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Green-Roof Project in Oman: Capillary Siphoning as a Novel and Thrifty Irrigation Technique

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Abstract: Experimental and theoretical data on a green roof project conducted in 2008-2010 in Oman with soil pots irrigated by capillary siphons are presented. Siphons were made of twisted T-shirts (daggling cylindrical, flexible U-shape conduits immersed into water supply containers and soil pots). Soil, water, air and roof temperatures, moisture content, EC of drained water (leachate) and of soil water, siphoning flow rates were measured by thermometers, thermocouples, theta-probes, EC-meter and by controlling water quantity added regularly to water supply containers. Siphoned water evaporated directly from the soil surface, transpired by cultivated tomato, petunia, succulent and other plants, percolated and drained to the roof where it was adsorbed by hot concrete and evaporated (roof cooling). Recorded diurnal temperature swings in the roof gravel, soil profile inside the pots and at the pot bottoms (roof surface) showed that the daily averages of the soil/cooled roof are at least 5-6 deg C (°C) less than of the bare roof. Variability of temperature in the pot-protected zone is significantly less and the daily peaks are attained later as compared with the bare roof with an average water consumption of 0.5 l/day/pot. Even plants with a relatively poor heat tolerance (tomato) developed well till May. Accumulation of salts in the soil of pots was detected. EC of a sudden flood water seeping through the whole pot surface was measured. Cost analysis, based on the current Omani prices of electricity and water, estimates the proposed technique as economically viable. In lysimeter experiments, siphoned pots even under normal wet operation conditions are shown to possess a significant buffering (water holding) capacity with respect to typical 20-mm rainfalls. Secondary salinization of the periphery of soil in the pots requires occasional leaching. Mathematical Washburn-Lukas models of flow in capillary tube bundles are used to predict the kinetics of imbibition and steady siphoning.

Key words: Siphon • Moisture content • Thermocouples • Seepage

INTRODUCTION

Green Roof (GR) with the corresponding irrigation device is a soil-vegetation system installed at the top of a building. Most GR are subject to direct solar radiation. In common private one-, two-storey houses, the roof is a significant or major conductor of heat from the sun-exposed exterior of the building envelope [1-3] into the interior. This commonly requires continuous or intermittent air-conditioning that can be reduced by various roof-cooling techniques, in particular by GR [3]. A standard GR or porous roof evaporator involves a layer of soil and a draining substrate (gravel or coarse sand) with a pipe-drainage network, water pump, valves and sprinklers/bubblers/emitters that is relatively costly and energy-labour consuming to install and maintain [4].

In the Gulf region, in general and in Oman, in particular, GR face three major limitations caused by extremely hot and hyper-dry environments. In the study area (Batinah coast of Oman) of the project these three peculiarities of climatic conditions affect the biotic and abiotic component of GR in the following manner:

- The thermal shock, which the plants experience in summer, is so severe (as our measurements showed, the bare roof temperature in the afternoon in June peaks to 70°+ C). Only heat-tolerant plants survive even with sufficient irrigation. This implies that GR may temporarily become a "brown" roof, i.e. soil with no (or dead) plants.
- Potential evaporation is high (>2000 mm/year) and natural precipitation is low (<100 mm/year). Rains occur 6-7 days a year with an average total depth of

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<30 mm per event. The intervals between two consecutive rains are very high such that the memory of the last rain is always lost by the soil of GR when the next rain occurs. Consequently, a natural leaching of the substrate is limited. This makes GR soils prone to secondary salinization. Consequently, after certain time (upon formation of the topsoil salt crust – soil particle salt coat) this will exert a salt-stress on the plants.

- Fresh water, especially in metropolitan areas, is costly and only limited water resources can be utilized for any new irrigation project, in particular, GR.

In this paper we present results on a GR in Oman with a novel irrigation system of soil pots full details can be found in [5]. Namely, water is supplied by capillary siphons providing a continuous descending seepage of moisture in the pots. Experiments conducted in 2008-2010 utilized flexible, quasi-cylindrical siphoning conduits. The siphons were made of cheap cotton T-shirts with soil cores, all wrapped into used plastics. The siphon fabric wicked water without any extra energy (by natural capillarity of the cloth and soil). This water fed pot soil, where different crops were cultivated. To avoid secondary salinization of the soil inside the pots the siphons/soils were designed in such a manner that the seepage flow rate through the pots was high enough to provide counter-salinization leaching. The siphoning rate was, however, small enough to minimize the overdraft of potable water diverted from water supply containers. Excess water (i.e. water not evapotranspired from the open soil surface in the pots and plant foliage), drained through the pot bottom holes, made wet quasi-circular spots on the roof surface, fringing from the area where the pot rims contact the concrete slab and, consequently, rendering an additional cooling effect of the roof.

MATERIALS AND METHODS

Three GR with various pots, water supply containers and wicks were allocated as shown in Fig.1a-c.

Fig. 1: a) GR module on the roof of a private b) Cascade of pots, GR module SQU building c) Single level GR module SQU building.

Fig. 2: Preparation of siphons: cotton tissue with soil core a), rolling b), wrapping c), plastic covering d)

Siphons were made of cheap cotton T-shirts and lab coats rolled into quasi-cylindrical tubes. The siphons were wrapped by three layers of used plastic bags that forestall evaporation losses into the air from the open part of the siphons. The core of the tubes was filled with a mixture of the Al-Khod (Oman) dam silt, coarse sand, wadi soil and soil form the Agricultural Experimental Station (AES) of SQU (Fig. 2a-d). During a regular irrigation stage, one end of the siphon was submersed into a water container and another was buried into a pot of soil (Fig. 1).

Containers, from which water was siphoned to the pots, were either refilled daily at SQU sites up to a “tally mark” with measurements of the siphoning rate (Fig. 3) or got water continuously from the house system through a floating valve (Fig. 1a module where wicking caused a continuous dripping of water into the house tank serving as an irrigation container). Succulent plants, alovera, marigold, tomato, petunia and other species were planted as seeds, transplanted seedlings and cuttings. Urea and plant food fertilizers were applied both in a dry form to the soil pots and by dissolving in water supply containers (with exception of the house tank from which water was used for regular domestic purposes).

Fig. 3: Container with a "tally mark" up to which water was regularly added

Moisture content, θ_v, in pots of the module in Fig. 1b-c was recorded manually by inserting a four-rod probe into the pot soil (a θ-probe device) Type M2x Delta-T device (Fig. 4) as a non-destructive (to the plants and siphons) readings of θ_v in the upper parts of the pot.

Although the “cruise irrigation regime” was steady state and continuous, kinetics of water imbibition into a dry siphon was of interest for assessing the incipient

Fig. 4: Moisture content reading by θ-probe device

Fig. 5: Measurements of accumulating mass of water imbibing into an initially dry vertical siphon

stages of irrigation (e.g., after a prolonged period of mid-summer “brown roof” stages). For assessing this suction of water into dry tissue, a siphon was made of one cotton T-shirt, i.e. had smaller radius of the “cylinder” than in the real irrigation siphons. The “kinetic” siphon was also shorter (62 cm). No plastic cover was wrapped in this case because the experiment was relatively short and conducted in a cold laboratory environment with no solar radiation. The siphon was not bent as in the real irrigation system but hung vertically with a stand clip (Fig. 5). A beaker was placed under the free end of the siphon. The beaker was filled with the tap water (approximately 1.5 l.) and its level was maintained constant during the experiment by adding water to the beaker tally-mark. When the hanging end of the siphon was submersed into beaker the cotton started to soak water. This vertical wick with accumulating water was weighed periodically. The time intervals between weighing were short at the beginning: 5, 5, 5, 5, 10 and 30 min and longer later. At $t = 0$, the dry siphon, stand, paper clip and plastic bag were weighted. Then, at each time interval, the siphon was quickly put in the plastic bag and hold with paper clip. Then the weight of the stand, siphon, paper clip and plastic bag with water were recorded and the siphon was returned to the beaker as soon as possible. Each weighing took several seconds and these few seconds are believed not to affect significantly the capillary rise (during weighing the siphon end was not in the supply water container, i.e. siphoning was interrupted). The mass of adsorbed water (kg), as a function of the time W (t) was calculated as follow: $W(t) = W_s(t) - W_o$ where $W_s(t)$ (kg) is the weight of the stand, siphon, paper clip and plastic bag with water and W_o is the weight the stand, dry siphon, paper clip and plastic bag at $t = 0$.

Temperature readings were taken by a thermometer, thermocouples (Model HH21 Microprocessor Thermometer, Type J- K- T Thermocouple, OMEGA) and an infrared radar (Fig.6) in several pots (inside the soil) of modules in Figs.1b and 1c by inserting the tips of corresponding devices into the soil or remotely. Similarly, temperature was measured in the gravel of the bare roof far from the pots, in water supply containers and in the air.

Topology of moisture motion from the pot holes into the roof is complex as Fig. 7 schematically depicts. Heat conduction and convection is even more topologically complicated because – unlike a quasi-steady seepage in the “cruise irrigation regime” – heat transfer is inherently cyclostationary due to diurnal and seasonal temperature swings. Consequently, point-wise temperature measurement by the above-mentioned instruments gave only limited spatial distribution of the temperature field (e.g., measurements inside the roof slab were impossible owing to constructive limitations).

In order to assess soil and water secondary salinization, lysimeter experiments were conducted for the module in Fig.1c. Plastic bags were placed under the soil pots to collect the drained water through the pots’ bottom holes. After three days (June 10-13, 2009), the plastic bags

Fig. 6: The measurement of the roof surface temperature by a thermocouple and radar under the pot

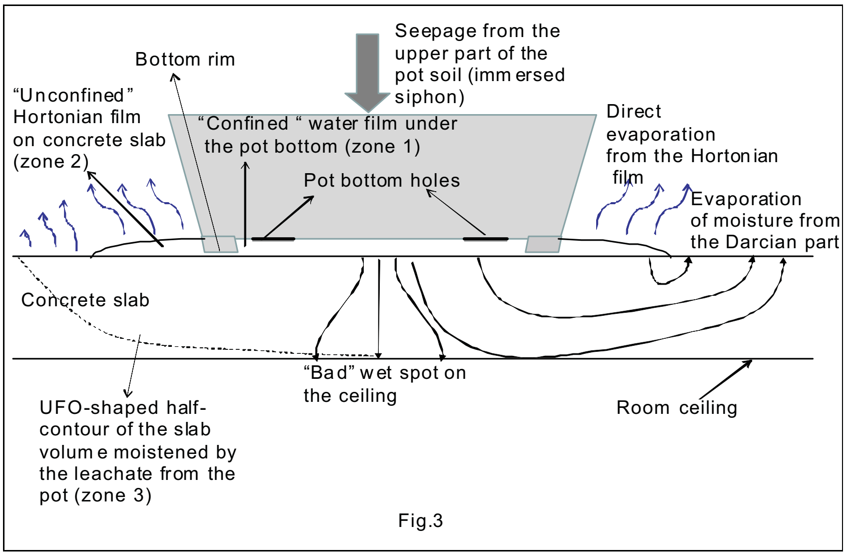

Fig. 7: Conceptual schematization of water motion over-inside the roof concrete slab

with all accumulated drainage water were removed from the pots and EC was measured. No plants grew in pots 7, 9 and 10 on that time. During six months preceding this experiment, the tap water with EC of 100-200 microS/cm was added to the containers.

GR – as, mainly, a passive thermal insulation technique of the buildings – should be hydrologically assessed as an element of the urban flood drainage network. By June 2009 we observed the formation of salt crystals on the soil surface of some pots in Fig. 1c. Therefore, the behavior and potential leaching of this accumulated salt by relatively intensive rainwater was of interest. Five pots (4, 6, 9 and 10) were selected and on June 14 we did a flood-simulation experiment. We removed the siphons, levelled the disturbed soil surface and transferred the pots to the lab (ambient air temperature of 22°C). Then for each pot we measured the surface area and the weight of the partially saturated soil in the pots. Next, we applied tap water in volumes equivalent to a 20-mm rainfall. Tap water was poured on the soil surface instantaneously. The effluent from the pot holes was collected and EC was measured by an EC-meter.

On June 16, 2009 one of the siphons from the set in Fig. 1c was decommissioned and unwrapped (Fig. 8). It has been noticed that the external layer of plastic exposed to direct solar radiation dilapidated. It could be torn out easily and the pieces crumbled into white powder when slightly rubbed. The second and third (contacting the wet fabric of the siphons) layers of plastic bags kept, however, their elasticity and counter-evaporation consistency. The two ends of siphons immersed into the container and soil (i.e. protected against direct solar

Fig. 8: Visual inspection and sensation of the opened siphon (the external layer of plastic exposed to direct solar radiation dilapidated)

radiation) had all three layers of plastic sheath unaffected by heat. Visual inspection and sensation showed that the fabric of the siphons was also mechanically stable with an exception of the end immersed into soil, where plant roots penetrated into the fabric and softened it. No clogging of the part of the siphons above the container water level was detected. Other siphons were used in 2010 (Fig. 2) regular irrigation experiments.

RESULTS AND DISCUSSION

Daily flow rates of one of the containers (feeding four siphons) of the module in Fig. 1c are presented in Fig. 9. For all other containers time series (daily flow rates and monthly-averaged bar-charts) similar to one in Fig. 9 are compiled. The flow rates varied from less than 1 L/day/container (January, 2009) to 2.5 L/day/container (June 2009). Overall, a season-averaged flow rate through a siphon in Fig. 1c was about 0.5 l/day.

Moisture content θ_v of the soil is shown in Fig. 10 (daily readings are averaged over one month). The variations of θ_v in different pots represented the different types of soil (different holding capacity of water). Pots 5, 6, 7 and 8 were filled with the AES soil and pot 9 contained a coarse sand. The flow rates from the siphons to the pots and temperature changes (evapotranspiration rates) during the season controlled the fluctuations of θ_v.

The mass of water adsorbed by the siphon (see Fig. 5) as a function of the square root of time is plotted in Fig.11. The relationship is linear (liner regression with R^2 value = 0.9889) that is in full congruity with the Washburn-Lukas theory.

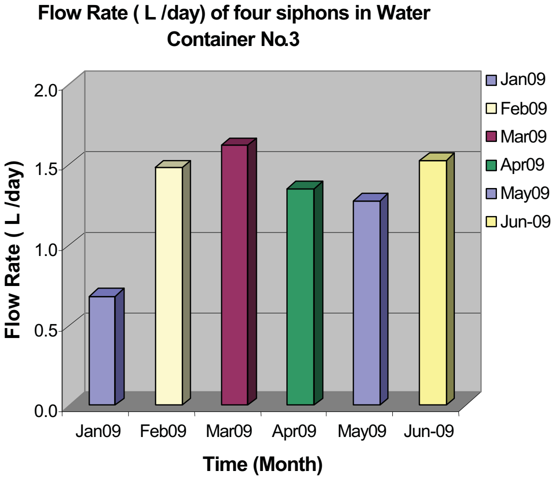

Fig. 9: Daily average flow rate of the four siphons fed from container no. 3

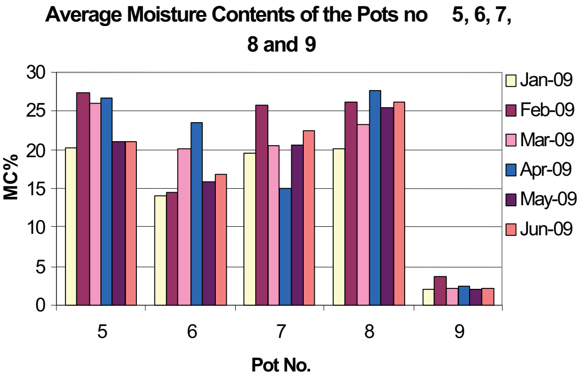

Fig. 10: Moisture contents of four pots in Fig. 3

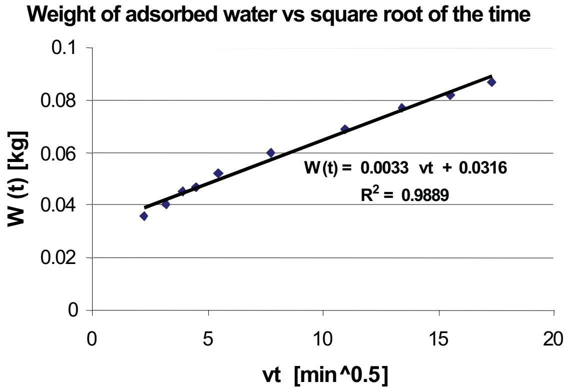

Fig. 11: Experimental weight of adsorbed water, versus square root of the time

The EC for the source (water containers) and the drained water for the lysimeter experiment in the “cruise regime” (June 10-13, 2009) are presented in Table 1.

Table 1: EC (microS/cm) of the water in the containers and drained water at "cruise operation" in June 2009

Pot no.	Water in supply containers EC(micros/cm)	Drained water EC (micros/cm)
4	134.2	515
7	139.3	392
9	203	334
10	203	483

Table 2: EC of leachate in June 14, 2009 ("rainfall") experiment

Pot No.	Weight of water added (g)	Pot weight prior to ponding (g)	EC of leachate (microS/cm)
4	693.0	7996	955
6	760.3	9176	4180
9	831.0	8621	1750
10	693.0	7561	1963

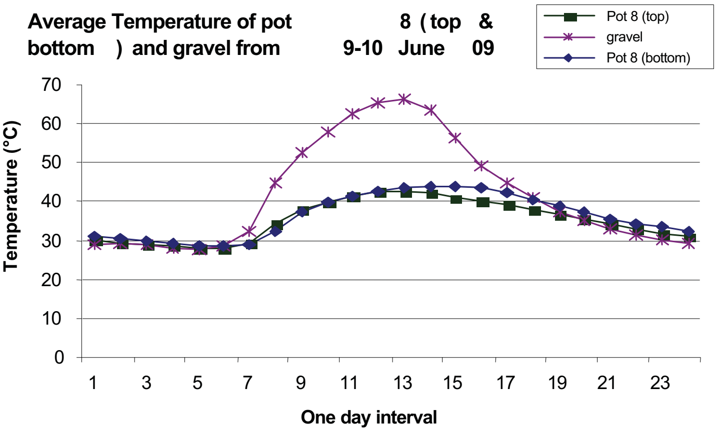

Fig. 12: Daily temperature variations of the bare gravel roof, top soil in the pot and bottom soil for pot 8 on June 9-10, 2009

The increase of EC in drained water is, obviously, due to the passage of water through the soil with accumulated salts. This increase is, however, moderate (indeed salinity of the leachate is well within the irrigation water limit) that allowed us to design and successfully operate a vertical cascade of pots (Fig. 1b) where the leachate from upper pots feeds the lower pots.

Table 2 Shows EC of the leachate in the rainfall-modeling experiment. Here the quality of leachate is much worse than at "cruise irrigation". In all pots EC is 10-40 times higher than that of "rainwater" (tap water). In pots 4, 9 and 10 EC is 3-4 times higher than what we get in lysimeter experiments with normal operation of the pots under continuous siphoning (Table 1). We surmise, this is caused by the difference in topology of water motion through the soil in uniform ponding during the flood and in normal siphoning operation. In the former case, the flood water applied on the surface moves vertically down, at least close to the soil surface and converges to the holes only near the pot bottom. In the latter case, the Darcian flow in the pots originated from the siphon end is essentially 3-D. One part is moving prevalently down from the source (tip of the siphon) to two sinks (pot holes). Another part is kinking up to the soil surface in the pot (evaporation route) i.e. is normally subject to ascending Darcian velocities. In this area of ascending velocities (periphery of the immersed siphon tip) salts accumulate.

Fig. 12 shows temperature graphs for pot 8 on June 9-10 (the module in Fig.3). Thermocouples in the bare gravel far from the pots, in the soil close to the surface in pot 8 (AES soil) and in the bottom part of this pot recorded temperature every minute but Fig.12 gives hour-averaged temperatures (the abscissa axis of Fig.12 indicates time in hours). The maximum of temperature under a seeping pot was 44.2 °C as compared with 67.4 °C of bare gravel. The peak of pot bottom temperature was attained after 396 min (14:46) and the maximum of the bare roof temperature occurred after 303 minutes (13:13), i.e. the phase shift was 1.5 hours. The maximum of top soil temperature was 42.9 °C, attained at 13:01.

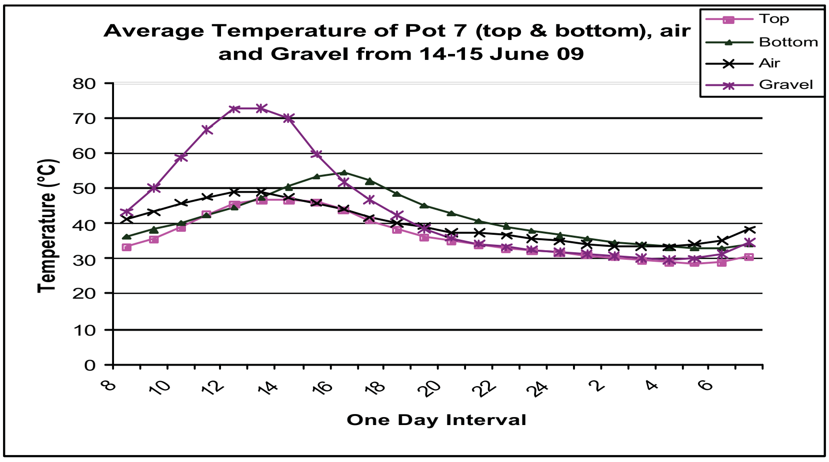

Fig. 13: Daily temperature variation in pot 7 on June 14-15, 2009.

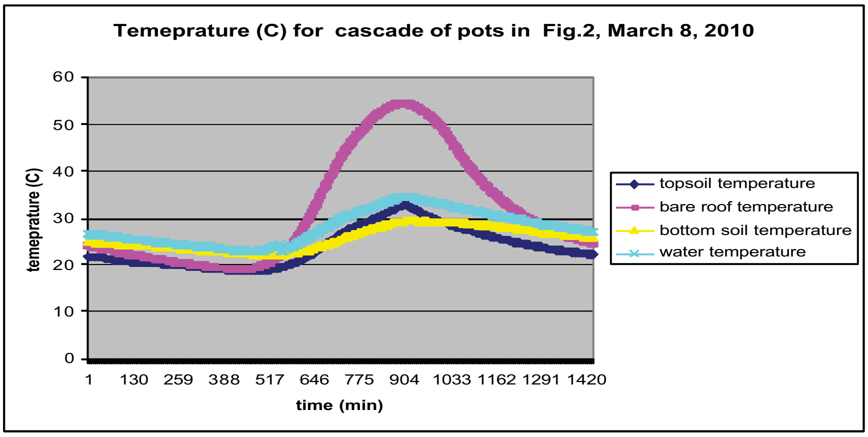

Fig. 14: Daily temperature variation in cascade of pots, Fig.2 on March 8, 2010.

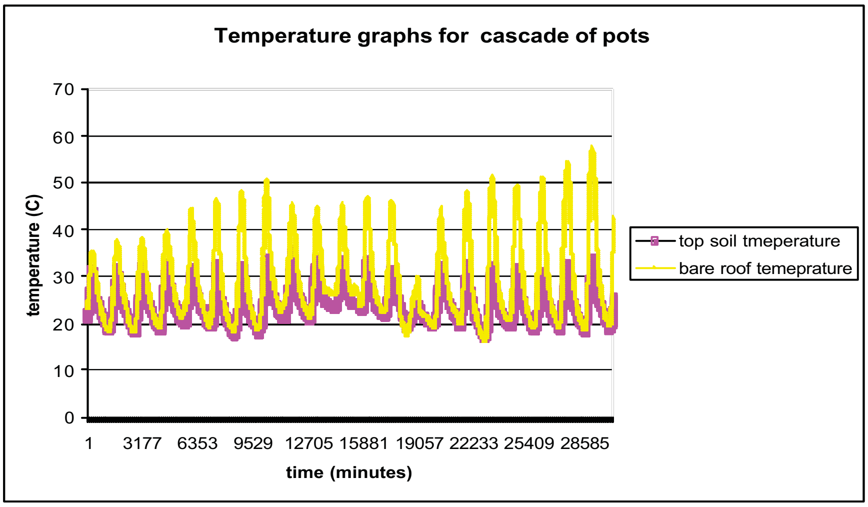

Fig. 15: Temperature fluctuations, cascade of pots, Fig.2 from February 17 to March 10, 2010.

Fig. 13 represents temperature for pot 7 (AES soil), readings taken from 8:20, June 14 to 8:20, June 15. Air temperature is also plotted.

Figs. 14-15 present temperature variations for the module in Fig.1b (the abscissa axis indicates time in minutes). Fig. 14 illustrates daily temperature swings on March 8, 2010 (topsoil of the top pot in the cascade, bare roof, the bed of the bottom container in the cascade and water in the supply container). Fig. 15 illustrates fluctuations of temperature in February-March retrieved by two thermocouples (bare roof and the topsoil of the upper pot in the cascade).

For significant parts of the day, the pots act as "counter-flow heat exchangers" with vertical thermal gradients of up to 20° -30°/m, being counter-oriented with the seepage gradients, i.e. heat in soil moves up against the direction of water motion. Preliminary assessments of the cost of water (0.5 Riyal/cubic meter, 1 Omani Riyal=2.5 US$) needed for irrigation versus energy savings (0.020-0.030 Riyal/kW*h) due to roof cooling showed that the suggested GR technology is economically feasible. As in all previous studies of evaporation-cooled roofs (including GR), there is a considerable decrease of temperature and diurnal amplitude of its variation on the pot-protected roof surface as compared with a bare surface. Similarly to Onmura *et al.* (2001, Figure 2a) and other published results on thermometry of GR, during a part of the day temperature of our bare roof is less than that of the pot-covered surface.

CONCLUSION

Our experiments showed that siphoning is a robust and reliable way to continuously convey water to the pots of GR in Oman. Daily and monthly variations of the flow rate through our single-pot siphons were within the range of 0.35 in January to 0.65 l/day/siphon in June. The siphons functioned hydraulically well and continuously (without any disruptions in irrigation). Plastic three-layer wrapping of the siphons occurred to be radiation-resistant during one cultivation season. A significant thermal cooling of the roof area close to the pot bottoms and inside the soil is attained by shading, evapotranspiration and increased thickness of the thermally resisting layer on the roof. The advected cooling agent (water) provides both continuous irrigation and leaching of the soil matrix that delays salt accumulation. The leachate drained through the pot bottom holes creates UFO-shaped wet and cool zones in the roof, on which the pots are deployed. With June bare roof afternoon temperature in the region blowing up to 70+°C, siphoned GR soil pot modules support temperature-moisture regimes tolerable by some plants. Secondary salinization of the soil in GR pots is a serious problem for long-term operation of siphoned modules if occasional rains leach the soil in regimes different from steady "cruise seepage".

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