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# Soil substrate as a cascade of capillary barriers for conserving water in a desert environment: lessons learned from arid nature

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**Abstract:** Interaction between soil pedogenesis, subsurface water dynamics, climate, vegetation and human ingenuity in a desert environment has been found to result in a unique ecohydrological system with an essentially three dimensional sedimentation structure in the bed of a recharge dam in Oman. A 3-D array of silt blocks sandwiched by dry sand-filled horizontal and vertical fractures was studied in pot experiments as a model of a natural prototype. Pots are filled with a homogenous sand-silt mixture (control) or artificially structured (smart design, SD) soil substrates. Rhodes grass and ivy (*Ipomea*, Convolvulaceae) were grown in the pots during the hottest season in Oman. Soil moisture content (SMC) was measured at different depths over a period of 20 days without irrigation. SD preserved the SMC of the root zone for both ivy and grass (SMC of around 25%–30% compared to <10% for control, 3 days after the last irrigation). Even after 20 days, SMC was around 18% in the SD and 7% in the control. This, similar to the case of a natural prototype, is attributed to the higher upward capillary movement of water in control pots and intensive evaporation. The capillary barrier of sand sheaths causes discontinuity in moisture migration from the micro-pores in the silt blocks to sand pores. The blocks serve as capillarity-locked water buffers, which are depleted at a slow rate by transpiration rather than evaporation from the soil surface. This creates a unique ecosystem with a dramatic difference in vegetation between SD-pots and control pots. Consequently, the Noy-Meir edaphic factor, conceptualizing the ecological impact of 1-D vertical heterogeneity of desert soils, should be generalized to incorporate 3-D soil heterogeneity patterns. This agro-engineering control of the soil substrate and soil moisture distribution and dynamics (SMDaD) can be widely used by desert farmers as a cheap technique, with significant savings of irrigation water.

**Keywords:** soil capillary barrier; infiltration; soil heterogeneity; ecohydrology; hydropedology; plant root; soil moisture content

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Integrated water resources management and understanding of the response of ecosystems to natural and anthropogenically alternated realizations of the hydrological cycle (Hannah et. al, 2007) are generic issues in ecohydrology of deserts and other water limited environments (Adams, 2007). Soil moisture distribution and dynamics (SMDaD) are primary factors controlling the water-nutrients uptake/heat stress by/to the roots and, therefore, the visible vegetation pattern in ecosystems (Green and Clothier, 1999; Rodriguez-Iturbe et al., 2001; Porporato et al., 2002; Francis et al., 2007), especially, in arid regions. Oman, whose climate varies from arid to hyper-arid (with an exception of few semi-arid mountain biomes at altitudes

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of 1,000–3,000 m) faces a dilemma of managing the "green" (natural and cultivated vegetation) and "blue" (very rare rains and no natural perennial water courses) components of ecosystems, which rapidly transform in time along with geomorphological settings (Wilcox, 2010).

Oman is characterized by precipitation of 50–100 mm/a, pan evaporation of more than 2,000 mm/a, short (several hours) flash-flood-type runoff events caused by torrential rainstorms 1–2 times/a, and extreme topsoil temperature (peaks to >70°C at 13:00 in June–July) (MRMWR, 2005). The proximity of plants to ephemeral water courses (wadis), through which most natural infiltration takes place and beneath which relatively long-living "hidden pockets" of perched mini-aquifers exist, pedology of mostly coarse soils, primary (sabkha) and secondary (irrigation-induced) soil salinization, and characteristics of local vegetation (large lengths of roots which are in permanent and desperate pursuit of always elusive water, relatively low density of roots, and thrifty transpiration regimes) are crucial to local Omani ecosystems.

SMDaD in water limited environments has been extensively studied in natural ecosystems and farm practices, in both field and laboratory experiments. Namely, hydrology, soil physics, botany, agronomy, plant physiology, among others, are involved in the studies of SMDaD. This multidisciplinary approach is needed to understand soils, vadose zone and shallow (often saline) groundwater. The corresponding fluxes of water and chemicals are caused by return drainage (irrigation) and natural recharge. On the catchment scale, several sectors (natural biomes, agriculture, industry and municipalities) compete for scarce water resources and various techniques (e.g. small-scale irrigation gadgets or construction of huge hydraulic structures like dams) are invented to improve water use efficiency (Burns et al., 1971; Singh and Bhushan, 1980; Hatfield et al., 2001; Aboudrare et al., 2006; Francis et al., 2007; Sadras, 2009).

Soil water moving from a finer to coarser soil zones experiences the so-called capillary barrier (CB), *viz.* impeding, diverting or even stopping the movement across the interface between these zones. CBs have been extensively studied and utilized by geotechnical engineers, soil physicists and agronomists (Ross, 1990; Morel-Seytoux, 1993; Kämpf et al., 1998; Mallants et al., 1999; Stormont and Anderson, 1999; Khire et al., 2000; Bussiere et al., 2003; Francis et al., 2007; Ma and Li, 2011). For example, a designed layered heterogeneity (fine over coarse layers) is widely used in landfill covers to divert infiltration of a descending leachate away from certain subsurface zones where intensive vertical water fluxes are unwanted (Stormont and Morris, 1997) and in various types of mulching when the ascending evaporative fluxes are impeded by a coarse gravel or sand layer, date palm litter and other plant residues on the topsoil (Lightfoot, 1996; Yuan et al., 2009; Huang, 2013). It is noteworthy that an inverse process of wicking (or siphoning) enhances evaporation (and cooling of the soil) when a finer soil compartment is in contact with a coarser one (Lehmann and Or, 2009; Kacimov et al., 2010).

CBs in layered soils are reported to enhance the plant growth and crop production. Stormont and Morris (1997) studied the water content distribution in a layered soil subject to infiltration and found that CB, formed across the interface between two layers, caused temporary water storage in the upper layer. This water is then either lost by evaporation or penetrates into the lower layer in case the suction head reaches a breakthrough (also called critical) value. Rooney et al. (1998) examined a CB placed under the root zone, and discovered that CB prevented the capillary rise and stopped salinization from underlying sources, thus allowing salt-sensitive plants to grow well. Ityel et al. (2011) found that water uptake and productive biomass of pepper plants were improved by introducing an artificial CB (at different soil depths) made up by a layer of gravel (of particle diameters ranged from 10 to 30 mm) below the root zone and composed of a finer texture soil (sandy soil). The volumetric soil water content, $\theta_v$, in the root zone was increased by 20%–70% depending on the soil texture and the depth of the barrier. For different layered textural heterogeneities, Zetti et al. (2011) and Huang et al. (2013) illustrated, through field-laboratory experiments and modeling, that a higher water storage at field capacity is associated with increased textural heterogeneity. The $\theta_v$ value at field capacity decreased by 50% when the gravel content (i.e. the proportion of particles >11 mm in diameter) increased from 0–40%

of the total soil weight (Paruelo et al., 1988). Ma and Li (2011) experimentally confirmed that gravel-sand mulches were more effective in conserving soil water as compared to bare soil. Francis et al. (2007) found that the surface and subsurface properties of soil (like dispersive crust, textural barriers and mineral hard pans) controlled the flow pattern and redistribution of soil water and its storage in Namaqualand soil. Water would be channeled deeply through a coarse-texture zone and retained by low permeable layers, which then may return the water to the root zone by thermal vapor transport with distillation.

The response of the root system to SMDaD in a texturally heterogeneous soil of arid zones is ecologically well-understood (Noy-Meir, 1973; Dodd and Lauenroth, 1997; Laio et al., 2001; Francis et al., 2007; Ma and Li, 2011; Jacobson and Jacobson, 2013): naturally coarser or mulched topsoils favour a deeper penetration of occasional infiltration pulses and CB-caused reduction of evaporation during the ensuing redistribution phase with a consequent establishment of woody plants. Finer topsoils with higher capillarity, evaporative losses and no CB facilitate herbaceous species.

In this paper, we studied SMDaD in a unique and fascinating type of structural-textural heterogeneity of soils, which we have recently discovered in the field (Al-Ismaily et al, 2013, b; Kacimov et al, 2013; Kacimov and Brown, 2014). Noy-Meir (1973) conceptualized soil heterogeneity as a vertical soil textural stratification (i.e. intermittently occurring of coarse and fine soil layering). With soils of alluvial deposits, formation of parallel with well-defined textural stratum is common and is routinely identified by both pedologists and sedimentologists. Our textural heterogeneity or layering, however, is different and is consisted of a 3-D intricate composition of silt blocks and cracks filled with a "proppant" sand. Although vertical/tilted cracks and fractures, wormholes and subterranean cavities (Philip et al., 1989) are also proved to influence SMDaD, these complexities are, to the best of our knowledge, not incorporated into ecohydrological analysis (Guswa et al., 2002; Newman et al., 2006). A regular cascade of 3-D heterogeneities, engineered to utilize and maximize the CB phenomenon as a water-saving technique, is the core of our paper.

## 1 Experimental site

During a hydropedological study of siltation in the Al-Khod dam of Oman, a new natural phenomenon (Al-Ismaily et al., 2012, 2013) of a "preferential" sediment load deposition and concomitant preferential Darcian infiltration with further intricate evapotranspiration and preferential plant growth in a "smartly self-heterogenizing" soil (Fig. 1a) has been revealed. Here we briefly describe this soil structure which served as a prototype of our engineered substrate. As shown in Fig. 1a, the reservoir bed, exposed to solar radiation, desiccates and naturally morphs into a cascade of blocks of a fine silt and cracks. The vertical (visible in the topmost layer) and horizontal (buried) cracks between the blocks are filled with prevalently coarse sand. This 3-D structure of cascades of CBs repeats with depth (we observed this in pedons dug up to 2.5 m deep) and serves as a footprint of flood depositions.

The dimensions of silt blocks are in average 30 cm (length)×20 cm (width)×20 cm (height) (Fig. 1a). The block at each horizon is separated by horizontal sand-filled fractures from its subjacent and superjacent neighbors, born by flooding-sedimentation events preceding and following the event that generated this particular block. The same block is separated from its horizontal neighbors by vertical fractures, whose origin is also explained in Al-Ismaily et al. (2013). The fractures (apertures ranging from 2.0 to 6.5 cm) are filled with a coarse sand. In other words, each block in each horizon is "coated" by a sand sheath or, to rephrase, sand layers are sandwiched between silt blocks. This network of vertical and horizontal sand-filled cracks is hydraulically important to make a maze of winding channels for infiltration and seepage (Fig. 1a). When the reservoir is full of flash-flood water, the infiltrated water, driven by gravity and under a relatively minor Darcian sand-resistance, moves easily through the maze of these sand-filled cracks. Consequently, the uptake of water by the blocks increases

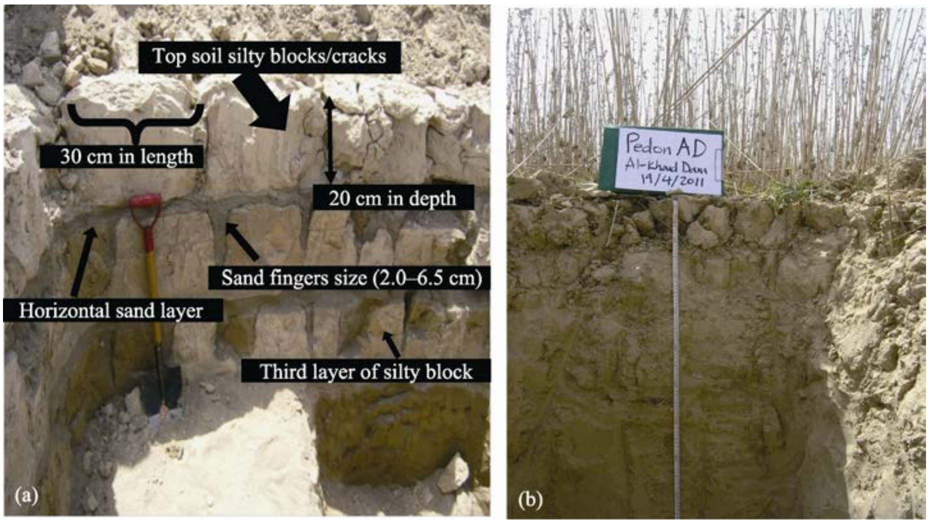


**Fig. 1** (a) Naturally morphed cascade of fine-textured silt blocks and horizontal-vertical fractures with a coarse sand filling (modified from Al-Ismaily et al., 2013), and (b) "regular" layered heterogeneity within a distance of 200 m from the smartly heterogeneous pattern of 3-D CBs in Fig. 1a. Dead ephemeral plants are the footprint of the last flood wetting event.

due to a longer contact time with water seeping in cracks. This preferential and relatively fast flow in the cracks winds through the sand sheath of each block. On the other hand, when the reservoir is empty and its bed is subject to a caustic solar radiation (most of the year), the evaporation from the blocks is very slow despite the extreme heat and dry topsoil conditions. Therefore, during the whole cycle of short flooding and subsequent long drying the discovered cascades of blocks-cracks preserve and hold much more water in the subsurface than a standard layered (only vertically stratified) sedimentation.

The rapid liquid drainage from fractures and inhibition of evaporation owing to the CB impedance are similar to what reservoir engineers model as block-fracture systems in oil formations. The role of sand "fingers" (formed naturally in dam beds, see Fig. 1a) is similar to the "proppant" injected by petroleum engineers into naturally fractured carbonate or artificially fractured sandstone rock zones, adjacent to oil wells. The sand sheaths in Fig. 1a ensure both a rapid wetting of the blocks, when the reservoir is full of water, and CB-caused maintaining of almost full saturation in the blocks (for up to several years) when the reservoir is empty and soil surface evaporates. The measured $\theta_v$ in the blocks remains up to 48%. After the next flood event, the winding infiltration-seepage occurs again, seeping fractures recharge the slightly evaporation-depleted blocks, and the whole cycle repeats.

The 3-D CB cascade of blocks-fractures (Fig. 1a) has been discovered in a relatively small area of the investigated dam lake. In most other sites, where soil pedons were dug, the "common" strata of sedimentation were found (Fig. 1b). In the standard soil lamina of Fig. 1b, the soil is extremely dry throughout the whole depth of the pedon ($\theta_v$<5%), while few hundred meters away (the locus of Fig. 1a) the SD soil, starting from the second layer of blocks (i.e. about 30–40 cm deep from the soil surface), is extremely wet ($\theta_v$=45%). In the former place, the vegetation consists of ephemeral natural herbaceous plants that die short time after the flooding event due to high capillarity and hence rapid loss of infiltrated water via evaporation (Fig. 2a). Within the cascade structure, however, permanent castor-oil plants and acacia trees flourished due to the presence of very wet blocks beneath, whose abundant moisture the roots of these plants apparently tapped (Fig. 2b).

A hydrologically similar phenomenon of impeding a vertical infiltration flux and channeling it towards the plant roots to make a clear band (strip) pattern of vegetation has been discovered on the slopes of the embankment of this dam (Kacimov and Brown, 2014). Figure 3

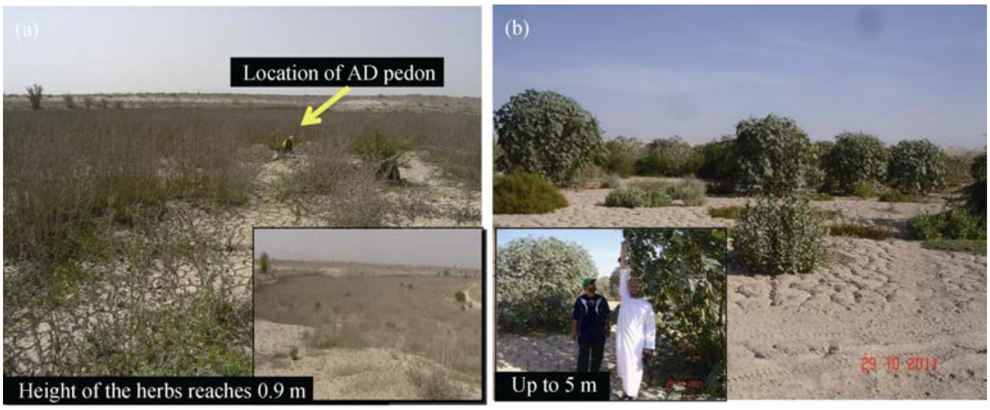


**Fig. 2** (a) Dead herbaceous species in the investigated lake area with a subjacent standard laminated soil, and (b) lush vegetation of castor-oil plants thriving on a substrate of CB-propped 3-D subsurface cascade of blocks-cracks exposed in the pedon of Fig. 1a.

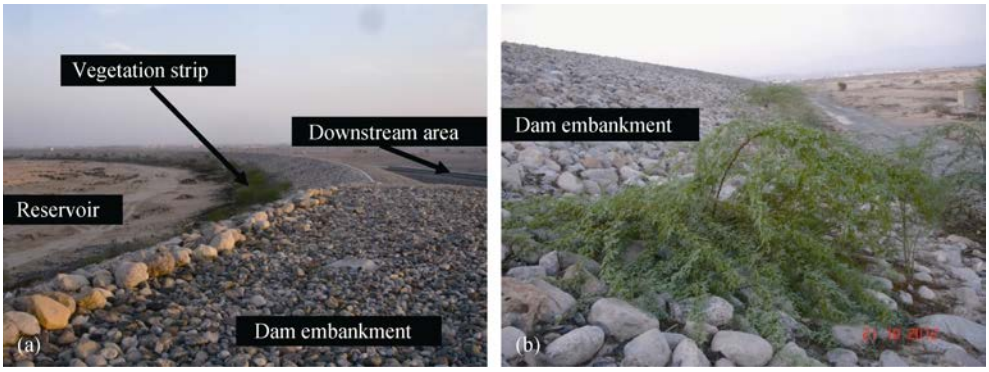


**Fig. 3** "Green" bands of natural vegetation along the toe of the embankment, Al-Khod dam. The SD zone of Fig. 1a is about 800 m from the embankment.

shows a distinct ecotone of lush vegetation rooted in a zone where a course dam filling and relatively fine subjacent soil are conjugated through a so-called seepage face (Strack, 1989), which vents evaporating water not intercepted for transpiration by the plant roots.

In the natural block-crack system of Al-Ismaily et al. (2012, 2013), the infiltration events are sporadic and unpredictable and vegetation benefiting from such unique compartments of block-stored moisture is natural (e.g. a castor-oil plant). In the engineered system reported in this paper, we supplied water to our "smart" soil substrate by a scheduled irrigation through emitters. We grew plants, which are used in Oman as either crops or ornamental cultivars. We explored the impact of such 3-D CB design and controlled unsaturated flow with the final goal of saving irrigation water.

To summarize, in this paper, we utilized a "nature-inspired heterogeneous design" (Fig. 1a) of soil texture in the root-zone as an essentially 3-D composition of CBs, i.e. a prototype discovered in a natural ecosystem of Oman (Al-Ismaily et al., 2013). We mimicked the observed natural phenomena: a lush vegetation in an extremely hot and dry environment thriving on moisture intercepted by a cascade of silty blocks and protected from evaporation and gravitational drainage by sand-filled cracks. We proved that the "smartly designed" (SD) natural block-filled crack system can be replicated as an engineered substrate in pots-barrels and that the plants grown in such substrate develop well under deficit irrigation. Instrumental measurements of SMDaD and plant responses to controlled water irrigation inputs, impossible in a natural reservoir bed of the natural SD cascade (Al-Ismaily et al., 2014), were carried out in this farm-replicated soil substrate. So, the newness of this work is in experimental observation and conceptual understanding of the moisture content-salinity distribution and dynamics in a 3-D cascade of silt blocks (approximately rectangular parallelepipeds) interspersed by 3-D sandy CB (mulches) sheathing the six faces of each parallelepiped. Correspondingly, we recorded the stages of plant development and confirmed a significant improvement of their hydro-ecological sustainability.

## 2 Materials and methods

### 2.1 Experimental design

Two sets of experimental pots having two types of soil textural patterns or structure were prepared for this study. All pots, with dimensions of 70 cm (length)×20 cm (width)×20 cm (depth), were made of 4-mm thickness fiberglass. Eight pots representing the two sets were used for the experiment. The first set of four pots were filled with substrate, whose structure mimics the natural block-fracture heterogeneity emerging from the sedimentation (Fig. 4a), while the second set of four pots, considered as a control set, were filled with thoroughly mixed silt and sand (Fig. 4b). Silt/sand proportion (70% silt and 30% sand) was the same for all the eight pots. The only difference between the control or mixed (M-pots, Fig. 4b) and block-fracture or SD pots (Fig. 4a) was in the soil structure. The pots were placed on a stand of 20 cm high and a distance of 15 cm was kept in-between the pots.

SMDaD and plant growth were investigated under controlled irrigation at the Agricultural Experimental Station (AES) of Sultan Qaboos University (23°37'N, 58°10'E) in the western part of Muscat city, Oman. The AES site was 3 km from the locus of the Al-Khod dam where the natural smart heterogeneity phenomenon was observed in 2010. We purposely put all the pots under direct solar radiation and conducted our experiment in June–September 2011, i.e. in conditions most unfavorable for plant growth (summer time in Oman).

The SD pots were filled with silt blocks interspersed by sand sheaths as illustrated in Fig. 4a. The composition of this soil includes: (1) vertical and horizontal cracks filled with sand, (2) two layers of silt blocks, and (3) a gravel layer (5 cm) underlying a thin layer of sand (5 cm) at the bottom of the pot to prevent clogging of the drainage valve. In the dam reservoir, block layers are more common (Fig. 1a) and thicker and, what is most important for the plant roots, all pots in Fig. 4 were heated from their sides by direct solar radiation and hot air (the roots of natural plants in the dam reservoir area were heat-stressed from the soil surface only).

M-pots, as presented in Fig. 4b, were filled with a homogeneous, 40 cm thick, mixed (sand and silt) soil overlying a 5-cm gravel layer.

Theta probes (Delta 2e; WET Sensor, Eijkelkamo) were installed in the silt blocks of the second layer at a depth between 20 and 35 cm below the soil surface in M1, M2, SD1 and SD2 pots (Fig. 4) for *in situ* soil moisture content measurements. This layer was

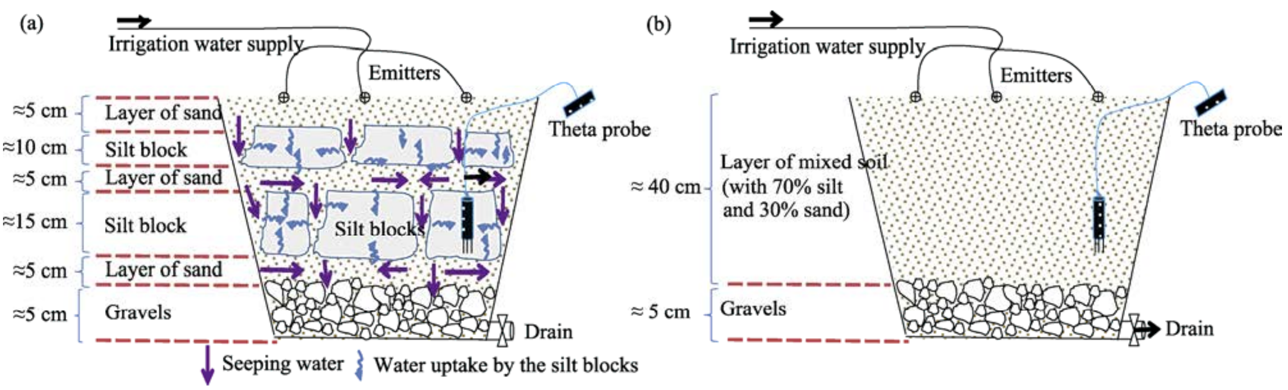


**Fig. 4** (a) Sketch of the experimental layout for the SD-pots with soil designed in a smart manner replicating a natural cascade structure of Al-Ismaily et al. (2014) and (b) sketch of the experimental layout for the control pots (commonly mixed soil, M-pots)

selected because the depth of the probe there would be less affected by direct solar radiation/evaporation, compared to the upmost layer of the blocks. The second layer was expected to be the main source of water supply to the plants in our SD-pots, especially, during a "dry" season of no irrigation. Again, our design is in full analogy with the desiccation-wetness of the topmost and subjacent block layers, which were monitored and measured in the dam reservoir (Al-Ismaily et al., 2014). The moisture content at a depth between 5 and 10 cm for all pots was also measured using Theta probes and by the gravimetric method.

One of the aims of our experiment was to subject the two types of soils (Figs. 4a and b) to irrigation regimes which are common in the landscape farming of the Muscat city (Oman). We note that the soil used by the Muscat municipality for growing plants (prevalently ornamental) is also engineered, but in a common "layered" manner, i.e. an imported finer texture soil is placed on the top of a parent soil, usually coarser than the imported one. Water is supplied twice a day for the landscape farming in the Muscat area, without considering the weather conditions and irrespective of the soil properties (in reality these factors affect the actual plant water requirement).

Two types of plants were grown in our pots: rhodes grass (main fodder crop in Oman, characterized by quick growth, and can germinate/survive under hot weather) by using seeds and ivy *Ipomea–Convolvulaceae* (ornamental plant) by using cuttings (a good hunter for soil water, as has been tested by Al-Ismaily et al., 2014, in naturally composed CB cascades of the dam reservoir).

Figure 5 illustrates the complete layout of the pot experiment and the type of plants grown in each pot, and the numeral following the labels indicates the number of the pot. A 5 g of rhodes grass seeds was germinated to pots M1, SD1, SD3 and M3, respectively. Three ivy cuttings were planted in each of the pots SD2, M2, M4 and SD4.

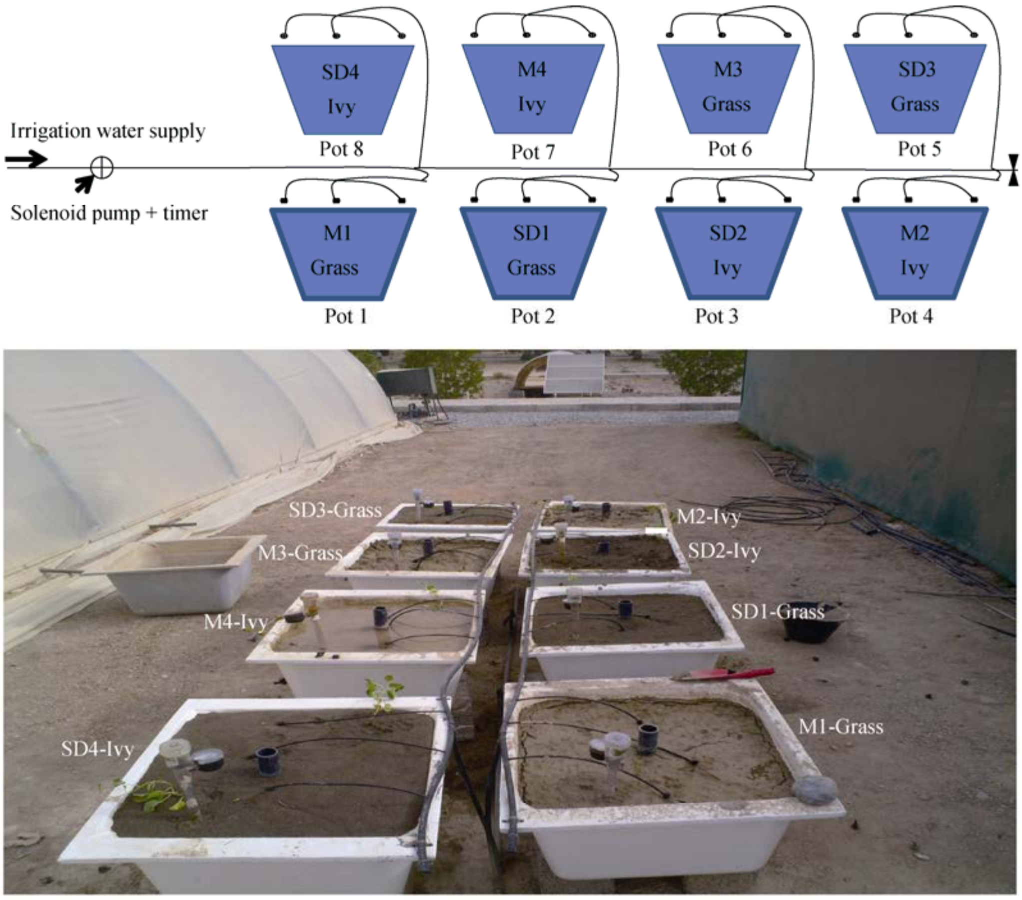


**Fig. 5** The experimental array of both SD- and M-pots

## 2.2 Hydro-physical properties of the soil

The measured soil bulk density for the silt was 1.66 g/cm$^3$. The saturated hydraulic conductivity $K_s$ of the sand filling of the fractures in pots SD1, SD2, SD3 and SD4 was determined using the constant head method (Freeze and Cherry, 1979) and was found to be 0.01 cm/s. The hydraulic conductivity of the silt (from the blocks) was $2.62\times10^{-5}$ cm/s. The background (pre-irrigation) salinity level for sand and silt used in the experiment was 0.973 dS/m and 1.14 dS/m, respectively. The irrigation water had a salinity of 0.63 dS/m.

The water retention curve for the silt (samples were taken from the silt blocks) and for the mixed soil were constructed using a pressure plate device (Eijkelkamp Inc., Giesbeek, the Netherlands). This curve is helpful in estimating the time needed for the moisture content to decrease to the wilting point of –15 bars (Miller and Donahue, 1990).

## 2.3 Irrigation regime

Three pressure compensating emitters (to ensure uniform distribution) with a discharge rate of 4 L/h were installed over the surfaces of the pots (Fig. 4). Drainage valves were installed close to the pot bottom to collect the potential leachate.

At the initial stage of the experiment (28 June 2011), all pots were ponded once to ensure enough water for the plants to start germination and establishment. This initial relatively-short term ponding models a flash-flood ponding of the dam reservoir, after which the growth of natural plants is triggered (Al-Ismaily et al., 2013).

The crop coefficients, $K_c$, of 0.4, 0.9 and 0.85 were applied during the initial, mid and harvest stages correspondingly. An irrigation pulse of 4.4 L/d was applied at the mid-season stage and 2.7 L/d in the harvest stage to each pot. Irrigation started from 3 July 2011 and lasted for 70 days (daily irrigation stopped on 10 September 2011). Then, there were 20 days of no irrigation (no natural precipitation took place during the whole period of the experiment). During this period all pots experienced drought, with a corresponding moisture re-distribution within the soils. The irrigation water requirement was scheduled based on the Reference Evapotranspiration rate ($ET_0$) that was obtained from the meteorological station located at the AES. The calculated $ET_0$ varied in the range of 6.5–10 mm/d. Irrigation was regulated using a Solenoid valve and a timer to deliver the daily assigned water norms at two times (5:00 am and 5:00 pm). The maximum average air temperature during the study period (July to September) was 45°C. We recall that this period of Omani summer was deliberately chosen to investigate the effect of the CBs on enhancing the water storage, maximizing transpiration, minimizing the evaporation loss, and maintaining biologically acceptable temperature in the root zone.

## 2.4 Soil sampling

Soil samples (for determination of the gravimetric water content, $\theta_g$,) from all pots at different depths were collected daily for 6 days following the termination of the irrigation phase, along with the Theta-probe readings during this last period of the experiment.

Secondary salt accumulation is a major concern in arid climates due to a high rate of evaporation from topsoil. At the end of the experiment (after 90 days), soil samples were collected from all pots (except pot SD1) for electrical conductivity (EC) measurements. The samples were taken from three depths: 0–10 cm, 15–25 cm and below 30 cm. Soil samples were also collected from the blocks (their centers and peripheries) and from the fractures (sand) in the SD pots to investigate the distribution/accumulation of salts across a CB interface.

The topology of the root systems is known to be sensitive to SMDaD (natural desert plants develop a prolate-oval-shaped root zone with an axis passing approximately through the stem and tap root). Figure 6 shows a tap root of a woody plant in a soil pedon excavated in the morphed cascade block structured soil. By observing a single cross-section of Fig. 6 (natural conditions of the dam reservoir), we noticed that the roots in the blocks and fractures differed in diameter and density. We also monitored variation in the dendritic topology and hairiness of the roots of acacia and castor-oil plants. We designed our pot experiment to check whether the natural root system in Fig. 6 is common and reproduces in a similar but artificially designed soil substrate. Namely, upon termination of the irrigation experiment we dissected one SD-pot and one M-pot and carefully investigated the post-cultivation soil substrate and the root topology.

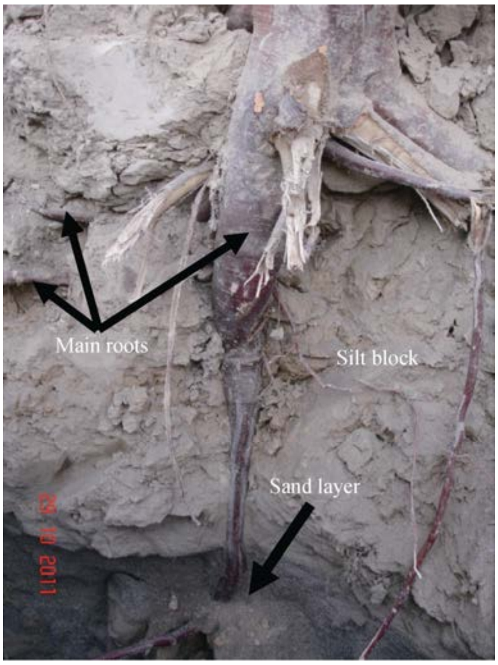


**Fig. 6** The tap root of a woody plant exposed in an excavated pedon (SD dam soil). The locus of this excavation is a few meters away from the site of Fig. 1a.

## 3 Results and discussion

The effect of soil structure on SMDaD was demonstrated by considering θ at different depths for all pots in Fig. 5. Figure 7 presented θ (obtained by the gravimetric method and by Theta probes) as a function of time for the SD and control soils. Overall, θ for SD-pots with both ivy and grass was much higher (around 25%–30% in average), as compared to that of the M-pots. This difference was more pronounced with soil depth. At the depth of 20–35 cm, θ in the M-pots decreased by less than 10% three days after terminating the irrigation. The SD-pots had θ of more than 33% in average at the same depth (Fig. 7d). The water retention curve (Fig. 8), measured for pure silt and a perfect mixture of sand and silt, manifested that at –15 bars of soil water pressure, θ for both macro-homogeneous soils was nearly 10%. Obviously, the pressure-plate apparatus cannot measure the water retention curve for the whole 3-D structure in Fig. 1a or its replicate in Fig. 4a.

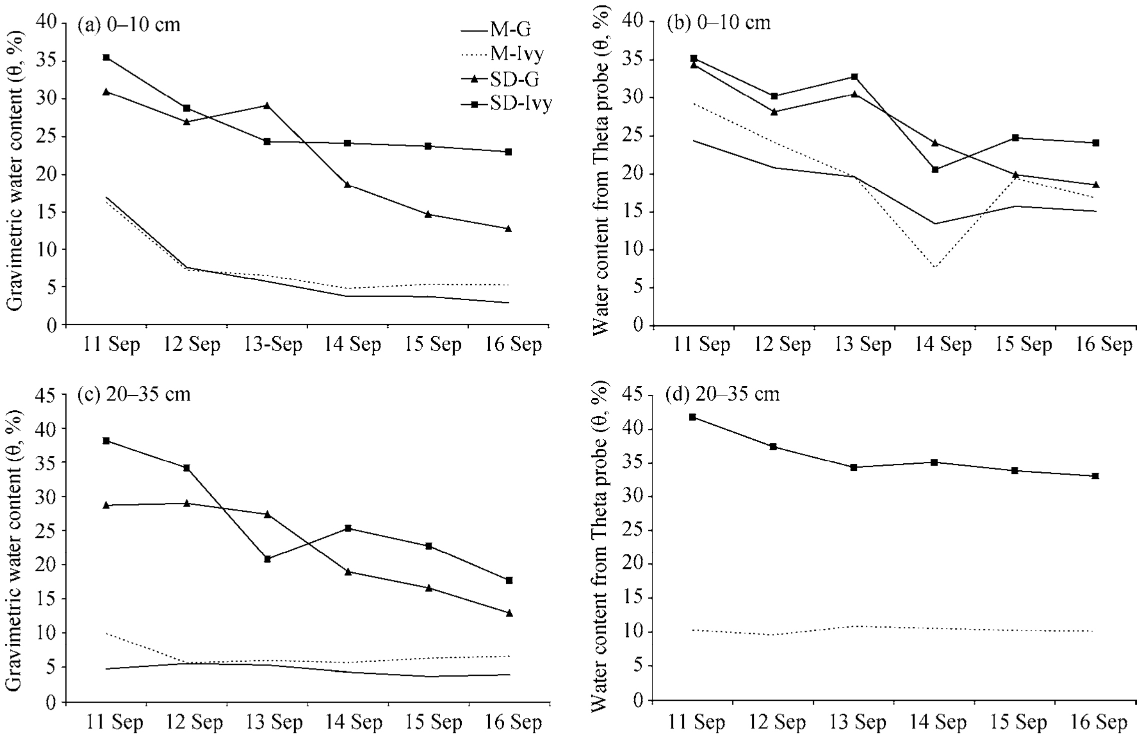


**Fig. 7** Measured soil water content as a function of time during the no irrigation period of 2011

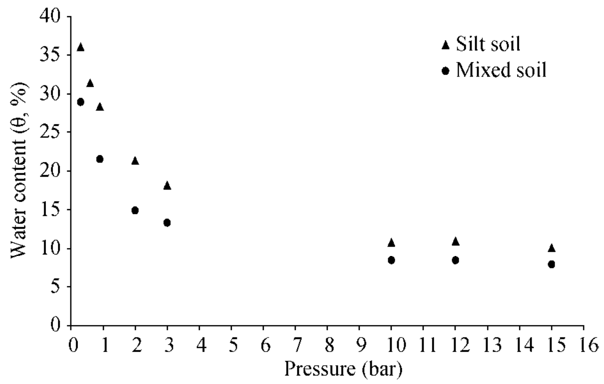


**Fig. 8** Water retention curves for the silt that makes the blocks and the mixed soil

The grass and ivy plants in the M-pots showed symptoms of wilting at day 3 of no irrigation, while the plants were healthy and grew well in the adjacent SD-pots (Fig. 9). By considering M- and SD-pots with ivy, θ was still around 18% in the SD-pots while it was lower than 7% in the control pots even after 20 days of no irrigation. This dramatic difference in moisture content, similar to the natural prototype of Al-Ismaily et al. (2014), can be attributed to the intensive, unimpeded upward capillary movement of water in the M-pots caused by an intensive summer evaporation (associated with a low air humidity of nearly 40% in average and high ambient air temperature). In the SD-pots, however, the sand in the fractures sandwiching the silt blocks acted as a CB that reduced evaporation, i.e. this 3-D "mulching" caused discontinuity in the vertical capillary creep of moisture from the blocks. Consequently, water drainage from the micro-pores in the silt blocks was reduced. This can be illustrated by comparing θ of SD-pots in the upper silt blocks (at the depths of 5–15 cm) and that for the lower silt blocks (at the depth of 20–35 cm). After 6 days of no irrigation, the Theta- probe read θ of 23% for the upper blocks and 34% for the lower blocks in the SD-pot with ivy (Figs. 7b and d).

The blips of the curves depicting the $\theta_g$ in Fig. 7 can be attributed to the defect of sampling process: samples were randomly collected and variations in $\theta_g$ were inevitable, even within a small volume of soil in the pots. The blips are more pronounced in the near surface samples, for both gravimetric and Theta-probe readings (depths of 0–10 cm). We also surmised that SMDaD was affected by circadian variations of atmospheric conditions. Indeed, a diurnally swinging evaporation-condensation from-to the topsoil is possible. During our experiment, we noticed by palpation that the soil surface got a little bit moist in the early mornings.

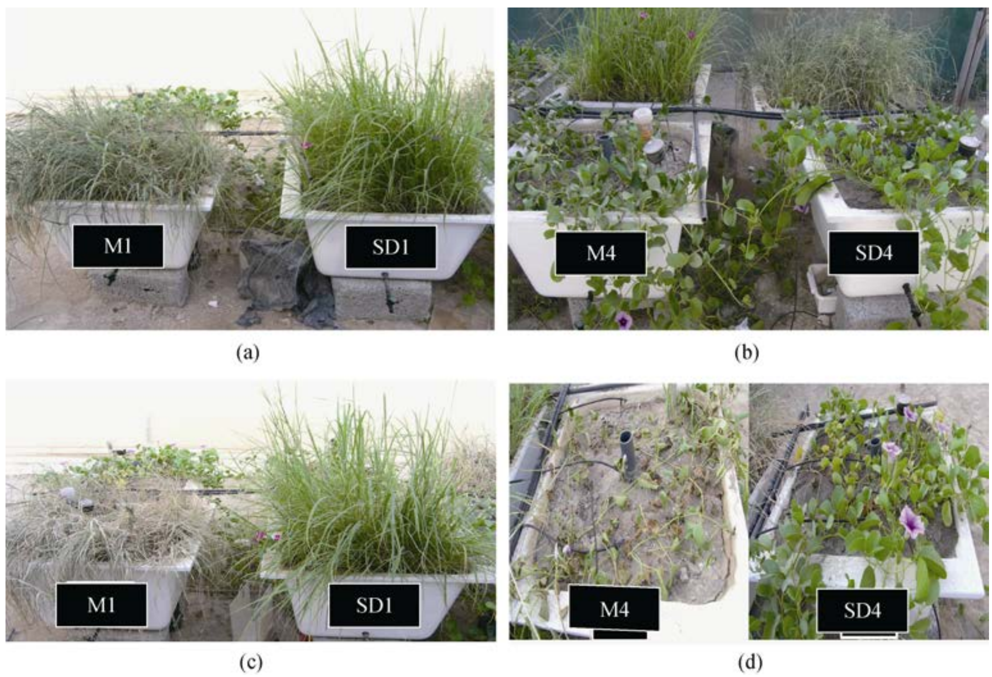


**Fig. 9** Pictures for pots M1, SD1, M4 and SD4 after (a, b) 3 days and (c, d) 7 days of no irrigation

### 3.1 Soil salinity

The results of EC measurements using saturated paste method are presented in Table 1.

Apparently, there is no clear trend in the EC data for all the pots, though, in general, the salinity is slightly higher near the soil surface (at 0–10 cm) compared to that at a depth of more than 20 cm. The difference is more pronounced for the M-pots. Considering the average EC values at the depth of 0–10 cm, the salinity is higher for M-pots (3.32 dS/m) than for SD-pots (0.98 dS/m). This could be again attributed to un-impeded capillary drive and consequently the higher evaporation rate for the mixed soil, while the CBs restricted the upward water movement in the SD-pots, resulting in lower evaporation and less pronounced build-up of salts in the "smartly-structured" soil.

**Table 1a** Salinity distribution at the end of the experiment at different soil depths

| Soil sampling depth | EC (dS/m) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Smart design pots | | | Mixed pots | | | |
| | SD2-Grass | SD3-Grass | SD4-ivy | M1-Grass | M2-ivy | M3-Grass | M4-ivy |
| 0–10 cm | 0.55 | 1.02 | 1.37 | 1.08 | 6.80 | 2.30 | 3.11 |
| 20–30 cm | 0.40 | 0.68 | 1.39 | 1.05 | 1.66 | 0.82 | 1.30 |
| >30 cm | - | 0.36 | 5.67 | 0.69 | 1.27 | 1.29 | 1.59 |

**Table 1b** Salinity distribution at the end of the experiment

| Sample location | EC (dS/m) |
|---|---|
| SD2-ivy (sand fracture below the 2nd block layer) | 0.402 |
| SD4 (from the surface of the 2nd layer block) | 1.000 |
| SD4 (from inside the 2nd layer block) | 0.900 |

### 3.2 Distribution of the root system

A complex topology and morphology of roots was observed upon termination of the experiment (Fig. 10a). The roots were developing in larger sizes (more cylindrical in shape) within the blocks while they were thinner within the sand fractures. The larger roots bridged between blocks at different depths, indicating the hunting of plants for water stored in adjacent fine-textured compartments. Although standard cone penetration tests were not conducted, sand in both the horizontal and vertical fractures was obviously not mechanically resistant to the roots, which easily transected from block to block through a thin sand sheath. Intense hairy roots also developed from each "main" lateral root within the blocks. This explains the healthy growth of the grass and ivy in the SD-pots, compared to that in the M-pots. The blocks served as capillarity-retained water buffers, which were depleted at a slow rate. A continuous supply of water to the roots for long time, observed in natural conditions (Al-Ismaily et al., 2014), is now confirmed in on-farm experiments. We emphasize that the no-irrigation stage of this experiment modeled the natural harsh weather in Oman, where no-rain periods last for several months.

As a general observation, the root system (for ivy) is more intense, better structured and well developed in SD-pots, compared to that for control pots (Fig. 10b).

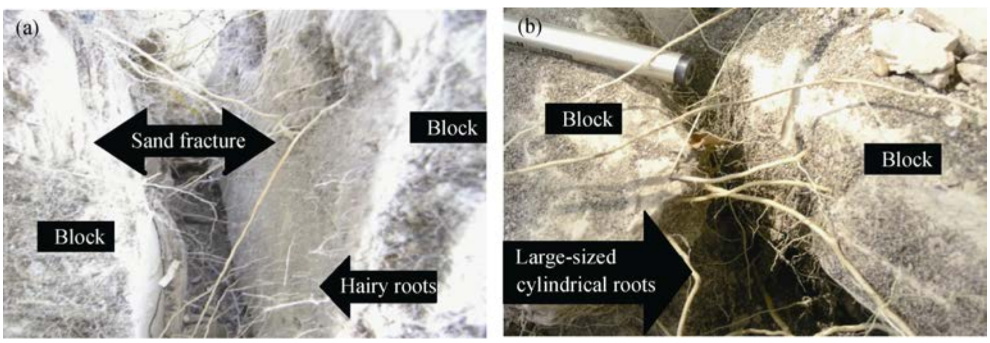


**Fig. 10** (a) Distribution of the roots for SD-ivy pot and (b) root patterns for SD-ivy and M-ivy pots

### 3.3 Zoological aspects

Our focus was on SMDaD and plants. However, eco-hydrologists dealing with zoology of arid environments (e.g. Jacobson and Jacobson, 2013) may be interested in the curious eco-niches in pedons which we dug in the SD-zone of the reservoir of the Al-Khod dam. Namely, the faces of the pedons, within a few days after excavation, were interspersed by numerous holes (1 cm in diameter) inhabited by wasps, spiders and frogs (Fig. 11). These holes emerged in all layers of the blocks. Therefore, not only plant roots but also fauna prospered in these relatively wet and well-shaded niches. Branches and leafs of ivy planted within the pedons (Al-Ismaily et al., 2014) create an additional shading comfort for the zoo-community inside.


**Fig. 11** Frogs and insect holes on a face of the pedon of Fig.1a, dug in the SD natural soil of Al-Khod dam

## 4 Conclusion and perspectives

The hydropedology of arid environments is a key factor determining soil-water-plant (SWP) evolution. Soil is usually considered as a component which varies with the least rapidity (decades and more). Soil moisture moves fast, varying within hours-days, while plant growth is seasonal-annual. In this paper we experimentally reproduced a natural SWP system for which these timescales overlap. Namely, both in the natural and designed soil structures consisting of silt blocks and sand-filled fractures, sandwiched between blocks, the soil accretion is fast (years), the soil moisture (in the blocks) may be almost stagnant for years and the plant roots develop very fast (weeks). In our on-farm experiments, we focused on SMDaD and did not involve soil accretion, which occurred due to sedimentation from the wadi runoff in the natural system. SMDaD is, therefore, controlled by soil physical properties, climate, and development of plant roots. The vegetation in arid regions adapts to SMDaD, which, in its own turn, strongly depends on soil heterogeneity.

Our experiments, mimicking the natural 3-D block-fracture pattern, illustrate how the intricate soil structure in the root zone helps in improving water availability for crop growth in desert environments. We found that similar to a natural ecosystem a designed block-fracture substrate preserves soil water, which plants can easily access. The roots in a smartly designed soil structure benefit from CB between fine-textured storage zones of silt blocks and coarse-textured fractures. These fractures impede block desiccation. As compared to a control (mixed homogenized) soil, more water is transpired than evaporated. If fracking (petroleum engineering technique) sand is injected as a “proppant” to preserve the rock apertures from collapsing, the coarse “proppant” not only serves against the swelling of blocks during a wetting stage of reservoir ponding (natural ecosystem) or irrigation (designed ecosystem) but also “props” the roots by retaining water within the blocks.

Secondary salinization is a long-term problem for natural biomes and agricultural plots in hot and water deficient climates. Consequently, a better understanding of the dynamics of salts in both M- and SD-pots requires multi-season experiments. In particular, we want to explore the redistribution of salts across the blocks and fractures, with occasional sporadic rains and ensuing intensive infiltration as pulse-type advective impacts.

The nature inspired SD not only supports the vegetation growth in a desert environment, but also provides a suitable living condition for such creatures as wasps, frogs, insects, and flies that prosper in these relatively wet and well-shaded niches. The activity of this zoo community affects the soil properties (e.g. porosity), and hence SMDaD.

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