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SHORT COMMUNICATION

Rheum palaestinum (desert rhubarb), a self-irrigating desert plant

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Abstract The rare plant *Rheum palaestinum* (Polygonaceae) is a perennial hemicryptophyte that grows during the rainy winter in desert mountainous areas in Israel and Jordan that receive an average annual rainfall of ca. 75 mm. It produces between one and four large round leaves that are tightly attached to the ground and form large rosettes of up to 1 m^2. These leaves differ markedly from the typical small leaves of most desert plants. Moreover, they have a unique 3D morphology resembling a scaled-down mountainous area with well-developed steep drainage systems, raising the question which selective agents were involved in their evolution. We propose that the large leaves collect rainwater that then infiltrates the soil surrounding the root. We measured the seasonal course of leaf growth, examined the area of wet soil surrounding the root after actual and simulated rain, and modeled the water harvesting capacity using the plant leaf area and the weekly precipitation. We show that even in the slightest rains, water flows above the veins to the leaf's base where it irrigates the vertical root. A typical plant harvests more than 4,100 cm^3 of water per year, and enjoys a water regime of about 427 mm/year, equivalent to the water supply in a Mediterranean climate. This is the first example of self-irrigation by large leaves in a desert plant, creating a leaf-made mini oasis.

Keywords Evolution · Irrigation · Leaf morphology · Negev desert · Rosette plant · Water

Introduction

Water shortage, caused by unpredictability of rainfall amount and timing, is the most important constraint on plant growth in arid environments worldwide. It has driven the evolution of numerous adaptations that increase water absorption, storage, efficient use, and decrease of losses (Evenari et al. 1982; Fahn and Cutler 1992). Many desert plants have dual root systems; (1) deep vertical roots with narrow xylem vessels to absorb deep soil water and (2) shallow horizontal roots with wide xylem vessels for rapid capturing of superficial and temporary water flows following light rains (Fahn 1964).

The rare plant *Rheum palaestinum* Feinbr. (Polygonaceae) is endemic to Israel and Jordan, growing in mountainous desert areas receiving an average annual rainfall of ca. 75 mm (Feinbrun 1944; Zohary 1966). Its highly atypical large, round leaves differ markedly from the typical small leaves of most desert plants (Smith 1978). This raises the question which selective agents were involved in the evolution of these unique leaves.

Our aim was to examine the adaptive role of this unique leaf morphology in the desert environment. We hypothesized that the large leaves efficiently collect rainwater from their total area, which is drained to their base, where it infiltrates the soil surrounding the root.

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Materials and methods

Study site and rainfall

Our study site was in the mountainous central Negev Desert, Israel (30°30′N, 34°38′E; 850–950 m a.s.l.). Rainfall data (1970–2003) were obtained from the nearest meteorological station at Mizpé Ramon, 30 km northeast of the study site.

Study plant

R. palaestinum is a perennial hemicryptophyte that grows during the rainy winter and produces one to four large round leaves (20–70 cm in diameter) that are tightly attached to the ground and form large rosettes of up to 1 m^2 (Fig. 1a) (Feinbrun 1944; Zohary 1966). To characterize the seasonal leaf growth, we performed four sequential leaf measurements of ca. 40 plants during the growing season of winter 2004/2005. *R. palaestinum* has a single deep main vertical root (Zohary 1966; Danin 1969, 1983) unlike many desert plants that have both deep vertical roots as well as shallow horizontal roots (Fahn 1964). However, the precise length of the root is not known because excavation of these protected plants in their natural habitat is forbidden.

Water infiltration into desert soil

To quantify water infiltration into typical desert loess soil, we simulated rains of 1, 2, 4, 6, 8, and 10 mm with similar intensities (e.g., 1 mm per 15 min, 2 mm per 30 min etc.) in five replicates of small plots (1,000 cm^2 each) for each intensity during a typical (partly cloudy, 17°C) winter day. To simulate water infiltration along the vertical roots, we measured infiltration depth along five 100-mm long and 4-mm thick iron nails inserted into the soil in the 10-mm simulated rain plots.

Actual and modeled water harvesting

We observed water harvesting by *R. palaestinum* during a light rain of 1–2 mm in its natural habitat. Immediately after the rain we measured the depth of water infiltration around the vertical root and in the surrounding bare soil, which was evident by color change in the wet soil.

To simulate the capacity to harvest rain water, we homogeneously dripped 10 ml of water (for 1 min for each plant) on well-developed leaves of ten *R. palaestinum* plants and 100 ml (for 10 min for each plant) on leaves of ten other similar plants (average leaf area 724±69.3 cm^2, $n=20$). Because of the differences in total leaf areas among the examined plants, the simulated rain intensities varied even among individual plants treated with the same amount of water and ranged from 0.1 to 2 mm with an average of 0.76±0.15 mm per minute. Fifteen minutes later, we measured the diameter of the wet zone around the roots. We define 'water harvest coefficient' as the ratio between the plant leaf area, which is the water catchment area, and the wet soil area around the root (Fig. 1c).

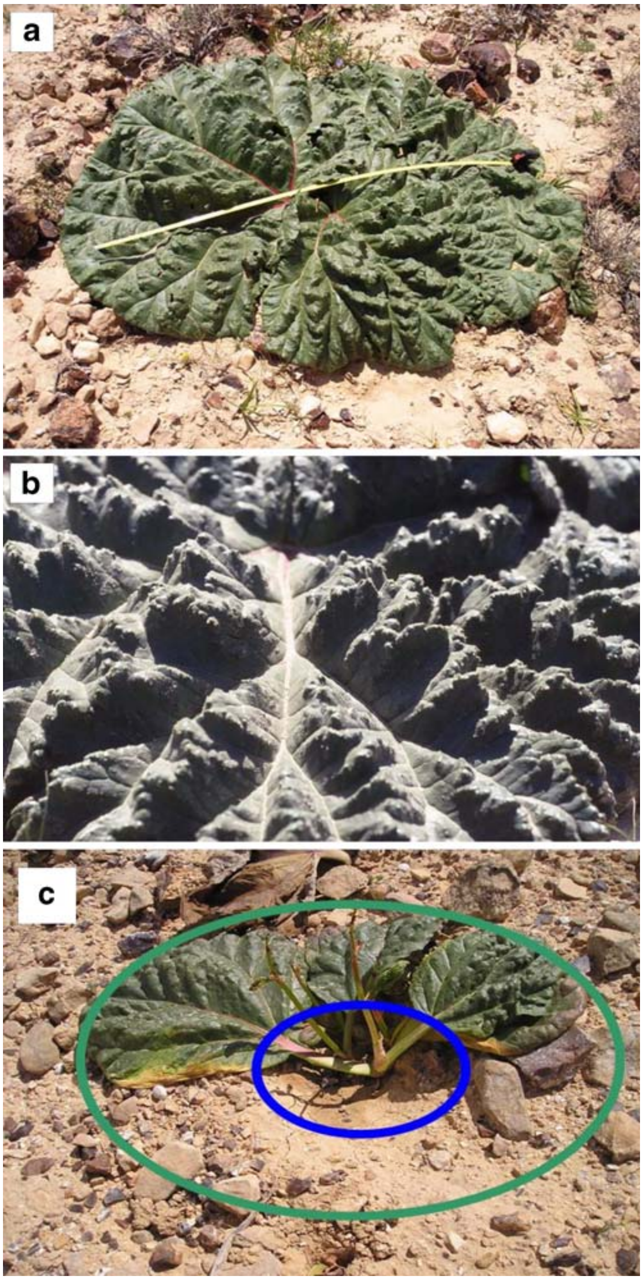

Fig. 1 **a** A general view of a large *R. palaestinum* specimen growing in the Negev Desert, Israel (scale rod 1 m). **b** A close-up of a mature *R. palaestinum* leaf (ca. 40-cm diameter) showing the steep "ridges" and "valleys". **c** The area of wet soil around the vertical root of *R. palaestinum*; water harvest coefficient is defined as the ratio between the leaf area (*green*/*light circle*) and the consequent wet soil area around the root (*blue*/*dark circle*)

Based on the average weekly leaf area growth (calculated by interpolation from monthly leaf area measurements) and the average weekly rainfall in Mitzpe Ramon over 34 years, we modeled the cumulative amount of water harvested by an average plant, from leaf emergence to the end of the rainy season (harvested water equals the sum of the products of weekly precipitation by the corresponding weekly leaf area).

Results

Rainfall

The average annual rainfall for 1970–2003 in Mizpé Ramon was 75±6.5 mm with an average of 2.99±0.16 mm per rainy day (n=1,218 days) and 25±1.5 rainy days per year (n=34 years). Most rains occurred from December to March with six to eight rainy days/month and 11–19 mm/month, with January being the wettest. Low intensity rains (5 mm or less per day), which cannot be utilized by most desert plants, comprise 41.2% (30.89±2.15 mm, n=34) of the average rainfall.

Study plant

A mature *R. palaestinum* plant has on average 1.76±0.44 (average±SEM; n=43) leaves, each with an average area of 1,026±110 cm^2, and an average total leaf area of 1,446±157 cm^2 per plant. The largest plant we found had a leaf rosette area of about 10,000 cm^2 (Fig. 1a). The leaves of *R. palaestinum* have a unique 3D morphology resembling a scaled-down mountainous area with well-developed steep drainage systems (Fig. 1b). The major leaf veins on the upper surface are located in deep depressions that are oriented towards its base, while the area between the veins is highly ridged (Fig. 1b). The smooth upper leaf surface is covered with a shiny, hydrophobic, waxy cuticle, possibly enhancing the plant's water harvesting efficiency due to a "lotus leaf effect" (Barthlott and Neinhuis 1997), which results in efficient water runoff even at extremely low rainfall intensities. Consequently, water is expected to flow along the veins to the leaf's base where it might irrigate the root.

Water infiltration in desert soil

Water infiltration into typical desert loess soil, as a result of 1-mm simulated rain (per 15 min) was to an average depth of 8.9±0.52 mm (n=5), which was dry after 2 h. Ten millimeters of simulated rain (per 150 min) resulted in an average infiltration depth of 24.6 ±0.76 mm (n=5) and infiltration depth was significantly correlated ($Y=8.852\times X^{0.408}$, $F_{1,4}=119.08$, $P<0.001$, $R^2=0.9675$) with simulated rain intensity (Fig. 2a). Infiltration depth along 100-mm long nails inserted into the soil, following 10 mm of simulated rain, was ca. 45 mm.

Actual and modeled water harvesting

Our observations during a light desert rain demonstrated the immediate rolling down of rain drops from the leaf ridges

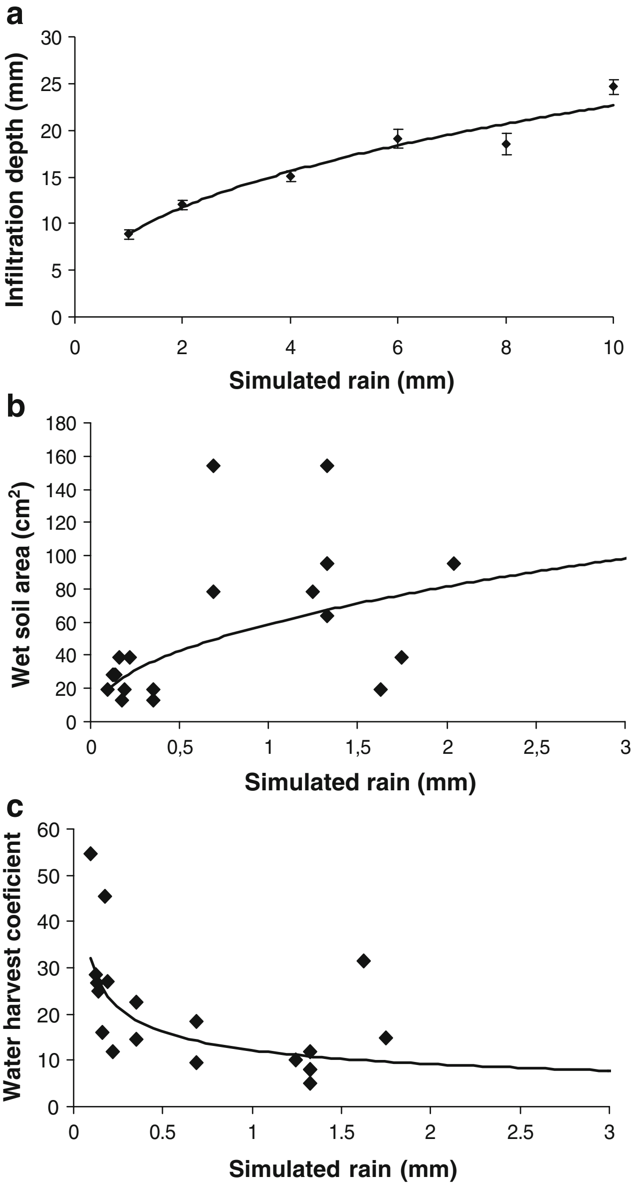

Fig. 2 Water infiltration depth (average, mm) into a typical loess soil in the experimental site as a function of an experimentally simulated rain (1–10 mm) at a constant intensity of 1 mm per 15 min; *bars* represent SEM and n=5 (**a**). The area of wet soil around the vertical root of *R. palaestinum* (**b**) and the water harvest coefficient and the consequent wet soil area around the root (**c**), as a function of simulated rain intensity by dripping water on the plant leaves (n=20)

to its depressions, located above the main veins toward the plant's base. Here it irrigated the soil directly above and around the single deep vertical root of *R. palaestinum* (Fig. 1c), which cannot absorb water from the upper soil layer. A light natural rain of 1–2 mm during ca. 1 h on the leaves wetted the soil in an area of ca. 100 cm^2 and infiltrated to a depth of more than 10 cm around the vertical root, approximately ten times deeper than in the surrounding bare soil.

The average wet soil area, following an experimental water dripping of 1 and of 10 ml of water (equivalent to a range from 0.1 to 2 mm of rain) on the leaves of *R. palaestinum*, was 55.9±9.9 cm^2 (n=20) and was exponentially, positively, and significantly correlated ($Y=58.887\times X^{0.467}$, $F_{1,18}=11.96$, $P=0.003$, $R^2=0.3994$) with the simulated rain intensity (Fig. 2b). The average water harvest coefficient, 19.7±3.0, was exponentially, negatively, and significantly correlated ($Y=11.513\times X^{-0.443}$, $F_{1,18}=18.27$, (1,026 cm^2) $P<0.001$, $R^2=0.504$) with the simulated rain intensity. For the average leaf area of a plant and an average precipitation per rainy day (3 mm) the extrapolated water harvest coefficient was 7.1 (Fig. 2c).

Based on four sequential leaf growth measurements, and using 40 randomly chosen plants, we found a significant regression between the plants' square root transformed total leaf area and the number of days that had elapsed from the beginning of the rainy season of 2005 [($Y=0.356X+5.616$) ($F_{1,148}=142.4$, $P<0.001$, $R^2=0.44$)]. The consequent potential cumulative amount of water harvested by an average size plant (total leaf area of 1,446 cm^2), from leaf emergence to the end of the rainy season was calculated to be 5,212 cm^3, or 4,170 cm^3 (Fig. 3), if a 20% water loss before leaf emergence and spilling is accounted for.

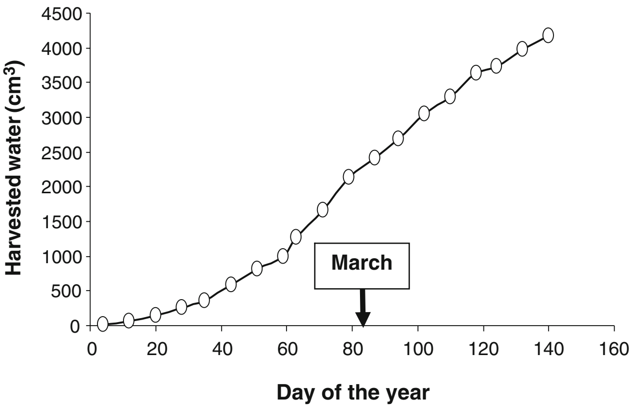

Fig. 3 The cumulative amount (cm^3) of water harvested by a *R. palaestinum*, calculated by integrating the average (n=40) weekly leaf area of a plant (assuming 20% water loss due to rainfall not collected before leaf emergence and to spillage and no leaf growth after March 25th) and the corresponding average (n=34 years) weekly rainfall over the entire growing season of the plant

Discussion

In the extreme deserts of the Near East, many plants grow only in places such as wadies, depressions, and bottoms of rocky surfaces where they take advantage of the collected runoff water (Danin 1972, 1999; Zohary 1973). However, *R. palaestinum* uses a unique alternative: by its leaf-made water harvesting system it succeeds in collecting water even under the lowest rain intensities and on flat terrain, producing its own mini-oasis of up to 1 m^2. This is the foliage parallel to rock surfaces and wadies. *R. palaestinum* grows in habitats with no ground water and the water harvested by the leaves irrigates the soil directly around its single deep vertical root. Infiltration depth along 100-mm-long nails inserted into the soil, following 10 mm of simulated rain, was ca. 45 mm. This was twice the unaided infiltration depth into soil, demonstrating the increased water infiltration depth along vertical roots. The vertical root most probably shrinks during summer, as does the loess soil, creating a space between it and the soil, permitting a direct vertical water flow along the root where it can be absorbed. The actual amount of water harvested by the leaves is much higher than the natural rainfall and all of it is directed towards the root and infiltrates deep in the interface between it and the soil. The positive, non-linear, but only square root relationship between the wet soil area and the simulated rain intensity (Fig. 2b), and the negative power relationship between the 'water harvest coefficient' and the simulated rain intensity, indicate that under higher rain intensities there is a linear increase in runoff. The negative relationship between the wet area and the 'water harvest coefficient' indicates that for any given rain intensity, the smaller the wet area, the higher the water harvest coefficient and probably more water infiltrates along the root. Because *R. palaestinum* is a rare endemic plant, we could not get a permit to measure roots or water infiltration along them in the field.

It was estimated that 45% of the rainfall in that region evaporates directly from soil surface and 20% is lost as runoff, with only 35% (equivalent to ca. 26 mm) penetrating the soil and made available to the plants (Hillel and Tadmor 1962). Indeed, in our simulated rain experiments, 10 mm of rain wetted only the upper soil (2.5 cm), which dried up in a short time. For the average precipitation on rainy days (3 mm), the extrapolated water harvest coefficient for a plant with average leaf area (1,446 cm^2) was 7.1 (Fig. 2c). This implies that *R. palaestinum* plants of an average size, growing under 75-mm annual precipitation, potentially increase their water regime to an equivalent of ca. 533 (7.1×75) mm per year. Assuming a 20% water loss due to rainfall not collected before leaf emergence and to spillage, the calculated water regime is equivalent to an annual precipitation of 426 (533×0.8) mm, similar to the water supply by annual precipitation in the Mediterranean climate. Relative to the net of 26-mm rainfall available to other desert plants in this region (Hillel and Tadmor 1962), *R. palaestinum* enjoys a 16-fold (426/26) increase in available water. A typical *R. palaestinum* plant harvests more than 4,100 cm^3 of water/year (Fig. 3). The largest plant we found, with a leaf area of 10,000 cm^2 could harvest 43,800 cm^3 of water/year, indicating the selective advantage of growing larger leaves with their unique morphology.

Thus, in spite of growing in a desert, *R. palaestinum* benefits from an improved water regime equivalent to a Mediterranean type climate. As their desert habitat is well lit, light harvesting cannot explain the evolution of the large leaves of *R. palaestinum*. Thus our preliminary results indicate that water harvesting capacity, which is directly correlated with the plant's leaf area, improves its fitness by self-irrigation. This can explain the evolution of the outstanding large leaf size and its unique morphology. Moreover, it is possible that this is an overlooked adaptation common in many other rosette plants growing in arid and semi-arid habitats around the world.

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