amounts. However, no significant differences were found in NRWI between aspects, regardless of soil water status (wet in winter or dry in summer). The higher dew condensation in the *NEF* slope was compensated by the higher WVA deposition in the *SWF* slope. However, even if the total amount of water gain by NRWI in both aspects was the same, the difference in the water source (dew or WVA) may have its ecological implications.

Few biocrust species, such as green algal lichen, are able to photosynthesise using water vapour only and cyanobacterial lichens and others biocrust species need free water (Lange et al., 2006; Pintado et al., 2005). The main NRWI source in each aspect (dew in the *NEF* slope and WVA in the *SWF* slope) may be responsible of the adaptive differences found in the lichen morphology of the site (Pintado et al., 2005). Other studies also found that biocrusts located in contrasted aspects have different strategies (Kappen et al., 1980; Kidron et al., 2011; Lange et al., 1997), with extended wetted periods but lower net photosynthetic rates at the shaded slope, and shorter active periods but higher photosynthesis rates at the sunny ones. Furthermore, several studies have demonstrated a relationship between lichen density, species richness, the exposure of the habitat and dew (del Prado and Sancho, 2007; Kappen et al., 1980; Kidron et al., 2011).

Dew alleviates moisture stress in plants in the early morning by cooling the leaves and reducing transpiration losses (Sudmeyer et al., 1994). Plant canopies can also harvest dew and transfer the water to the soil surface where it is absorbed by the superficial roots (Hutley et al., 1997), which may also uptake the nearby soil moisture added to the soil by water vapour adsorption. This may influence the distribution and abundance of vegetation in arid areas (Matimati et al., 2013). Plants use free water and most lichens have greater efficiency using free water as a water source than when using vapour, which is consistent with the vegetation and biocrust distribution (greater in *NEF* slopes than in *SWF* slopes). But our hypothesis is that this difference in free water yield between both aspects seems insufficient to explain the large differences in plant and biocrust cover. These large differences in cover would be the result of divergent feedback processes increasing vegetation in the *NEF* slopes while increasing erosion in the *SWF* slopes (Lázaro et al., 2000; Cantón et al. 2004); processes possibly associated with thresholds in erodibility (Mora and Lázaro, 2013).

5. CONCLUSIONS

Aspect in this site controlled the microclimatic conditions. Differences in dew deposition between aspects were mainly driven by differences in insolation pattern, because it controlled surface temperatures, the soil water content and, in turn, the dew duration, which was directly related with the dew deposition amounts. No differences from this pattern where found between seasons and dew amounts were always higher in the NEF slopes.

In the case of WVA, the spatial variation of microclimate was insufficient to explain the differences between aspects. Water vapour adsorption deposition amounts and rates were higher in the Southwest facing slope because of its higher clay content and electric conductivity and because of its lower soil water content. Water vapour adsorption was directly governed by different meteorological variables depending on the soil status, which was directly related to season, following a high dependence on the *RH* amplitude in summer, but not in winter. A significant amount of water evaporation was attained by NRWI, reaching 100% in dry periods and WVA was the main non-rainfall water input during the dry season. Non-rainfall water input availability (especially dew) depended on the slope exposure and it was also correlated with lichen and vegetation abundance in the site.

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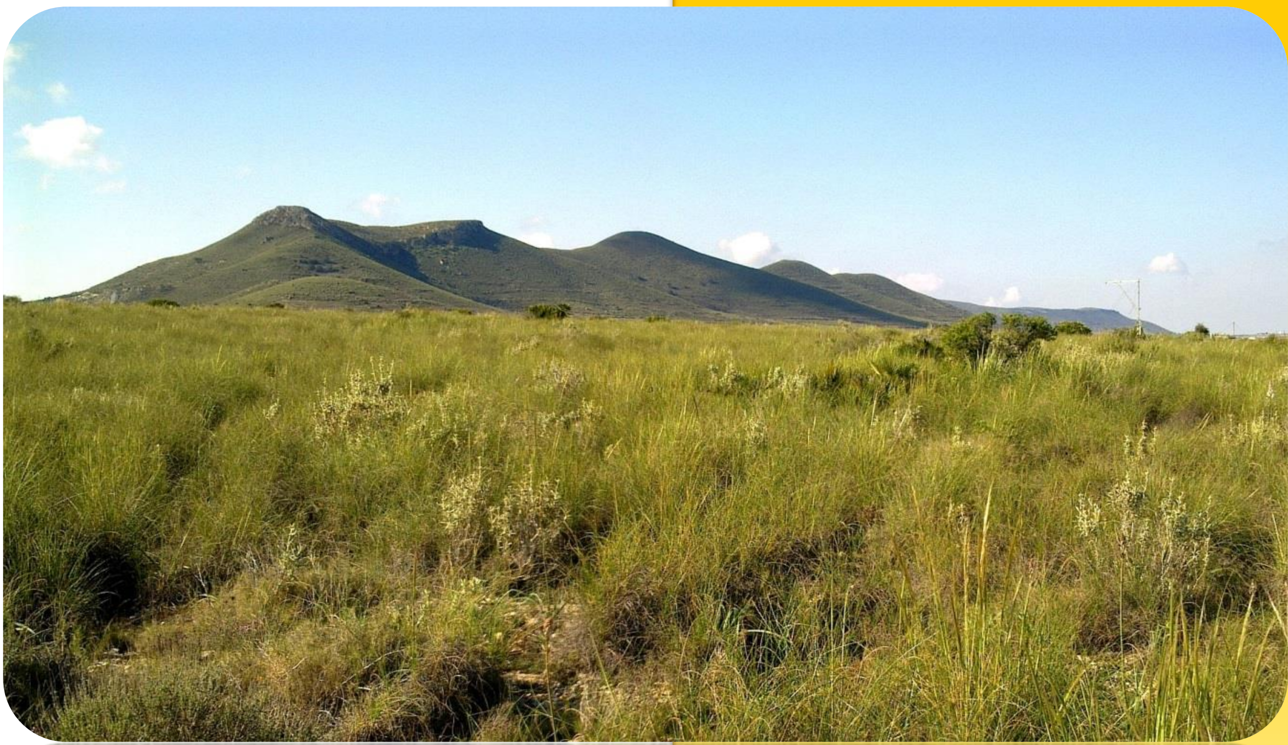
Capítulo IV

Role of dewfall in the water balance of a semiarid coastal steppe ecosystem



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Capítulo IV

ROLE OF DEWFALL IN THE WATER BALANCE OF A SEMIARID COASTAL STEPPE ECOSYSTEM

Abstract

Dewfall is widely recognised as an important source of water for many ecosystems, especially in arid and semiarid areas, contributing to improve daily and annual water balances and leading to increased interest in its study in recent years. In this study, occurrence, frequency and amount of dewfall were measured from January 2007 to December 2010 (4 years study) to find out its contribution to the local water balance in a Mediterranean semiarid steppe ecosystem dominated by scattered tussocks of *Stipa tenacissima* (Balsa Blanca, Almería, SE Spain). For this purpose, we developed a dewfall measurement method, "The Combined Dewfall Estimation Method" (CDEM). This method consists of a combination of the potential dewfall model, i.e., the single-source Penman-Monteith evaporation model simplified for water condensation, with information from leaf wetness sensors, rain gauge data, soil surface temperature and dew point temperature. To assess the reliability of the CDEM, dewfall was measured in situ using weighing microlysimeters during a period of 3 months. Daily micrometeorological variables involved in a dewfall event were analysed in order to assess the significance of dewfall at this site. Dewfall condensation was recorded on 78% of the nights during the study period. Average monthly dewfall duration was 9.6±3.2 hours per night. Average dewfall was 0.17±0.10 mm per night and was mostly dependent on dewfall duration. Dewfall episodes were longer in late autumn and winter and shorter during spring. Annual dewfall represented the 16%, 23%, 15% and 9% of rainfall on 2007, 2008, 2009 and 2010, respectively. Furthermore, when a wet period was compared to a dry one, the dewfall contribution to the water balance at the site was found to be 8% and 94%, respectively. Our results highlight the relevance of dewfall as a constant source of water in arid ecosystems, as well as its significant contribution to the local water balance, mainly during dry periods where it may represent the only source of water at the site.

Keywords: dewfall, semiarid, water balance, *Stipa tenacissima*.

1. INTRODUCTION

During the night, free liquid water on the Earth's surface can come from three different sources (Garratt and Segal, 1988): i) the soil (dew rise), ii) plants (guttation) and iii) the air (fog, dewfall, and soil water vapour adsorption). Water is the limiting resource in arid and semiarid regions, influencing vegetation density, cover and biomass (Puigdefabregas and Sanchez, 1996). As these environments are characterized by very low soil moisture and scant perennial vegetation, dewfall, although yielding relatively small amounts of water, can contribute significantly to the local water balance (Jacobs et al., 1999), especially during dry years (Kalthoff et al., 2006). In particular, dewfall occasionally constitutes a constant, stable water source (Veste et al., 2008), and its inclusion in energy and water balance models for arid and semiarid areas may thus be of great interest. The optimal atmospheric conditions for dew formation are discussed by many authors. Monteith and Unsworth (1990) stated that dew amount is dependent not only on the local atmospheric humidity, but also on the radiative, thermal and aerodynamical properties of the substrate and of its surroundings. Later, Zangvil (1996) mentioned that to obtain maximum radiation cooling, the following conditions must be met: clear skies, light winds and cold, dry air overlying a shallow moist layer near the ground. But information regarding dewfall deposition is scarce, and there is no international agreement on the measurement method both because it is considered a minor component of the water balance, and because of the difficulty in measuring it.

However, studies in dewfall deposition have been carried out in very few arid and semiarid ecosystems, they have used different measurement methods (Table 1), and only a few of these have analysed dewfall deposition in the long term. Furthermore, data on frequency, duration and amount of dewfall, or its contribution to the local water balance in semiarid coastal steppe ecosystems are not available. Only Moro et al. (2007) provided estimations of dewfall in a semiarid ecosystem in SE Spain but it was not a long-term study, and was therefore unable to determine the contribution of dewfall to the local water balance.

We selected a semiarid steppe ecosystem in Almería, SE Spain, for our study. The site, called Balsa Blanca, is located 6 km away from the Mediterranean Sea, and its vegetation cover is sparse and dominated by *Stipa tenacissima* L. The density of plants and animal communities (Aranda and Oyonarte, 2005; Rigol and Chica-Olmo, 1998) is much higher than would be expected in view of the mean annual precipitation of 220 mm [historical data recorded by the Spanish Meteorological Agency (1971-2000); www.aemet.es] with very hot, dry summers. Previous studies in the Mediterranean area demonstrated the importance of non-rainfall water inputs in the physiological status of *Stipa tenacissima* L. in SE Spain (Ramirez et al., 2007), in crops in Turkey (Ben-Asher et al., 2010) and in Greece (Kosmas et al., 1998). Our hypothesis is that the relatively dense plant cover and composition in this ecosystem is because another source of water must be available in addition to rainfall, especially in summer. Hence, the main objective of this study was to estimate the long-term dewfall contribution to the local water balance in a Mediterranean semiarid coastal steppe ecosystem during a four–year period (2007- 2010). For this purpose, we developed a dewfall measurement method, “The Combined Dewfall Estimation Method” (CDEM), which combines information from the single-source Penman–Monteith evaporation model (Monteith, 1965) simplified for water vapour condensation, information given by leaf wetness sensors (WS) and other complementary meteorological information. The meteorological data from our meteorological station at Balsa Blanca during the study period were analysed in order to state if conditions for dewfall formation are present or not and in order to explain the annual dewfall pattern. To assess the reliability of this method (CDEM), dewfall was measured *in situ* using weighing microlysimeters during a period of 3 months.

2. MATERIAL AND METHODS

2.1. Study site

This research was conducted at the Balsa Blanca experimental field site, which is one of the driest ecosystems in Europe and it is located in the Cabo de Gata-Níjar Natural Park in Almería, Spain (36º56’30”N, 2º1’58”W, 208 m a.s.l.) (Figure 1). This site is representative of the coastal-steppe ecosystems widely distributed along the Mediterranean coast. Balsa Blanca is in the Níjar Valley catchment, only 6.3 km away from the Mediterranean Sea. It is surrounded by the Serrata de Níjar Mountains to the NW and the Sierra de Gata Mountains to the SE. These two mountain ranges create a corridor running Southwest to East, which winds from the Mediterranean Sea blow through.

The Balsa Blanca landscape is made up of alluvial fans with gentle 2% to 6% slope gradients. Vegetation is sparse, with about 57% of cover (Rey et al., 2011) dominated by *Stipa tenacissima* combined with bare soil, stones and biological soil crusts in the open areas. Balsa Blanca has a mean annual air temperature of 18ºC, with a maximum of 33ºC in summer and a minimum of 6ºC in winter. Its long-term average rainfall is 220 mm, with a mean of 26 days per year with 1 mm or more of precipitation, mainly in winter (historical data recorded by the Spanish Meteorological Agency (1971-2000); www.aemet.es). The mean annual soil temperature is 21.9ºC and the mean soil water content is 13.8% (Rey et al., 2011).

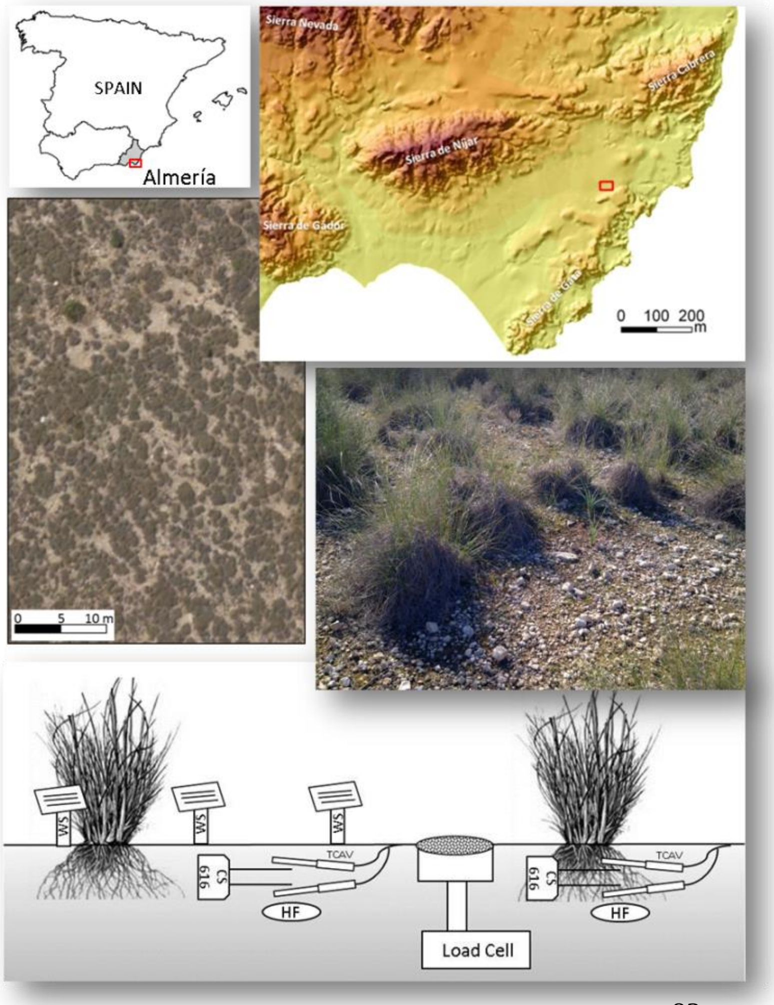


Figure 1. *Balsa Blanca experimental site location and examples of soil sensors and load cell situation*

Table 1. *Dewfall studies on arid and semiarid environments.*

Reference	***Study site***	***Study duration***	***Measurement method***	***Dewfall***
(Evenari et al., 1971)	Negev Desert, Israel	1963-66	Duvdevani wood blocks	180 nights $year^{-1}$ 30 mm $year^{-1}$ 110% of rainfall
(Subramaniam and Kesava Rao, 1983)	Rajasthan Desert, India	1973-76 (Sept-April)	Duvdevani wood blocks	0.14 mm $night^{-1}$ (máx. value) 37% of rainfall (máx. value)
(Zangvil, 1996)	Negev Desert, Israel	6 years	Hiltner dew balance	200 nights $year^{-1}$ 9.7-5.5 h $night^{-1}$ 17 mm $year^{-1}$ 0.075-0.125 mm $night^{-1}$
(Malek et al., 1999)	Goshute Valley, Nevada, EEUU	Oct.1993 – Sept.1994	Bowen ratio system	13.24 mm $year^{-1}$ 0.08 mm $night^{-1}$
(Kidron, 2000) & (Kidron et al., 2000)	Negev Desert, Israel	Autumns 1987-89	Cloth plate method	3.4 h $night^{-1}$ 0.23 mm $night^{-1}$ 10-12 % of rainfall
(Jacobs et al., 2002)	Negev Desert, Israel	Autumn 1997	Theoretical model (Penman Monteith) and microlysimeters	0.15–0.3 mm $night^{-1}$
(Beysens et al., 2005)	Bordeaux	Aug.1999-Jan.2003	Condensing surfaces	58% days 7.7 h $night^{-1}$ 9.8 mm $year^{-1}$ 0.05mm $night^{-1}$
	Ajaccio, Corsica			33% days 5.98 h $night^{-1}$ 8.4 mm $year^{-1}$ 0.07mm $night^{-1}$
(Kalthoff et al., 2006)	Atacama Desert, Chile	2000–02 and Nov.2004	Bowen ratio system	5–10 mm $year^{-1}$ 0.01-0.1 mm $night^{-1}$ 5-10% of rainfall
(Moro et al., 2007)	Rambla Honda, Almería, Spain	Feb.–Jun. 2003	Eddy Covariance, wetness sensor and theoretical model (Penman Monteith)	13.2 mm 6.8 h $night^{-1}$ 0.08 mm $night^{-1}$ 12% of rainfall
(Lekouch et al., 2012)	Mirleft, Morocco	May 2007 – April 2008	Condensing surfaces and artificial neural network	178 nights $year^{-1}$ 18 mm $year^{-1}$ 40% of rainfall

2.2. Dewfall estimation and data processing

Moro et al. (2007) found that the single-source Penman-Monteith evaporation model simplified for water vapour condensation (potential dewfall), adequately predicted actual dewfall in a semiarid, sparse shrubland at the Rambla Honda experimental site (Almería, SE Spain). The relative agreement between potential and actual daily and monthly dewfall found in that study suggested that dewfall condensation in these semiarid areas with sparse vegetation cover could be driven mainly by the radiative balance being the advective term of the Penman-Monteith equation negligible (Equation 1).

$$\lambda E = \frac{\left[s(R_n - G)\right]}{\gamma + s} \qquad (1)$$

where R_n is the net radiation, G is the soil heat flux, λE is the latent heat flux, s is the slope of the vapour pressure versus temperature curve and γ is the psychometric constant.

Other studies conducted in semiarid areas have also found agreement between potential and actual dewfall by using the single-source Penman-Monteith evaporation model simplified for water vapour condensation (Jacobs et al., 2002).

This study developed a simple dewfall measurement method called “The Combined Dewfall Estimation Method” (CDEM) (Figure 2). This method consists on an improvement of the validated method used by Moro et al. (2007) which combined the potential dewfall approach (Equation 1) and information from wetness sensors (WS). The CDEM eliminates subjectivity in the detection and delimitation of the dewfall events and its clear and simple application makes the CDEM a reliable tool in the estimation of dewfall deposition in arid and semiarid environments. The CDEM is divided in two steps.

1. WS information is essential for the identification of a dewy night, which along with rain gauge data, is used to distinguish rainy and foggy nights. But special care must be given rain gauge data, because in an intense dewfall event, the rain gauge may record water (normally only one “tip”), which could be misinterpreted as rain. To avoid such errors in selecting these nights, dew point temperature and soil surface temperature are used.
2. Once nights with dewfall had been selected, dewfall is calculated every 30 minutes using Equation (1), where positive values correspond to evaporation and negative to condensation. WS data is used to determine the beginning of a dewfall event, so no data can be taken from Equation (1) when WS are dry. We did not find any events where values in Equation (1) continued to be negative after WS dried. Finally, potential dewfall is accumulated daily, monthly and yearly.

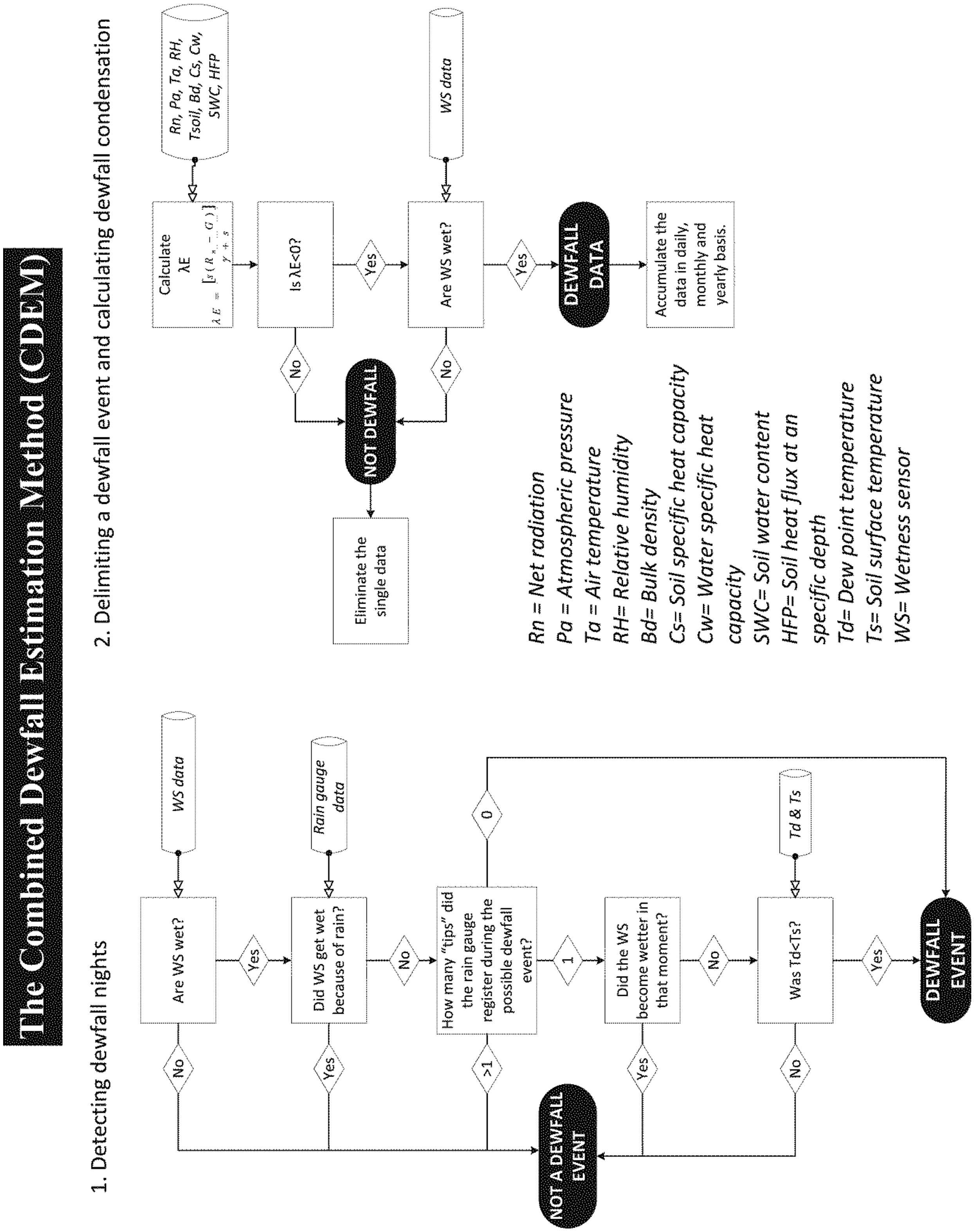


Figure 2. *The Combined Dewfall Estimation Method (CDEM).*

2.3. Accuracy of dewfall estimation

Modified Heusinkveld et al. (2006) automated weighing microlysimeters, using single-point aluminium load cells (model 1022, 3 kg rated capacity, Vishay Tedea-Huntleigh, Switzerland) were installed in the field for 3 months in April and July 2012 to compare the dewfall estimates. The load cell was inserted in a PVC box and a piece of aluminium was placed in the loading end for overload protection. The balance had a 0.01-g resolution (0.00055 mm), and according to the manufacturer, the total error was 0.02% of the rated output with internal temperature range compensation. In any case, the balance was made of aluminium, and the PVC box was placed inside a 0.015-m-thick polyspan box with a waterproof cover to minimize the remaining temperature dependence. The microlysimeters were located in the intershrub area.

Ninari and Berliner (2002) stated that for measuring dew, the minimum depth of a microlysimeter should exceed the depth at which the diurnal temperature is constant. In their case in the Negev desert, this occurred at 0.5 m. In our area of study, it occurs at 0.40 m depth (data not shown). However, Jacobs et al. (1999) carried out several tests with microlysimeter of 0.06 m diameter and various heights in the Negev (0.01, 0.035 and 0.075 m) and they obtained consistent results for the 0.035 and 0.07 m height microlysimeters. In fact, Heusinkveld et al. (2006) used a 0.14 m diameter and 0.035 m depth sampling cup with success. Furthermore, we had to reach a compromise between the load cell and soil characteristics. The PVC sampling cup was 0.152 m in diameter and 0.09 m depth, and levelled with the surrounding surface so that the load cell itself was at a depth of 0.3 m.

Twelve load cells were located in the field. Six microlysimeters contained small *Stipa tenacissima* plants, and the other six microlysimeter contained bare soil, stones and biological soil crusts. Changes in mass weight and temperatures were monitored at 15-second intervals and averaged every 15 min by a CR1000 data-logger (Campbell Scientific, Logan, UT, USA). Final load cell data in mm consisted in a weighted average between plants and the other soil surface cover types. Since the plants used in the microlysimeter were smaller than the average size of *Stipa tenacissima* in the area, their Leaf Area Index (LAI) was used to extrapolate this information to the real surface covered by plants in the site. Field calibrations were made once a week using standard loads and WS information was used as a filtering tool for removing possible water vapour adsorption effect in the sample. Some windy nights and two small rainfall events occurred during this period, hence a total of 65 data nights were registered.

2.4. Meteorological and complementary measurements

The experimental area is equipped with a micrometeorological station and all the information necessary for the CDEM was measured. Net radiation (R_n) was monitored in a representative area of the ecosystem with an NR Lite radiometer (Kipp and Zonen, Delft, The Netherlands). Soil heat flux (G) was measured by the combination method (Fuchs, 1986; Massman, 1992). Four heat flux plates (HFT-3, Campbell Scientific, Logan, UT, USA) were installed 0.08 m deep, and their corresponding soil thermocouples (TCAV, Campbell Scientific, Logan, UT, USA) were buried 0.02 and 0.06 m deep above each plate. The soil water content was measured by three water content reflectometers (CS616, Campbell Campbell Scientific, Logan, UT, USA) buried at a depth of 0.04 m. The heat flux plates and the water content reflectometers were located under bare soil and under plant, to provide a final estimation of the soil heat flux (*G*) representative of the whole ecosystem. Water vapour pressure, air temperature and humidity were monitored at a height of 2.5 m by a thermo-hygrometer (HMP45C, Campbell Scientific, Logan, UT, USA).

The number, frequency and length of dewfall episodes were measured automatically by wetness sensors (WS) (model 237, Campbell Scientific, Logan, UT, USA). The WS is a wiring grid that generates output in electrical resistance (kΩ) that varies with the wetness of the sensor. The wet/dry transition point was determined in the field by visual observations. WS data were recorded every 5 s and averaged every 30 min. Rainfall was measured by a tipping bucket rain gauge (ARG 100, Campbell Scientific, Logan, UT, USA). Wind speed and direction were measured at a height of 3.5 m (CSAT-3, Campbell Scientific, Logan, UT, USA). The soil surface temperature was monitored by thermocouples buried 0.002-0.003 m deep (Type T, Thermocouples, Omega Engineering, Broughton Astley, UK), thermocouples also measured the plant and the WS surface temperatures. Data were sampled and recorded by data-loggers (Campbell Scientific, Logan, UT, USA).

Some data were lost due to instrument failure (42% in October 2009, 3% in November 2009, 100% in December 2009 and 35% in January 2010). December 2009 was not included in this study.

3. RESULTS

3.1. Meteorological dewfall formation conditions

During the study period, mean annual air temperature was around 18ºC with the maximum mean in August (31ºC) and minimum in December-January (6ºC) (Figure 3). Annual rainfall was 264 mm in 2007, 246 mm in 2008, 324 mm in 2009 and 371 mm in 2010. The precipitation pattern was irregular, with a summer dry season and a relatively wet season in autumn and winter (Figure 3), and with a total percentage of rainy and foggy nights of 13±2% and 3±3% per year, respectively. So, temperature and rainfall regimes were in agreement with historical data, with hot, dry summers and warm, wet winters. Annual rainfall was average in 2007 and 2008, whereas 2009 and 2010 were wetter. Differences in daytime and night-time relative humidity (*RH*) were 32% in summer and 18% in winter. Daytime *RH* showed seasonal variation, with maximums in winter and minimums in summer. At night this variation was almost absent and the mean *RH* was 76±4% (with no rainfall), and 78±3% during a dewfall event.

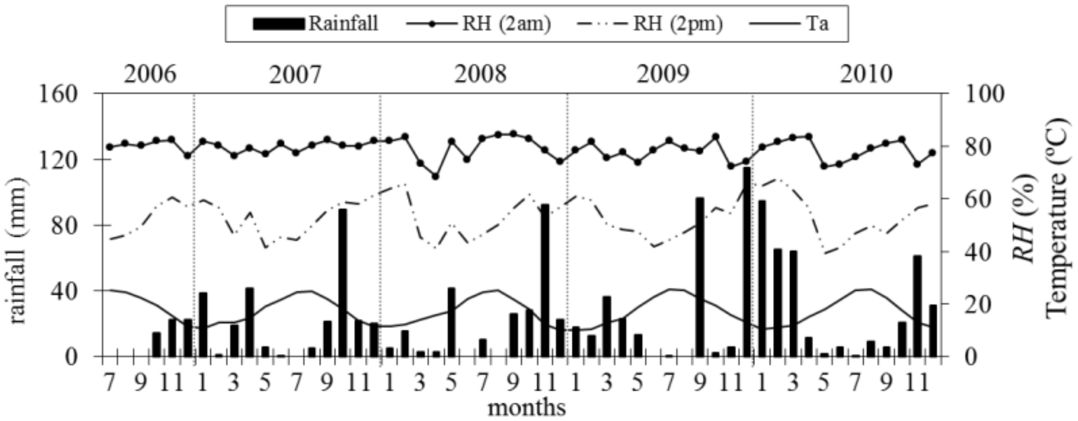


***Figure 3.** Measurements of monthly average air temperature (Ta), monthly rainfall and monthly average of relative humidity (RH) at 2 am and at 2 pm (solar time).*

Wind was predominantly from the East and Southwest (Figure 4) with maxima from the East in summer and from the Southwest in winter. Average wind speed at night was 2.2±1.7 m s^{-1}, less than 3 m s^{-1} during 86% of dewfall events, and less than 1 m s^{-1} only on 7% of dewy nights. No linear correlation was found between amount of dewfall and nocturnal wind speed.

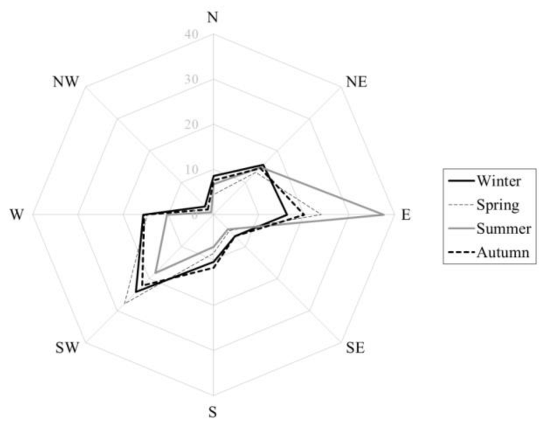


***Figure 4.** Wind rose with average values for the four seasons during the study period on percentage.*

All nights during the study period have been studied separately. During a dewfall night, air and soil surface temperatures dropped in the evening. After sunset they reached the dew point temperature and the wetness sensors got wet. Surface temperatures could stay below the dew point temperature during the entire dewfall event, or could arise and drop again several times. The night selected to be presented in Figure 5 meets the requirements of a representative dewfall night. After dusk, when the soil surface temperature (*Ts*), the plant temperature *(Tp)* and wetness sensor temperature (*Tws*) had dropped below the dew point temperature of the air (*Td*), the WS started to get wet. Then the WS signal arrived at its peak and stayed there for over 13 hours. At dawn, *Tp* and *Tws* exceeded *Td*, and one hour later *Ts* rose above *Td* and the WS dried out. Air temperature (*Ta*) reached *Td* later in the night and followed a different pattern.

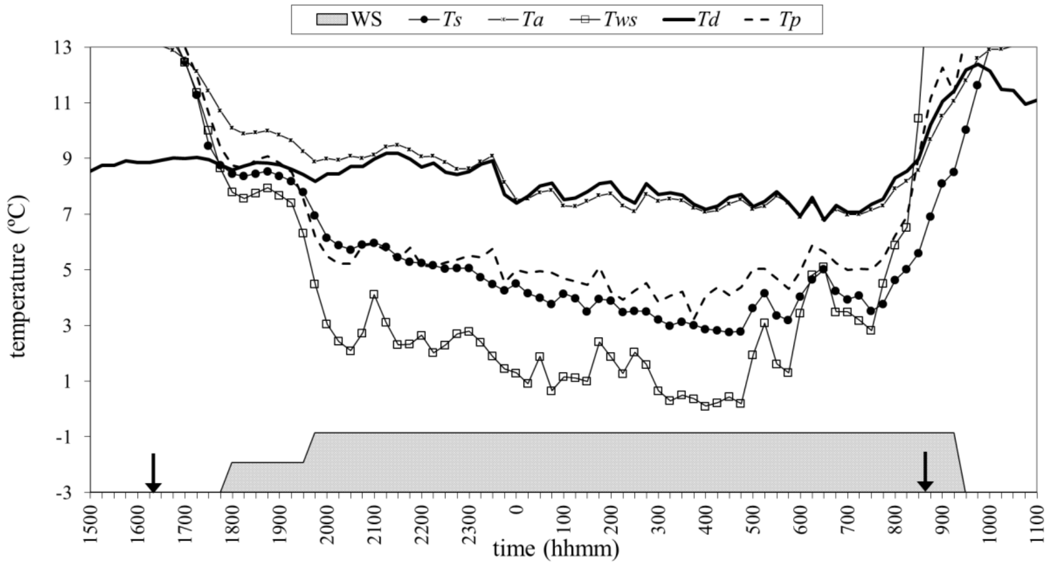


Figure 5. *Measurements of dew point temperature (Td), air temperature (Ta), wetness sensor temperature (Tws), plant temperature (Tp) and soil surface temperature measured with surface thermocouples at 0.002 m depth (Ts). Wetness sensor (WS) information in arbitrary values: value 0 is dry, value 1 is wet and value 2 is very wet. Arrows indicate sunset and sunrise. DOY 39- 40, year 2011.*

On a typical night (Figure 6), WS became wet when values in Equation (1) became negative, (17:30-18:00 hours). At dawn, (7:00-7:30 hours), the WS started to dry out just when values from Equation (1) became positive. Detailed dewfall patterns can be compared with the WS wet and dry cycles in the insert in Figure 6. From 23:30 to 1:00, values in Equation (1) became positive. In this 90 min period, the WS curve rose, meaning that water was evaporating from the WS. So when WS dried out it coincided with positive values in the Penman-Monteith equation (Equation (1)). These small evaporation events were present in almost all dewfall events in this study.

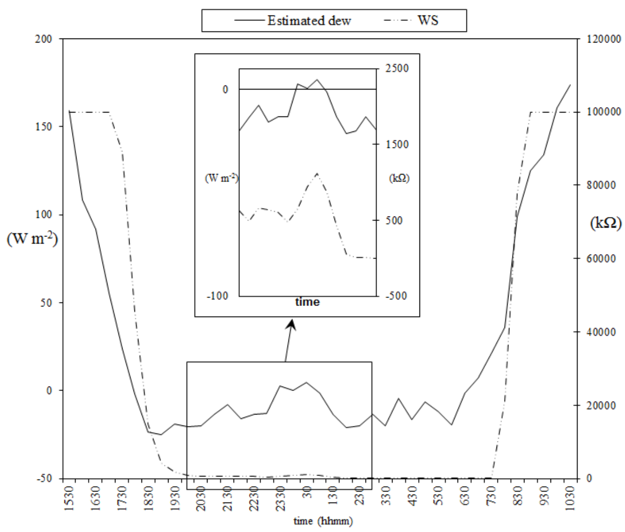
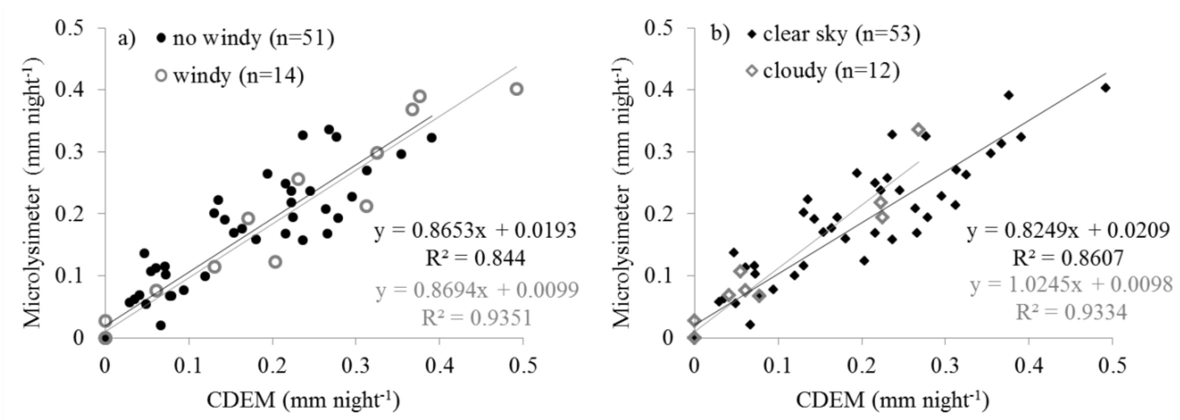


Figure 6. *Wetness sensor (WS) data and estimated dewfall. It is also shown in detail when estimated dewfall is over zero. NOTE: WS is wet when kΩ are below 99999 and the lower the resistance is, the wetter the sensor. DOY 260-2061, year 2007.*

We did not find any events where values in Equation (1) continued to be negative after the WS dried out. But in some dewfall events they became negative a few minutes before the WS got wet, and in others the WS remained completely dry all night long. Differences in total dewfall using only Equation (1) and using the CDEM are non-negligible. For instance, at annual scale, dewfall events (using CDEM) were reduced by 6.8±0.9% (nights), dewfall duration by 12.7±9.0% (hours) and dewfall amount by 20.8±11.8% (mm).

A significant daily correlation was found between dewfall measured by the weighing microlysimeters and amounts estimated with the CDEM under all kind of weather conditions: wind/no wind or cloudy/clear skies (Figure 7). During the time the microlysimeters were installed in the field, estimated dewfall with the CDEM was 9.2 mm and total dewfall measured with the microlysimeters was 9.0 mm. The contribution of plants to this dewfall quantity measured with the microlysimeter was of 64%, since the rest of surface covers (bare soil, BSC and stones) contributed with the 36%.



c) **TOTAL (n=65):** $y = 0.8426x + 0.0192$; $R^2 = 0.8716$

Figure 7. *Daily relation between dewfall amount estimated with the CDEM and dewfall amount measured with the microlysimeters for: a) no windy and windy nights (wind speed ≥ 4 m s^{-1}); b) clear sky and cloudy nights; c) Total dewfall nights. Linear regressions: $p<0.0001$.*

3.2. Dewfall frequency, duration and amount

The CDEM estimated dewfall on 78% of the nights in the study period (January 2007-December 2010) that is, on 276, 293, 254 and 259 nights in 2007, 2008, 2009 and 2010, respectively. There were slightly more dewy nights in summer and less in winter (Figure 8a). Mean monthly dewfall length was 9.6±3.2 hours per night with monthly means of 9.4 hours in 2007, 10.3 hours in 2008, 10.4 hours in 2009 and 8.3 hours in 2010. Dewfall events were longer in late autumn and winter and decreased in spring with maximums in December-January and minimums in May-June (Figure 8a).

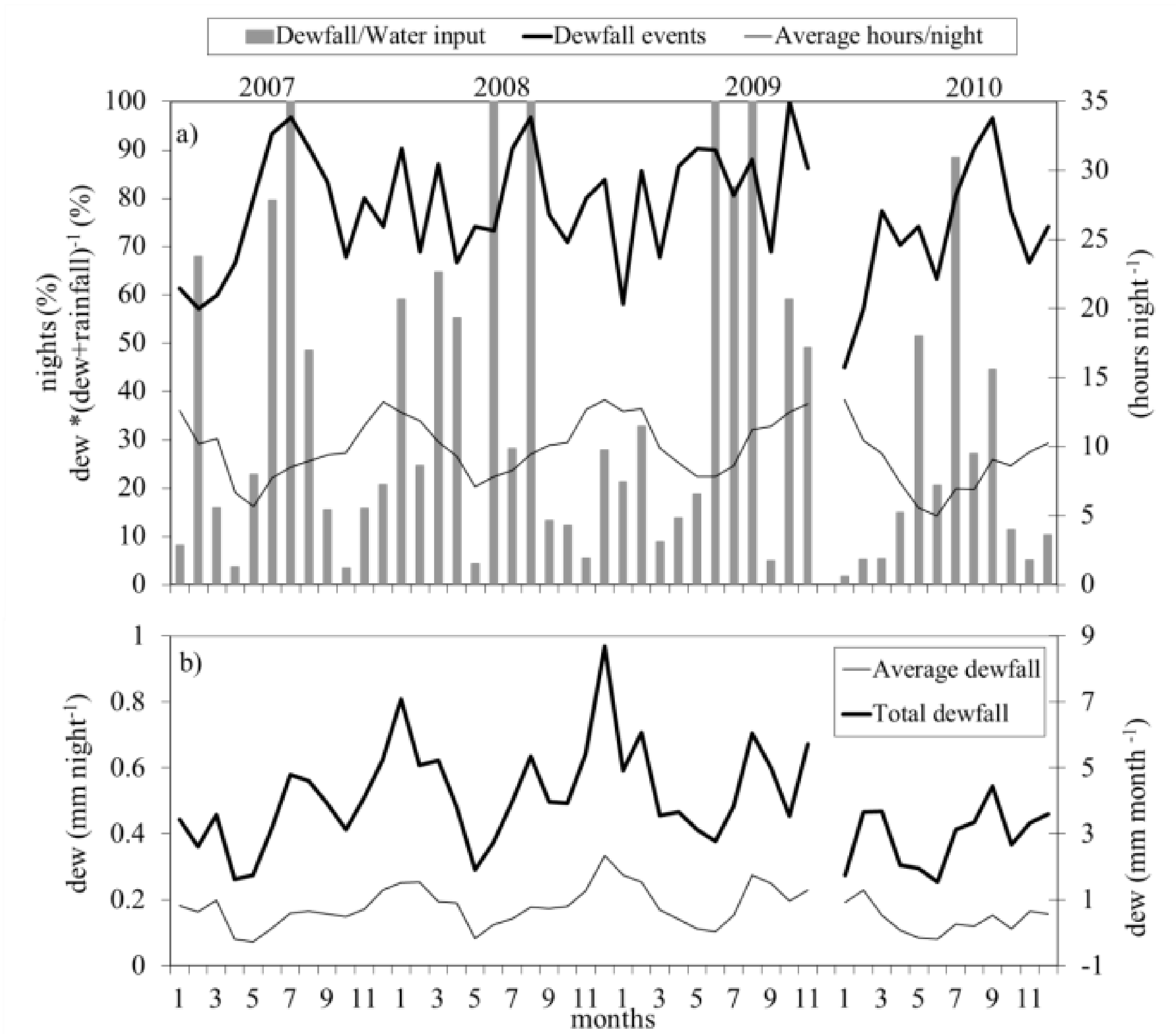


Figure 8. *a) Dew events in percentage of the total days of the month, average number of hours per night with dewfall condensation and percentage of dewfall against all the water input (dewfall*(dewfall + rainfall)$^{-1}$); b) Average dewfall amount (mm night^{-1}), and total monthly dewfall amounts (mm month^{-1}).*

Total dewfall during the study period was 182 mm, with annual amounts of 42 mm, 57 mm, 48 mm and 35 mm on 2007, 2008, 2009 and 2010 respectively. Mean dewfall condensation rates per night were 0.152±0.08 mm night^{-1} in 2007, 0.195±0.10 mm night^{-1} in 2008, 0.190±0.10 mm night^{-1} in 2009, and 0.136±0.10 mm night^{-1} in 2010. Dewfall showed a seasonal pattern with a maximum deposition rate in mm in winter and a minimum in spring (Figure 8b). As mentioned above, some data were missing in October 2009 and January 2010, so dewfall in the graph is low for these months. There was a significant linear relationship between amount of dewfall (y) and duration (x) on a monthly basis, ($y = 0.0179 x$, $R^2 = 0.7807$, $p < 0.0001$).

In dry periods in summer, dewfall was the only source of water in the ecosystem, and in spring and autumn it fell to a minimum (Figure 8a). Dewfall and rainfall are shown together in this Figure to eliminate problems with rates where rainfall was zero. Dewfall contributed about 16% of the mean annual precipitation in 2007, increased to 23% in 2008, and decreased to 15% in 2009 and to 9% in 2010 because of higher rainfall in 2009 and 2010. The contributions of dewfall to the local water balance during a wet (September-November 2008, 146.27 mm rainfall) season and a dry season (June-August 2009, 0.82 mm rainfall) were compared. The contribution to the water balance was 8% in the wet season and 94% in the dry one.

4. DISCUSSION

4.1. Meteorological dewfall formation conditions

Our results showed the presence of good meteorological conditions for dewfall formation during the study period at the study site. Winds from the NW and SE were blocked by the Serrata de Níjar and the Sierra de Gata Mountains, respectively (Figure 1). Predominant East winds in summer probably supply moisture directly from the nearby Mediterranean Sea (Figure 4). In winter, Southwest winds blowing through the Níjar Valley released moisture until their arrival at Balsa Blanca, explaining why differences in *RH* between day and night are much higher in summer than in winter at this site. Wind speed at 3.5 m height was mostly from 1 to 3 m s^{-1}, during dewfall events, but it could be even higher. These values seem to be too strong for dewfall condensation, but wind speed was certainly less on the soil surface because of the influence of plant canopies. Furthermore, in literature we can find dewfall events with wind speed values till 7 m s^{-1} (Clus et al., 2008).

Dewfall only forms if the surface temperature where the process is about to take place is below the dew point temperature (*Td).* In our study this was measured by thermocouples on the soil and plant surfaces (Figure 5). We consider temperatures from surface thermocouples buried at 0.002-0.003 m (*Ts*) a good economical option for soil surface temperature measurement. Furthermore, *Ts* agreed with wetness sensor (WS) data, which indicated the beginning of wetting just when *Ts* and the plant surface temperature (*Tp)* dropped below *Td*. The WS temperature (*Tws*) was monitored to understand its response better, and *Tws*, *Ts* and *Tp* dropped below *Td* at the same time. But several studies in the bibliography have reported increases in soil surface moisture even when the soil surface temperature did not drop below the dew point temperature (Agam and Berliner, 2004; Graf et al., 2004; Jacobs et al., 1999; Pan et al., 2010). Some authors have considered this initial wetting due to water vapour adsorption and combined both processes (dewfall and water vapour adsorption) as dewfall (Pan et al., 2010), but others did not find visual dewfall deposition and considered water vapour adsorption the main soil wetting mechanism (Agam and Berliner, 2004). Kidron et al. (2002) rarely found dewfall deposition on bare soil in the Negev, due to the soil thermal properties that impeded its condensation, but dew amounts increased with height above ground and dewfall deposition on the aerial section of mosses was not a rare event. Our meteorological measurements and temperatures monitoring show predominant dewfall activity in Balsa Blanca on soil and plants. Furthermore, plants have shown a relevant role in the dewfall condensation, since the 64% of dewfall in Balsablanca condensed on its surface.

Finally, dewfall condensation in the site was corroborated by visual observations and by the WS response. The highest rate of dewfall formation with Equation (1) was in agreement with the highest WS wetness (Figure 6). Dewfall can form for a very long time, but it does not seem to be constant or homogeneous process, as the dewfall condensation rate may rise or decrease during the night, and there may even be small evaporation events during a dewfall event. A dewfall event must therefore be analysed in detail and the WS data can be very useful for this. This study found wide differences between the results just applying Equation (1) and the CDEM. Moreover, the reliability of this method (CDEM) has been proven by the good agreement between estimated dewfall and dewfall field measurements made using weighing microlysimeters (Figure 7). Dewfall condensation on windy, no windy, cloudy o clear nights has been estimated successfully. The CDEM has proven to be a rough method in the estimation of dewfall deposition under different weather conditions in the site.

4.2. Dewfall frequency, duration and amount

By applying the CDEM, we found that dewfall condensation occurred on 78% of the nights in the study period, which is very high compared to what other authors have found (Table 1). Measurement methods used in these studies are different from our method and this affects the measured amounts. However, dewfall days and temporal pattern comparisons can be made as this adds significant information about dewfall deposition in our study site. Taking into account that there was rain and fog on 16% of the nights, there was no water input at the site on only 6% of the days. Contrary to studies in the Negev Desert (Zangvil, 1996) and in India (Subramaniam and Kesava Rao, 1983) with the most dewfall events in winter, in Balsablanca the maximum of dewy nights was in summer and the minimum in winter (Figure 8a). The long duration of the dewfall events in Balsa Blanca and the differences in dewy days in summer and winter can be explained by the absence of rainy days and the higher relative humidity (*RH)* increase at night in summer, because of the prevailing humid easterly wind from the Mediterranean Sea that refreshes the site more than in winter (Figure 3). This moist contribution makes *RH* high enough for dewfall condensation to begin early in the evening and end late in the morning. On the contrary, Ajaccio, in Corsica, because it is on an island, is highly exposed to winds, causing an unstable atmosphere, and thus preventing dewfall condensation. The average duration of dewfall per dewfall night appears to closely follow the length of the night. Dewfall events were longer in late autumn and winter and decreased in spring with maxima in December-January and minima in May-June, a pattern in agreement with findings by Zangvil (1996) in the Negev Desert.

Dewfall showed a seasonal pattern with a maximum deposition rate per night in winter and a minimum in spring (Figure 8b). Total dewfall follows the same pattern with the fewest days with dewfall in winter overcompensated by longer duration and deposition rates at night.

There is a significant linear relationship between amount and duration of dewfall, which is in agreement with Moro et al. (2007), who found the same pattern in Rambla Honda, Almería (Spain), with Beysens et al. (2005) in Corsica and Bordeaux (France), and with Zangvil (1996), Kidron (2000) and Kidron et al. (2000) in the Negev Desert (Israel).

Dewfall contribution to the water budget was extraordinary during dry periods. In summer, both in dry and wet years, dewfall represented the only source of water in the ecosystem (Figure 8a). In dry years (2007 and 2008), dewfall contributed about 20% of the annual precipitation, and in wet years (2009 and 2010), it represented 12%.

5. CONCLUSIONS

The meteorological data from our station at Balsa Blanca during the study period showed the presence of good conditions for dewfall formation.

Dewfall can form over a very long period of time, but it is not a continuous or homogeneous process, as the dewfall rate changes and there may be short evaporation events. Surface thermocouples have demonstrated that wetness sensors are useful tools in identifying the beginning of a dewfall event. A simple method combining this data and meteorological data with the single-source Penman-Monteith evaporation model, "The Combined Dewfall Estimation Method" (CDEM), was developed in this paper. The reliability of the CDEM results were checked successfully using weighing microlysimeters, and along with the micrometeorological variables, proved that dewfall is an important mechanism for water input to this ecosystem when there is no rainfall.

In Balsa Blanca, dewfall rates and durations were high. Dewfall deposition has been demonstrated to be a reliable source of water in Balsa Blanca because it is a constant, stable source of water, while precipitation is scarce and limited to a few months of the year. These results therefore draw attention to the relevance of dewfall condensation, and its significant role in the local water budget, especially during dry periods.

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Anexo

BALANCE DE ENERGÍA Y ECUACIÓN DE PENMAN-MONTEITH

El balance de energía sobre una superficie determina en gran parte el microclima sobre la misma ya que controla los procesos biológicos e hidrológicos. El balance de energía puede ser definido como la manera en la que se distribuye la radiación neta (R_n), (radiación total incidente menos la reflejada y emitida por las superficies), que es la radiación disponible para el desarrollo de los procesos que ocurren a nivel de superficie:

$$R_n = \lambda E + H + G \qquad \text{(Ecuación 1)}$$

donde R_n corresponde a la radiación neta, G al flujo de calor sensible intercambiado entre la superficie y el suelo, H al flujo de calor sensible intercambiado entre la superficie y la atmósfera (energía utilizada para calentar el aire) y λE al flujo de calor latente (energía consumida en el proceso de evaporación de agua). Todas las variables se expresan en unidades de energía ($W\ m^{-2}$).

λE se estima como término residual de la Ecuación 1 ya que a escala local el resto de los términos pueden estimarse con cierta facilidad si se dispone de una instrumentación específica. En 1948, Penman combinó el balance energético con el método de la transferencia de masa y derivó una ecuación para calcular la evaporación de una superficie abierta de agua a partir de datos climáticos estándar de horas de sol, temperatura, humedad atmosférica y velocidad de viento. Esta ecuación combina información meteorológica y fisiológica y asume que las copas vegetales pueden asimilarse a una superficie uniforme como una única fuente de evaporación (big-leaf). Este método fue desarrollado posteriormente por muchos investigadores y finalmente derivó en la ecuación combinada de Penman-Monteith (Monteith, 1965):

$$\lambda E = \frac{s(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\gamma\left(1 + \frac{r_s}{r_a}\right) + s} \qquad \text{(Ecuación 2)}$$

donde λE es el calor latente, R_n es la radiación neta, G es el flujo de calor en el suelo, (e_s-e_a) representa el déficit de presión de vapor del aire, ρ_a es la densidad media del aire a presión constante, c_p es el calor específico del aire, *s* representa la pendiente de la curva de presión de vapor de saturación, γ es la constante psicrométrica, y r_s y r_a son las resistencias superficial y aerodinámica, respectivamente.

La resistencia superficial describe la resistencia al flujo de vapor a través de los estomas, del área total de la hoja y de la superficie del suelo. La resistencia aerodinámica describe la resistencia en la parte inmediatamente superior a la vegetación e incluye la fricción que sufre el aire al fluir sobre superficies vegetativas (Allen et al., 1998).

Según lo formulado arriba, el enfoque de Penman-Monteith incluye todos los parámetros que gobiernan el intercambio de energía y el flujo de calor (evapotranspiración) de áreas uniformes de vegetación dividiéndose en dos partes diferenciadas: por un lado el término radiativo y por otro el término aerodinámico. La mayoría de los parámetros son medidos o pueden calcularse fácilmente a partir de datos meteorológicos.

Así pues, dicha ecuación nos calcula la evaporación que se produce en una superficie (λET positiva), pero en el caso de que λET sea negativa, significa que la energía está siendo utilizada en la condensación de agua, es decir, en la formación de rocío. Si asumimos que cuando se produce un evento de rocío la atmósfera está saturada [(e_s-e_a)=0] y el viento es nulo (resistencias nulas), la Ecuación de Penman Monteith nos estimaría la condensación de rocío potencial y quedaría así (Moro et al., 2007):

$$\lambda E = \frac{\left[s(R_n - G) \right]}{\gamma + s} \qquad \text{(Ecuación 3)}$$

Esta ecuación se compone del término radiativo de la ecuación original de Penman Monteith y queda eliminado el término aerodinámico (más difícil de medir). El “Combined Dewfall Estimation Method” (CDEM) desarrollado en el Capítulo IV de esta tesis utiliza esta sencilla ecuación como base y añade información procedente de placas de rocío e información meteorológica complementaria (temperatura de punto de rocío y temperatura superficial) para la estimación del rocío a nivel de ecosistema. Las estimaciones se realizan tanto de forma cuantitativa (cantidad de rocío) como cualitativa (su duración). Gracias a este tipo de modelos, se pueden realizar estimaciones a largo plazo usando una pequeña cantidad de variables meteorológicas fácilmente medibles en campo.

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Otras aportaciones científicas derivadas de la Tesis Doctoral

La publicación correspondiente al Capítulo I de esta Tesis Doctoral:

Uclés, O., Villagarcía, L., Canton, Y. and Domingo, F., 2013. Microlysimeter station for long term non-rainfall water input and evaporation studies. Agricultural and Forest Meteorology, 182–183(0): 13-20.

Fue posteriormente comentado:

Agam, N., 2014. Comment on "Microlysimeter station for long term non-rainfall water input and evaporation studies" by Uclés et al. Agricultural and Forest Meteorology, 194: 255-256.

Por lo que, a su vez, dicho comentario fue contestado y publicado:

Uclés, O., 2014. Response to comment on "Microlysimeter station for long term non-rainfall water input and evaporation studies" by Ucles et al. (2013). J. Agric. Forest Meteorol., 182–183, 13–20. Agricultural and Forest Meteorology, 194(0): 257-258.

Response to Comment on "Microlysimeter station for long term non-rainfall water input and evaporation studies"

by Uclés et al. (2013). Agricultural and Forest Meteorology, 182–183(0): 13-20.

This study (Uclés et al., 2013) develops a non-rainfall water input (NRWI) measurement system. Since the bibliography on NRWI only shows short term studies using a low number of replicates, this article presents a new system that allows the NRWI measurement during long periods of time using a higher number of replicates. An automated microlysimeter is also developed as an example of how this system can be operated. The limitations of this system are determined by its technical instrumentation. As long as the technology industry progresses creating more accurate and sophisticated measuring instruments [i.e.: load cells, data loggers…] this system will improve.

Dr. Agam expresses several specific concerns that she suggests could influence our article (Uclés et al., 2013). Here, we address each comment in turn.

We apologize for listing Ninari and Berliner's microlysimeter (Ninari and Berliner, 2002) among the manual ones. The authors did not explain how their automated microlysimeter was designed and constructed and we assumed they weighed it manually. On a further reading of their work it is clear to us that they used a balance and they placed a soil sample on it and registered the output continuously.

Dr. Agam states that the depth of the microlysimeter sample used on Uclés et al. (2013) is not enough for an accurate detection of NRWI. This assumption is based on a previous study made by the same researcher: (Ninari and Berliner, 2002). In that study, Ninari and Berliner (2002) tested the adequacy of microlysimeters to estimate dew deposition by comparison of their values with: i) the Energy-Balance equation; and ii) the Hiltner dew balance. In that work they established that the depth of the microlysimeter must be at least the depth at which the diurnal temperature is constant, in order to ensure similar temperature profiles inside and outside the microlysimeter. They concluded that the layers below 15 cm contributed to more than 60% of the total flux. But there are some misunderstandings that made us believe that this influence could have been overestimated:

First of all, Ninari and Berliner (2002) did not differentiate between dew and water vapour adsorption. Since microlysimeters are able to capture NRWI from dew and water vapour adsorption; and the Hiltner is able to register only dew, the comparison of these two methods in Ninari and Berliner (2002) may be not adequate on a NRWI study. Two different depths samples were also tested in Ninari and Berliner (2002), but no repetitions were used and the study was developed with only one soil sample of 15 cm and one soil sample of 30 cm depth. Furthermore, several thermocouples were inserted in the samples soil cores (13 and 15 thermocouples in the 15 cm and 30 cm depth samples, respectively). Based on our experience, we are worried about the possibility of an interference of the wires in the continuous weighing of the samples [another reason that made us believe Ninari and Berliner (2002) used manual microlysimeters].

Moreover, Ninari and Berliner (2002) developed their microlysimeter studies under completely different weather conditions since the first one (15 cm depth) was developed in Spring, and the second one (30 cm depth) was developed in Summer with probably dryer soil conditions and drier atmosphere (weather data were not shown in the manuscript). Indeed, from the results they found, it can be hypothesized that during the Spring period dew and, probably, fog events were common, as the high condensation on the Hiltner showed. In Summer, it seems that fog and dew episodes were almost absent, since the Hiltner did not register water input. But the microlysimeter registered high water inputs, surely as a result of high water vapour adsorption events. Hence, two microlysimeter depths were tested using completely different conditions. We think Ninari and Berliner´s study (2002) may be influenced by these weather differences and the measurement techniques used.

Soil surface temperature is a good indicator of the representativeness of a soil sample on a dew study since differences in the surface temperatures may result in different dew amounts (Kidron, 2010; Ninari and Berliner, 2002). A night surface temperature test was successfully developed in Uclés et al. (2013) to confirm the representativeness of the soil samples. Dr. Agam pointed out that no diurnal surface temperatures were shown on that study (Uclés et al., 2013). We agree on the fact that the bigger the soil sample is, the better the soil heat flux similarity with the surroundings will be during the day and night. Surely, daily temperatures variation will influence the soil heat flux and the dew condensation, but we assume this temperature relation is mainly important during the night, when dew occurs. Indeed, Kidron (2010) checked this assumption and stated that similar temperatures at dawn implies similar dew amounts regardless their temperature difference during the day [which reached 5 ºC on Kidron (2010)]. The temperature tests in Uclés et al. (2013) using two contrasted soil textures, silty and sandy soils, showed no significant differences on the surface temperatures of the samples and the surroundings. However, small differences among these two soil types were found and we agree with Dr. Agam on the fact that these surface temperature similarities are dependent on the soil type.

Agam and Berliner also developed a further research (Agam and Berliner, 2004) where they studied the depth to which the daily change in water content penetrated in a sandy loam soil. These water daily changes occurred maximum in the uppermost five centimeter layer of the soil. No dew events were registered on that study (Agam and Berliner, 2004) and this water input was entirely produced by water vapour adsorption. In view of this result in Agam and Berliner (2004) we still consider that the depth of our microlysimeters (9 cm) in Uclés et al. (2013) may be adequate for a NRWI. However, water vapour adsorption is directly related with the affinity of clay to adsorb water (Kosmas et al., 1998) and therefore we agree on the fact that clayish soils may need deeper soil samples than silty or sandy soils. Hence, each time a NRWI study is developed, the representativeness of the soil sample should be checked, especially with soils rich in clay minerals.

Finally, Dr. Agam stated that the evapotranspiration rates measured for the plants on the microlysimeters in Uclés et al. (2013) are not representative of the surroundings. A plant surely does not grow in a pot as from soil. This is a preliminary study (Uclés et al., 2013) that shows the valuable possibility of the development of a NRWI study on plants, an attempt not done on literature before.

In summary, this study (Uclés et al., 2013) develops a complete system that allows the NRWI measurement during long periods of time, using a high number of replicates and avoiding damage from rain, soil movements and other field conditions. This system can be used as a base in the development of further and more accurate studies as soon as the scientific equipment available on the market improves.

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Conclusiones generales

CONCLUSIONES GENERALES

1. El microlisímetro automático desarrollado en esta tesis doctoral hace posible la medición en continuo de la evaporación y la precipitación oculta (niebla, rocío y adsorción de vapor de agua) en varios tipos de cubiertas de suelo. Asimismo, el protocolo de instalación en campo desarrollado en esta tesis permite la colocación de tantos microlisímetros como sean necesarios y su uso durante largos periodos de tiempo.

2. La monitorización del aumento de peso de los microlisímetros, junto con la de la lluvia, la temperatura de las superficies consideradas y la temperatura y humedad del aire permite determinar la contribución relativa de la niebla, el rocío y la adsorción de vapor de agua al balance hídrico de un ecosistema.

3. Los resultados obtenidos en un estudio comparativo entre cuatro tipos de cubiertas (suelo desnudo, costras biológicas, piedras y pequeñas plantas de *Macrochloa tenacissima*) permitieron discernir el tipo de precipitación oculta que predominó en cada superficie: rocío en la superficie de plantas y piedras; y adsorción de vapor de agua en suelo desnudo y costras biológicas.

4. La entrada de agua a un ecosistema por precipitación oculta varía en función del tipo de cubierta de suelo. Las plantas demostraron ser grandes captadoras de agua, seguidas por las superficies con piedras, mientras que las superficies cubiertas por costras biológicas y el suelo desnudo mostraron unas menores entradas de agua.

5. En esta tesis se ha desarrollado un modelo para la estimación de rocío (CDEM) basado en la ecuación de Penman-Monteith y, que junto con otras variables meteorológicas e información de placas de humectación, permite estimar y estudiar el patrón de rocío de un ecosistema a largo plazo. Este modelo fue validado en campo usando microlisímetros automáticos.

6. Gracias al registro en continuo de los microlisímetros automáticos y a los datos obtenidos con CDEM se ha podido comprobar que un evento de rocío no es un proceso continuo, si no que se encuentra interrumpido por pequeños eventos de evaporación. Además, cuanto mayor sea la diferencia entre la temperatura de la superficie y la temperatura de punto de rocío, mayor será la tasa de condensación de agua sobre dicha superficie. A su vez, la cantidad de agua condensada por rocío en una superficie se encuentra directamente relacionada con la duración del evento.

7. La adsorción de vapor de agua muestra una gran dependencia con la humedad relativa del aire, sobre todo durante periodos secos, y está relacionada con la cantidad de arcilla de un suelo y con su conductividad eléctrica.

8. Las diferencias en el patrón de insolación y en la composición del suelo entre dos laderas contrastadas modificó el patrón de deposición de la precipitación oculta en éstas. La ladera de umbría recibió un mayor aporte de precipitación oculta en forma de rocío mientras que en la ladera de solana la adsorción de vapor de agua fue la principal fuente de precipitación oculta.

9. El agua aportada por la precipitación oculta puede llegar a jugar un papel fundamental en el balance hídrico de un sistema tanto a escala diaria como anual, satisfaciendo gran cantidad del agua evaporada durante el día y llegando incluso a representar la única entrada de agua en un ecosistema en periodos secos.

GENERAL CONCLUSIONS

1. The automated microlysimeter developed in this Thesis allows the continuous measurement of the evaporation and non-rainfall water input (fog, dew and water vapour adsorption) on different soil cover types. Furthermore, its design, construction and field installation have proven to be a rough and useful tool in long term non-rainfall water input and evaporation studies.

2. The different sources of non-rainfall water input (fog, dew and water vapour adsorption) were differentiated and their partial contributions to the water balance of an ecosystem were analyzed. For this purpose, the daily changes in the water content of the samples in the automated microlysimeters were registered and some meteorological variables were also monitored, such as rain, surface temperatures, air temperature and air humidity.

3. A study of non–rainfall water input on different cover surfaces of the soil (bare soil, biocrusts, stones and small *Macrochloa tenacissima* plants) detected that dew represented the main non–rainfall water input source in plants and stones, while water vapour adsorption was the main input on bare soil and biocrusts.

4. The differences in the soil surface cover type affected the non-rainfall water input deposition in a natural ecosystem. The total amount of non-rainfall water input in the site highlighted a minor contribution of bare soil and biocrusts in the total input and a significant participation of plants and stones.

5. This Thesis develops a dew measurement method (CDEM; Combined Dewfall Estimation Method) which consists of a combination of the potential dew model, i.e., the single-source Penman-Monteith evaporation model simplified for water condensation, with information from leaf wetness sensors, rain gauge data, soil surface temperature and dew point temperature. This method was validated in a natural ecosystem using automated microlysimeters.

6. Information from automated microlysimeters and CDEM revealed that dew can form over a very long period of time, but it is not a continuous or homogeneous process, as the dew rate changes and there may be short evaporation events. Furthermore, dew deposition is highly dependent on dew duration and the higher the difference between the air dew point temperature and the surface temperature of a substrate, the higher the dew rate on that surface.

7. Water vapour adsorption in a surface is directly governed by the air relative humidity amplitude, especially in summer, and by the clay content and electric conductivity of the soil.

8. Differences in the insolation pattern of two contrasted slopes and differences in their soil composition modified the non-rainfall water input deposition on them. Dew was the main non-rainfall water input in the shaded slope, since water vapour adsorption was the main input in the sunny exposed one.

9. Non-rainfall water input may play an important role in the daily or annual water balance of an arid or semiarid ecosystem. It can satisfy a great part of the evaporation demand and it may represent the only source of water at the site during dry periods.

Resumen

RESUMEN

En sistemas áridos y semiáridos el aporte de agua a través de la precipitación oculta (niebla, rocío y adsorción de vapor de agua) puede ser de vital importancia para el balance hídrico y el funcionamiento del ecosistema. Sin embargo, pese a la importancia de la precipitación oculta, el número de estudios centrados en este tema son escasos y los métodos utilizados para su detección poco precisos y difíciles de aplicar. Por tanto, para comprender el papel que desempeña la precipitación oculta en zonas áridas es necesario el desarrollo de métodos de medida que sean de fácil aplicación y repetitividad y que permitan establecer la verdadera influencia de esta precipitación en el balance hídrico de este tipo de ecosistemas. Esto es importante tanto para el estudio de esta fuente hídrica a largo plazo como para la diferenciación de cada uno de sus componentes y el estudio en detalle de estos procesos (rocío, nieblas y adsorción de vapor de agua) tanto a nivel ecosistémico como específico en cada tipo de cubierta del suelo (suelo desnudo, costras biológicas, piedras y plantas).

El objetivo general de esta tesis es establecer los mecanismos y variables meteorológicas implicadas en los aportes de agua a través de la precipitación oculta y evaluar la influencia de dichas precipitaciones en el balance de agua de ecosistemas áridos, así como su variabilidad estacional y la influencia del tipo de cubierta de suelo. Para esto se desarrollan dos metodologías de medición de la precipitación oculta: un microlisímetro automático para la medición directa en campo de las entradas (por precipitación oculta) y salidas (por evaporación) de agua en el suelo, y un modelo teórico de estimación de rocío a partir de valores medidos de variables micrometeorológicas. Para llevar a cabo los objetivos propuestos, se seleccionaron dos áreas en el Sureste de España, Almería: El Cautivo, situada en el Paraje Natural del Desierto de Tabernas; y Balsa Blanca, en el Parque Natural de Cabo de Gata-Níjar.

Esta tesis doctoral se compone de los siguientes capítulos:

I. Desarrollo de un microlisímetro automático para la medición en continuo de la evaporación y las precipitaciones ocultas en varios tipos de cubiertas de suelo. Asimismo, el protocolo de instalación en campo desarrollado en esta tesis permite la colocación de tantos microlisímetros como sean necesarios y su uso durante largos periodos de tiempo sin riesgo de roturas o mal funcionamiento.

II. La monitorización de variables meteorológicas como la lluvia, la temperatura y humedad del aire y la temperatura de las superficies consideradas, permite diferenciar las diferentes fuentes hídricas que componen la precipitación oculta (niebla, rocío y adsorción de vapor de agua) y calcular, a partir de los datos obtenidos por los microlisímetros automáticos, las contribuciones relativas de cada una de estas fuentes al balance hídrico de un ecosistema. Los resultados obtenidos en un estudio comparativo entre cuatro tipos de cubiertas (suelo desnudo, costras biológicas, piedras y pequeñas plantas de *Macrochloa*

tenacissima) permitieron discernir el tipo de precipitación oculta que predominó en cada superficie: rocío en la superficie de plantas y piedras; y adsorción de vapor de agua en suelo desnudo y costras biológicas.

III. Estudio de la precipitación oculta en un ambiente semiárido y comparación de estos aportes de agua entre dos hábitats (laderas contrastadas). Las diferencias en el patrón de insolación y en la composición del suelo entre dos laderas contrastadas modificó el patrón de deposición de la precipitación oculta en éstas. La ladera de solana recibió un mayor aporte de precipitación oculta en forma de adsorción de vapor de agua mientras que en la ladera de umbría el rocío fue la principal fuente de precipitación oculta. La adsorción de vapor de agua mostró una gran dependencia con la humedad relativa del aire, sobre todo durante periodos secos, y está relacionada con la cantidad de arcilla de un suelo y con su conductividad eléctrica.

IV. Desarrollo de un modelo sencillo de estimación de rocío basado en la ecuación de Penman Monteith, llamado “The Combined Dewfall Estimation Method” (CDEM). CDEM estima la condensación de rocío a nivel ecosistémico utilizando la ecuación de Penman-Monteith simplificada para la condensación de agua potencial y añadiendo información procedente de placas de rocío e información meteorológica complementaria como la temperatura de punto de rocío y la temperatura superficial. Con este modelo se analiza el patrón de aporte de agua a través del rocío en un sistema semiárido costero y estepario (Balsa Blanca, Almería, Sureste de España) y su variabilidad estacional durante 4 años. Los eventos de rocío fueron muy frecuentes, contabilizándose en el 78% de las noches durante el periodo de estudio. Los episodios de rocío fueron más largos en otoño e invierno, disminuyendo su duración durante la primavera. La cantidad de agua condensada por rocío representó, con respecto a las precipitaciones anuales, el 16%, 23%, 15% y 9% en 2007, 2008, 2009 y 2010, respectivamente.

Como conclusión general de esta tesis doctoral se puede afirmar que el agua aportada por la precipitación oculta puede llegar a jugar un papel fundamental en el balance hídrico de un sistema tanto a escala diaria como anual, satisfaciendo gran cantidad del agua evaporada durante el día y llegando incluso a representar la única entrada de agua al ecosistema en periodos secos.

SUMMARY

Non-rainfall atmospheric water input, which is comprised of fog, dew and water vapour adsorption, may be an important water source in arid and semiarid environments. However, literature about it is scarce and the measurement methods developed are inaccurate or difficult to implement. To really understand the role that non-rainfall water input may have in arid environments, accurate and easy to implement measurement methods should be developed. Furthermore, the different sources of non-rainfall water input (fog, dew and water vapour adsorption) should be also differentiated and their partial contribution to the total non-rainfall water input and to the evaporation of a site should be analyzed. The influence of the soil cover type (plants, stones, biocrusts and bare soil) in the non-rainfall water input deposition should be also evaluated.

The objective of this Thesis is to stablish the mechanisms and the meteorological variables implicated in non-rainfall water input and to evaluate their influence in the water balance of arid and semiarid environments. Furthermore, the season variability and the influence of the soil cover type are also studied. For this purpose, two measurement methods are developed: an automated microlysimeter for *in situ* measurements of the water input (non-rainfall atmospheric water input) and output (evaporation); and a theoretical dew measurement method. In the development of this Thesis, two study areas were used in the southeast of Spain, Almería: “El Cautivo”, located in the Paraje Natural del Desierto de Tabernas; and “Balsa Blanca”, in the Parque Natural de Cabo de Gata-Níjar.

This Thesis comprises the following chapters:

I. Development of an automated microlysimeter that enables accurate studies of non-rainfall water input and evaporation on different soil cover types. Furthermore, the strategy for their placement and installation in the field developed in this Thesis prevents their damage from the environmental conditions and allows the installation of all the repetitions needed during long periods of time.

II. Fog, dew and water vapour adsorption were distinguished by using automated microlysimeters and the monitoring of meteorological variables, such as rain, air temperature, air humidity and the surface temperatures where non-rainfall water input would condense. The relative contribution of these water sources to the water budget of a system was also found and the differences in non-rainfall water input on different cover surfaces of the soil (small *Macrochloa tenacissima* plants, stones, biocrusts and bare soil) in a natural ecosystem were evaluated. Dew played a significant role in the water input of plants and stones surface covers and water vapour adsorption was the dominant non-rainfall water input source on biocrusts and bare soil.

III. The micrometeorological and soil conditions involved in non-rainfall water inputs were compared between two habitats (contrasted slopes). Water vapour adsorption deposition amounts and rates were higher in the sunny slope since dew was the main non-rainfall water input source in the shaded one. Differences in dew deposition between aspects were mainly driven by differences in insolation pattern, because it controlled surface temperatures, the soil water content and, in turn, the dew duration, which is directly related with the dew amounts. Water vapour adsorption showed a high dependence on the relative humidity amplitude, mainly on dry periods, and was directly related with the clay content and the electric conductivity of the soil.

IV. A simple dew measurement method, “The Combined Dewfall Estimation Method” (CDEM) was developed. It consists of a combination of the potential dew model, i.e., the single-source Penman-Monteith evaporation model simplified for water condensation, with information from leaf wetness sensors, rain gauge data, soil surface temperature and dew point temperature. Using this model, the dew contribution to the local water balance and its dew occurrence, frequency and amounts were measured during 4 years in a Mediterranean semiarid steppe ecosystem (Balsa Blanca). Dew condensation was recorded on 78% of the nights during the study period. Dew episodes were longer in late autumn and winter and shorter during spring. Annual dew represented the 16%, 23%, 15% and 9% of rainfall on 2007, 2008, 2009 and 2010, respectively.

This Thesis results highlight the relevance of non-rainfall water input as a constant source of water in arid ecosystems, as well as its significant contribution to the local water balance, mainly during dry periods where it may represent the only source of water at the site.

Journal Citation Reports de las publicaciones presentadas

Factor de impacto y cuartil del Journal Citation Reports (SCI) o de las bases de datos de referencia del área en el que se encuentran las publicaciones presentadas.

Publicaciones presentadas

Uclés, O., Villagarcía, L., Canton, Y. and Domingo, F., 2013. Microlysimeter station for long term non-rainfall water input and evaporation studies. Agricultural and Forest Meteorology, 182–183(0): 13-20. DOI: 10.1016/j.agrformet.2013.07.017.

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Journal Citation Reports

Journal Title	ISSN	Total Cites	Impact Factor	5-Year Impact Factor	Immediacy Index	Citable Items	Cited Half-life	Citing Half-life
J ARID ENVIRON	0140-1963	5899	1.772	2.095	0.281	203	7.6	>10.0
ISI Journal Citation Reports © Ranking: 2012: 69/127 (Ecology); 91/191 (Environmental Sciences)								
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AGR FOREST METEOROL	0168-1923	10024	3.421	4.118	0.747	182	8.4	8.8
ISI Journal Citation Reports © Ranking: 2012: 5/78 (Agronomy); 1/60 (Forestry); 12/74 (Meteorology and Atmospheric Sciences)								
CATENA	0341-8162	4618	1.881	2.528	0.450	140	9.0	>10.0
ISI Journal Citation Reports © Ranking: 2012: 25/80 (Water Resources); 61/170 (Geosciences, multidisciplinary); 12/34 (Soil Science)								

Those people who tell you not to take chances
They are all missing on what life is about
You only live once so take hold of the chance
Don't end up like others the same song and dance

Metallica,
Motorbreath, Kill ‘Em All (1983)

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