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Mulching as a means of exploiting dew for arid agriculture?

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Abstract

A traditional mulching technique used in Lanzarote, Canary Islands, allows dry farming as well as pronounced water savings in irrigation. It is known to reduce evaporational losses, but is also supposed to enhance the nocturnal condensation of water vapour from the atmosphere. The mulch layer consists of porous volcanic rock fragments abundantly available on the island. The mulched surface is believed to cool rapidly and to be more hygroscopic than a bare soil surface. This was investigated during a field experiment conducted over 68 nights during different seasons in 2001 and 2002, as well as some simple laboratory measurements. It was found that nocturnal condensation on the mulch surface (max 0.33 mm) was lower than on the bare soil surface (max 0.57 mm) or any one of three alternative mulch substrates. However, a slightly stronger nocturnal cooling of the mulched as compared to the bare surface was present. It is shown that these contrary findings can be explained by the higher hygroscopicity of the dry loam soil, resulting in condensation gains beyond the strict definition of dew. Differences in plant-availability of non-hygroscopic dew water and hygroscopic water uptakes are discussed, and conditions under which mulching would show positive condensation effects are defined. This includes a theoretical section demonstrating that non-hygroscopic mulch layers of a proper thickness can provide small amounts of dew to plant roots at the mulch–soil interface. This condensation could also happen during the day and would be favoured by a high amplitude of the diurnal atmospheric moisture cycle.

Keywords: Condensation; Dew; Hygroscopicity; Lanzarote; Lapilli; Mulch

1. Introduction

Few studies have considered the possibility of dew as an additional water source for arid agriculture (cf. Monteith, 1963; Stone, 1963; Acosta Baladón, 1996, for overview; Sharma, 1976; Sudmeyer et al.; 1994; Li, 2002, as examples). A traditional mulching technique used on the Canary Island of Lanzarote (Fig. 1), however, is believed not only to reduce evaporational losses, but also to supply water by enhanced nocturnal condensation (Matznetter 1958; Acosta Baladón, 1973; 1996). The mulch layer consists of black lapilli, volcanic rock fragments between 2 mm and 64 mm in diameter, abundantly available on the island. After experiencing the hydrological benefits of about 1 m thick natural lapilli sheets for the cultivation of perennial plants, farmers have covered almost all fields with 0.05 m to 0.2 m thick lapilli layers over the past 250 years.

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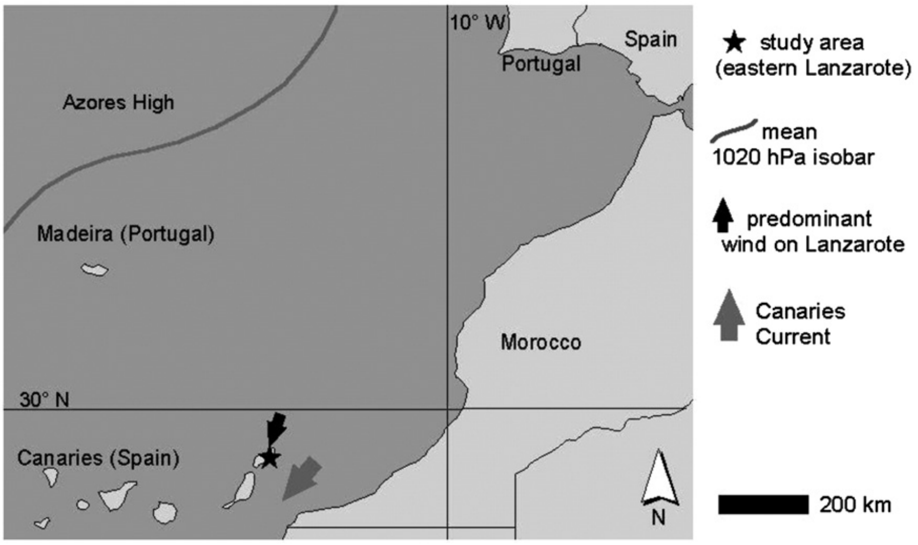

Fig. 1. Location of the study area.

Recent studies demonstrated the ability of these mulch layers to keep soil water content high (Tejedor et al., 2002; Diaz et al., 2004). However the hypothesis that enhanced condensation contributes to this long-term effect, as assumed by Matznetter (1958) and Acosta Baladón (1973, 1996), is still subject to discussion as sufficient experimental evidence is not yet available. Dewfall measurements on lapilli mulched surfaces with microlysimeters (Gonzáles et al., 1964) or by sampling (Höllermann, 1991) yielded a broad range of nocturnal amounts (up to 0.59 mm). Though judged as disappointing by the above authors, such amounts would contribute significantly to the water balance in places where rainfall and fog precipitation are low and dew nights are frequent (Acosta Baladón, 1996). The mean annual precipitation at Lanzarote ranges from around 100 mm to 260 mm depending on location (Marzol, 1988). Although mean relative humidity is high (71%), few (1 per year) days with fog are observed at Lanzarote's less elevated parts (data from the airport meteorological station) in contrast to higher locations of the Canary Islands where fog is abundant (Marzol, 2002, 2008−this issue).

A summary of possible mulching effects, as suggested from literature, is shown in Fig. 2. Favourable

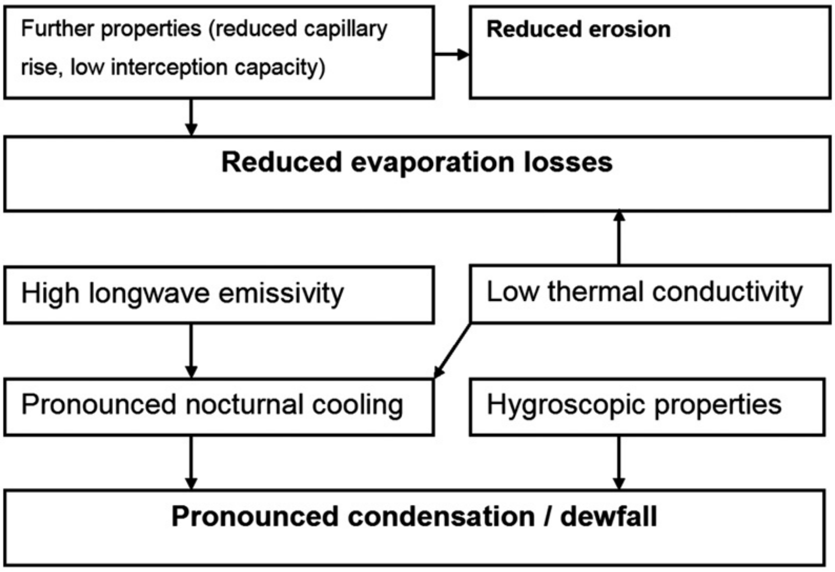

Fig. 2. Effects of lapilli mulch layer as assumed in dew literature (references given in text). Small letters: features not discussed here. Bold: effects resulting from the given properties.

properties that are assigned to the lapilli as a mulch substrate by authors in support of enhanced condensation include high long-wave emissivity and low thermal conductivity. This enables nocturnal cooling to below the dewpoint of the ambient air and thus dewfall. Furthermore, hygroscopic properties are assumed, enabling condensation independent of cooling below the dewpoint (Matznetter, 1958; Acosta Baladón, 1973, 1996). Hygroscopic soil properties affecting condensation have been discussed by Monteith (1963, using the term "absorption" to stress the thermodynamic difference) and demonstrated on bare soil desert surfaces by Jacobs et al. (2000).

Crucial for the assessment of mulch layers as condensation modifiers is simultaneous condensation measurement on a mulched and a nearby bare surface. This had not yet been done on Lanzarote. The results of such measurements, carried out in 2001 and 2002, will be provided in the first part of the article. This includes comparison to three alternative mulch substrates. Based on this, some theoretical considerations are provided concerning the conditions of beneficial condensation enhancement through mulch layers in general.

2. Measurements

2.1. Area and methods

Comparative condensation measurements for two substrate samples were conducted for 68 nights between 02 and 25 June 2001, 24 January and 17 February 2002, and 03 and 28 October 2002. The experiments were carried out on a lapilli-mulched field next to the agrometeorological station of the island administration (28°59′59″ N 13°33′30″ W, Fig. 3). The substrate samples were placed on two electronic balances (Ohaus DP6, New Jersey, USA) in a container in the ground. One balance always carried a two-layered sample consisting of the prevailing soil (loam) in a plastic container (0.03 m thick) and a lapilli mulch layer (0.07 m thick) in a metal cylindrical sieve with a surface diameter of 0.28 m. When calibrating the balances and making wind-shielded high accuracy readouts, a process conducted several times a day, the water storage of both soil and mulch layer could be determined independently by removing the sieve. The sample on the second balance was either one layer (0.06 m thick) of soil without mulch, or the same as on the first

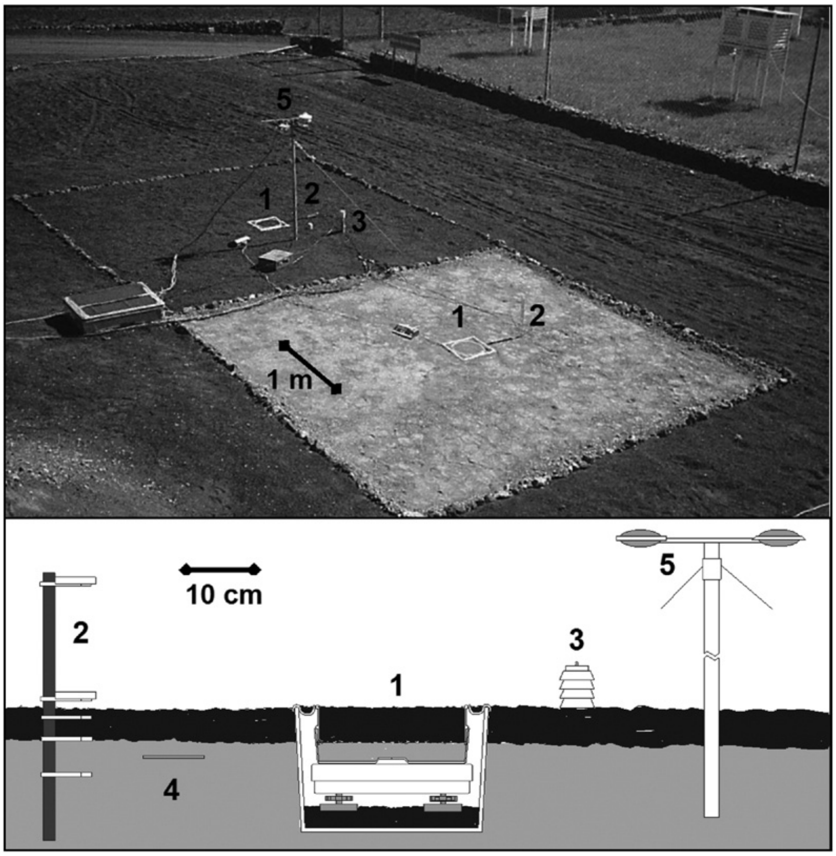

Fig. 3. Experimental set-up. 1 balance; 2 combined temperature/humidity probes; 3 combined temperature/humidity/wind speed probes; 4 soil heat flux plate; 5 net pyrradiometer and albedometer (measurement heights given in text).

balance (for quality assurance), or covered with a 0.07 m thick layer of one of three alternative mulch substrates (bark mulch, tire crumbs, and sand). To determine the absolute water storage of the samples and control for solid particle gains or losses during the experiments, water content samples of the substrates were taken before and after each experiment. 4 m by 4 m around each balance were covered by the same surface substrate as the sample. For the three alternative mulch substrates, this area was only 1 m by 1 m due to limited substrate supply.

At a distance of 0.5 m from each balance, temperature and relative humidity at different heights above and depths below the surface (−0.28 m to +0.3 m) were measured with six combined thermistor/capacity sensors (Hygrotec 1310, Titisee-Neustadt, Germany). During the measurements in 2002, two combined sensors with heat anemometers (Testo 452, Lenzkirch, Germany, various heights between 0.05 m and 1 m), a net pyrradiometer (Thies 8111, Göttingen, Germany, 1.5 m above lapilli or soil surface), an albedometer (Kipp & Zonen CM7B, Delft, The Netherlands, 1.5 m above lapilli or soil surface) and a heat flux plate (Hukseflux HFP01, Delft, The Netherlands, various depths between −0.04 m and −0.14 m) were used additionally. An infrared thermometer (Novasens i-tec 2003, Lüneburg, Germany, automatic emissivity correction for $\varepsilon > 0.8$) was used for occasional surface temperature measurement.

In the laboratory, hygroscopic properties of all substrates between pF 6.7 and pF 4.1 were measured ($\mathrm{pF} = \log_{10}$ of negative water potential). Small, initially oven-dry (105 °C) substrate samples were placed in a desiccator where the relative humidity of the air was monitored by a sensor (Hygrotec 1310) and raised in steps by successively filling in silica gel (2% RH), various salt solutions (intermediate RH) and water (100% RH). At each humidity level, the sample water content was determined by weighing. The procedure was repeated with decreasing humidity to control for hysteresis effects.

2.2. Results

Out of 68 field measurement nights, 38 showed condensation gains of the lapilli-mulched surface. A time series of the water storage of mulched and bare sample, as reflected by the highest nocturnal condensation sum recorded from 0 h 5 June to 0 h 7 June 2001, is shown in Fig. 4. The nocturnal sum of condensation is the difference between evening minimum and morning maximum. This was found to be 0.33 mm in the case of the mulched surface, only 0.07 mm of which reach the covered soil, but 0.57 mm in the case of bare soil. Both values are well within the range of the few measurements recorded in earlier studies (Section 1). However, the relation between both surfaces, not having been measured before, is contrary to literature expectations discussed in Section 1. This is not an isolated case: A more statistical dew potential measure of the different substrates, is given as the “factor” in Table 1. This represents the slope of the functional relationship between the lappilli-covered (factor 1) and any other surface, based on the comparison of all hourly condensation rates of the comparison period. R^2 values between the datasets are also given. As an aid to understanding the condensation behaviour of the different tested surfaces, the following four physical properties related to energy balance, are discussed. Short-wave albedo as measured with the albedometer governs energy uptake from global radiation in the day. Long-wave emissivity gives the fraction of heat energy as related to a perfect blackbody (100%) that the surface will radiate — thus governing nocturnal cooling. This parameter, obtained by solving the Stefan–Boltzmann-law with surface temperature and outgoing long-wave

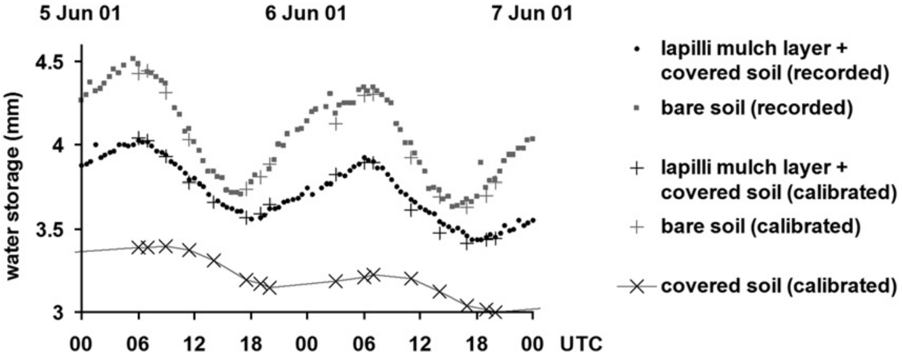

Fig. 4. Diurnal water storage cycle of lapilli-mulched and bare soil, 5–7 June 2001, the night with the highest condensation observed. Nocturnal sum is the water storage difference between evening minimum and morning maximum. Recorded: calculated from automatically recorded balance output. Calibrated: from readouts with prior calibration (refer Section 2.1).

Table 1
Surface substrate properties

	Factor[a]	R^2[b]	α[c] (%)	ε[d] (%)	λ[e] (W m^{-1} K^{-1})	Hy[f] (%)
Lapilli	1	1	8	98	0.14	0.3
Tire crumbs	1.05	0.84	9	–	0.35	1.5
Sand	1.36	0.47	23	–	0.29	0.9
Bare soil	1.58	0.77	16	99	0.37	9.3
Bark mulch	2.54	0.67	17	–	0.27	23.2

[a] Ratio of condensation as compared to lapilli (cf. text).
[b] R^2 of compared lapilli and substrate datasets.
[c] Short-wave (0.3–2.8 μm) albedo.
[d] Long-wave (2.8–30 μm) emissivity.
[e] Thermal conductivity.
[f] Hygroscopicity (cf. appendix).

radiation values, could only be obtained for those substrates covering a sufficiently large area of 4 m by 4 m (see Section 2.1). Thermal conductivity is obtained from temperature profile and heat flux measurements in the field and supported by a laboratory experiment in the case of lapilli (Weber et al., 2007). Hygroscopicity is derived from the experiment described at the end of Section 2.1.

All surfaces show higher nocturnal condensation gains and daily evaporation losses than that mulched with lapilli. Albedo α and emissivity ε show that the black colour of the lapilli surface only accounts for a stronger heating during the day by short-wave radiation. Nocturnal cooling through radiation is governed by long-wave emissivity, a property that is equally high for both lapilli and bare surfaces. Thermal conductivity (λ) is the only property enhancing nocturnal cooling of the lapilli surface. Reduction of the lapilli surface temperature below the dewpoint of ambient (0.02 m above ground level) air resulted in condensation gains that could not be explained by hygroscopic water uptake alone. For bare soil, hygroscopic uptake alone could still explain all the condensation measured during the only occasion when a surface temperature slightly below the ambient air dewpoint was observed. The condensation ranking of all substrates corresponds well with hygroscopicity (Hy).

Further results of the study are given in Graf (2004) and include the following: A comparison of three tested dewfall measurement methods (destructive sampling, simple microlysimeters and continuous weighing balances) yielded significantly different results due to the inhomogeneous structure of the lapilli surfaces. The balance measurements presented here were shown to best represent dewfall in the undisturbed surrounding. Regression analysis of measured dewfall and meteorological data of the airport station gave an estimated mean annual dewfall of 31 mm. Simple mobile measurements at six different sites showed an almost linear altitude-dependent increase in dewfall of about 70% per 100 m between 75 m and 608 masl. At the peak site, however, the highest values were accompanied by fog observations, in agreement with findings about the importance of fog in elevated parts of Tenerife (Marzol, 2002, 2008−this issue) and Lanzarote (Riebold, 1993). Due to the role of trade winds in moisture replacement, some of the highest nocturnal dewfall totals were found at high wind speeds (up to 10 m s^{-1}) at 10 m above ground level (in detail in Graf et al., 2004). Dew formation on an island at higher wind speeds than at inland locations has also been described by Beysens et al. (2005) for Corsica (France).

3. Discussion and theoretical considerations

The results of the field study as described in this article, show that coarse-grained mulch layers are unlikely to provide additional water by nocturnal condensation. Their somewhat stronger superficial cooling due to reduced thermal conductivity is overcompensated for by the stronger hygroscopic properties of typical bare soil surfaces. This is in good agreement with theory (Or and Wraith, 2000) suggesting a negative correlation between pore size and hygroscopicity. According to this study, the entries “High long-wave emissivity” and “Hygroscopic properties” (Fig. 2), as compared to non-mulched surfaces, are wrong.

Nevertheless, the positive effect of such mulch layers on condensation should not be summarily rejected. Some possible advantages remain:

a) The nocturnal atmosphere is cooled to a greater extent by a mulched than by a (dry) bare soil surface. Dew formation on plants is thus slightly enhanced. Although often considered undesirable, this might be advantageous to some species when suffering water stress (Stone, 1963). For the same reason, radiation fog will form more often above a mulched surface of sufficient extent than above a dry bare surface.
b) If the moisture content of a bare soil surface already exceeds equilibrium with ambient air humidity, hygroscopic water uptake does not occur. On the other hand, non-hygroscopic dewfall, which occurs preferentially on mulched surfaces, is only indirectly affected by increased surface moisture through a slightly higher soil heat flux. However, in most arid regions the surface of a bare soil will be dry enough

to enable hygroscopic water uptake even if the root zone is sufficiently moist to enable plant growth (Monteith, 1963).

c) Hygroscopic water is not available to most agricultural plants (pF > 4.2) if the atmospheric relative humidity is below 99%. Its benefits are thus only indirect, e.g. cooling and moistening of the atmospheric plant environment for the first few hours after sunrise. Non-hygroscopic dew as formed on mulched surfaces, on the other hand, is not subject to such restrictions. In the present study, the small portion of dew in mulched surfaces that actually reached the covered soil, was not plant-available any more by then. However, a surface to root zone transfer of plant-available water through the gaseous phase is generally possible if the penetration of the nocturnal temperature minimum into the ground in the morning hours creates a vapour pressure gradient from surface to deeper layers.

d) The same penetration of nocturnal minimum temperatures into the ground might lead to a direct non-hygroscopic condensation of atmospheric water vapour at the mulch–soil interface in the late morning. During the day, the atmosphere's dewpoint temperature is often higher than at night due to evapotranspiration from surrounding moister surfaces. If there is sufficient exchange between the atmosphere and those soil depths where soil temperature is below that dewpoint, there will be a vapour flux from air to depth of condensation. A mulch layer with its coarse pores provides better exchange than a typical soil surface, maintains a steep temperature gradient through its low thermal conductivity, and will not disturb such a flux through evaporation if dry. Therefore, daytime condensation would be enhanced if certain meteorological conditions are fulfilled, i.e. if, at a given time in the morning, the soil temperature at a certain depth is below the air's dewpoint. Ideally, the mulch–soil interface would be situated in that depth.

The following simple model can help to identify places where or occasions when such meteorological conditions occur. It is subject to the following simplified assumptions. Firstly, temperature cycles other than the diurnal one are neglected and a constant daily mean soil temperature is assumed for all depths (temperature gradients resulting from the annual cycle would be much weaker and only enable condensation in depths of several meters, which shall not be discussed here). Secondly, the soil temperature cycle is assumed to be sinusoidal — as is usual for modeling purposes (De Vries, 1975). Then the strength and delay of a temperature signal dependent on depth are given by the equations (Zmarsly et al., 2002).

$$\Delta T_2 = \Delta T_1 \exp\left[(z_1 - z_2)\sqrt{\pi/a\tau}\right] \tag{1}$$

and

$$\Delta t_{2,1} = (z_2 - z_1)\tau/2\pi\sqrt{\pi/a\tau} \tag{2}$$

with index 1 or 2 indicating depth levels 1 and 2, ΔT = temperature amplitude of the (daily) cycle at the given depth in K, z = depth in m, a = thermal diffusivity of the substrate in m^2 s^{-1}, τ = duration of the cycle = 86,400 s, $\Delta t_{2,1}$ = delay of minimum occurrence in level 2 as compared to level 1 in s.

By combining these equations, the interdependence of damping and phase shift can be expressed as

$$T_2 - \overline{T} = \left(T_1 - \overline{T}\right) \exp\left[-2\pi\Delta t_{2,1}\tau^{-1}\right]. \tag{3}$$

Thus with a given minimum surface temperature, T_1, the time of its occurrence, and the mean temperature of the cycle, $\overline{T}$, a time series can be generated that gives the lowest temperature to be expected in the soil column for any time during the rest of the cycle ($T_{\min} = T_2$ for T_1 = minimum surface temperature). This column minimum temperature, unlike the depth of its occurrence, is independent of soil thermal properties. During any period when the current value of this time series is lower than atmospheric dewpoint temperature, condensation of atmospheric water vapour within the ground is possible if the pores are coarse enough to enable turbulent vapour exchange, e.g. in a mulch layer. Fig. 5 contains a theoretical plot of daily atmospheric dewpoint temperature (T_d) and surface temperature (T_0) cycle for a clear summer day in the midlatitudes, together with soil column minimum temperature ($T_{\min}$) as derived from Eq. (3).

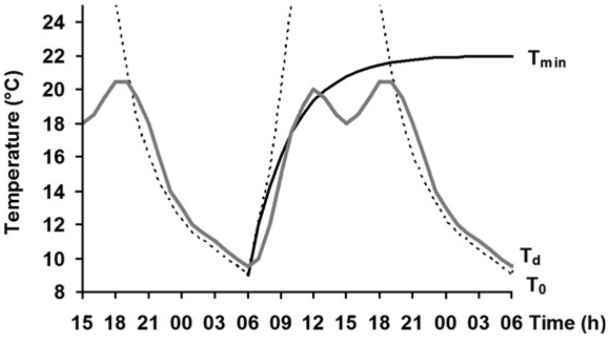

Fig. 5. Plot of a theoretical daytime condensation event. Daily atmospheric dewpoint temperature (T_d) and surface temperature (T_0) cycle for a clear summer day in the midlatitudes, and soil column minimum temperature ($T_{\min}$).

Apart from the nocturnal dewfall period with $T_0 < T_d$ (20 h to 6 h), a second period of possible condensation in the late morning hours (10 h to 13 h) can be seen in the deeper layers. On Lanzarote, the amplitude of the diurnal dewpoint cycle is low and thus does not favour such "daytime condensation". It might, however, be expected in less arid regions where evapotranspiration provides a significant morning rise in atmospheric dewpoint temperature. This might be one topic for future dew research.

4. Conclusions

Comparative measurements on bare and mulched surfaces have indicated that the popular assumption that lapilli mulching enhances nocturnal condensation in arid agriculture as practiced on Lanzarote, is largely incorrect. This is especially true for the hygroscopicity attributed to lapilli, which was found to be much weaker than for bare soil. Some advantageous effects of mulching on dew may theoretically be possible, but in this study no positive net effect on nocturnal water gains were shown. If optimisation of nocturnal condensation gains had been a factor in the evolution of agriculture on Lanzarote, at least three alternative mulch substrates could have given better results. On the other hand, the lapilli substrate was shown to be the most effective for the reduction of evaporation. This accords well with other studies with regard to both condensation reduction by coarse-grained surface substrates (Li, 2002) and evaporation reduction by volcanic coarse-grained surface substrates (Pérez, 2000). It is therefore suggested that evaporation reduction was the critical factor governing the development of Lanzarote's specific farming method. The conditions outlined in Section 3(a–d) could be used to find cases of successful on-field condensation enhancement in both new and indigenous agricultural methods.

Acknowledgments

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Appendix

The following symbols are used:

a	thermal diffusivity of the substrate in $m^2\ s^{-1}$
Hy	hygroscopicity (gravimetric equilibrium water content at 94.3% RH and 20 °C, ascending curve) in %
T_n	temperature at level n in K
T_0	surface temperature in K
T_d	dewpoint temperature of the air in K
T_{min}	minimum of the momentary depth–temperature function in K
z	depth of level n in m
α	short-wave (0.3–2.8 µm) albedo in %
ΔT_n	temperature amplitude of the (daily) cycle at level n in K
$\Delta t_{2,1}$	delay of temperature minimum occurrence in level 2 as compared to level 1 in s
ε	long-wave (2.8–30 µm) emissivity in %
λ	thermal conductivity in $W\ m^{-1}\ K^{-1}$
τ	duration of the (daily) temperature cycle in s

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