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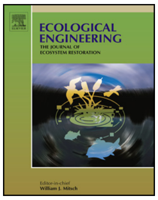

Effect of rock fragments content on water consumption, biomass and water-use efficiency of plants under different water conditions

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ABSTRACT

The proportion of rock fragments in soil affects water availability and therefore the characteristics of plants. The objective of this study was to evaluate the effect of rock-fragment content on plant water consumption, biomass, growth and water-use efficiency (WUE) under different water conditions. Four gravimetric treatments of rock-fragment contents (0, 10, 30 and 50%) and four treatments of water content were tested in sandy loamy soils. The water contents of the rock-free soil were 15–19% (80–100% of field capacity), 11–15% (60–80% of field capacity), 9–11% (47–60% of field capacity) and 6–9% (32–47% of field capacity). Transpiration, plant height, basal stem diameter and biomass of korshinsk peashrubs in the treatments were measured and compared. Plants grown in the soil with rock fragments transpired less, especially under well-watered conditions. The mean daily transpiration of plants in the soils with 30 and 50% rock-fragment contents was 18% ($P = 0.021$) and 34% ($P = 0.001$) lower, respectively, in 2014, and 25% ($P = 0.008$) and 31% ($P = 0.002$) lower, respectively, in 2015 relative to the soil without rock fragments and was not lower in the soil with 10% rock fragments. Plant height, basal stem diameter and biomass did not differ significantly between rock-fragment contents of 0 and 30% but were lower at 50%. WUE, the ratio between total transpiration and biomass, was highest at 30% and then decreased at 50%. Increasing plant water stress could thus improve WUE. The rock fragments in the soil had significant effects on plant water consumption, biomass, growth and WUE. Optimizing the rock-fragment content is necessary when the relationships between plants and water in stony ecosystems are evaluated.

1. Introduction

A soil rock fragment is defined as a particle with a diameter >2 mm. Fragments forming as a result of processes of soil genesis and human activity exist at the soil surface and within the soil. Stony soils are widespread and can reach land-cover ratios up to 60% in the Mediterranean region of Western Europe (Poesen and Lavee, 1994). The proportion of stony soil is >30% on the Loess Plateau of China (Hou, 1993).

The presence of rock fragments significantly affects hydrological functioning such as water storage, infiltration and evaporation and soil hydraulic properties such as hydraulic conductivity and water retention (Van Wesemael et al., 1996; Ma and Shao, 2008; Li et al., 2008; Zhou et al., 2009; Baetens et al., 2009; Ma et al., 2010; Novák et al., 2011; Tetegan et al., 2011). Water movement in, and the hydraulic properties of, soils are strongly dependent on the availability of water for plants. Rock fragments in stony areas should therefore be considered in studies of water availability for plants and of water exchange among plants, rock fragments and soils.

Tetegan et al. (2011) proposed pedotransfer functions based on the linear relationship between the available water content (AWC) of rock fragments and the Napierian logarithm of bulk density and the relationship between water content at −100 and −15 840 hPa. The simulation showed that excluding 30% of the pebbles in a stony horizon underestimated the soil available water content (SAWC) by 5% for chert pebbles and by 33% for chalk pebbles. Novák and Kňava (2012) demonstrated that the presence of stones can decrease soil water-holding capacity and hydraulic conductivity, which can decrease the availability of soil water for trees. Tetegan

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Table 1
Main physical properties of the fine soil.

Sand >0.02 mm (%)	Silt 0.02–0.002 mm (%)	Clay <0.002 mm (%)	Organic content (%)	Field capacity (cm^3 cm^{-3})
80.3	13.6	6.1	0.89	0.190

et al. (2015a) subsequently improved the method proposed in 2011 (Tetegan et al., 2011) to calculate the SAWC at a regional scale (36 200 ha). They demonstrated that rock fragments could contribute to the AWC of stony soils. SAWC could thus be underestimated if rock-fragment content is neglected. Water exchange would be more complex when plants are added to the system. Tetegan et al. (2015b) included the dynamics of water exchange between fine and stony soil. They demonstrated that rock fragments in soil could act as water reservoirs for plants. Water was exchanged between rock fragments and soils, plants and soils, and plants and rock fragments.

The growth and physiological features of plants should differ between stony and rock-free soils due to the effect of rock fragments on the water availability for plants and water exchange. Danalatos et al. (1995) reported that water conservation was generally better in stony soils under conditions of moderate water stress, and the presence of cobbles on the soil surface increased total dry-matter yield of rainfed wheat by 20%. The presence of stones in soil also affects the growth of plant roots. Estrada-Medina et al. (2013) demonstrated that rock fragments changed the distribution of root systems. Plant roots can grow in both soil and rock. Changes in plant growth have been attributed to hydraulic and nutrient redistribution resulting from the presence of rock fragments (Carrick et al., 2013). Root growth is linked to the compressive strength of rocks; the penetration resistance of soil ranges from 2 to 4 MPa (Arshad et al., 1996), and root growth is restricted above this range (Schwinning, 2013).

In addition to changing the yield and root distribution of plants, rock fragments can also change other features of plants such as transpiration (a feature of water consumption), stem height and diameter (features of plant growth), and water-use efficiency (WUE). Few studies, however, have investigated changes in these features, which limits our understanding of the features of plant growth in stony soil.

We hypothesized that (1) the responses of plant transpiration, stem height and diameter, and biomass to water conditions can be affected by the rock-fragment content of the soil and (2) rock-fragment content would affect WUE under different water conditions. The objectives of this study were therefore to (i) assess whether the features of plants such as transpiration, stem height and diameter, and biomass respond to rock-fragment content under different water conditions, and (ii) quantify and compare WUEs and then determine a feasible strategy of management of rock fragments and water conditions for increasing WUE.

2. Materials and methods

2.1. Description of the sampling site

The experiment was conducted at the Shenmu Erosion and Environmental Research Station of the Institute of Soil and Water Conservation, Chinese Academy of Sciences. The station is in the Liudaogou catchment on the northern Loess Plateau of China (38°46′–38°51′N, 110°21′–110°23′E; 1081.0–1273.9 m a.s.l.). This area has a semiarid climate with a mean annual temperature of 8.6 °C and a mean annual precipitation of 412 mm (1996–2015) falling mainly from July to September. The mean frost-free period is 169 days, and the mean annual pan evaporation is 785 mm (Jia et al., 2011).

The main rock fragments in the catchment are concretions of calcium carbonate formed from loessial deposits that have a high content of calcium carbonate (Zhu and Shao, 2008). The concretions have formed by the synthetic action of pedogenesis, soil erosion, and human activity and are randomly distributed in and on the surface of the soil. These rock fragments have the capacity to absorb water.

Table 2
Size distribution of the rock fragments.

2–10 mm (%)	10–20 mm (%)	20–30 mm (%)	30–40 mm (%)	>40 mm (%)
2.15	6.69	52.92	11.38	26.86

The soil and rock fragments for this study were collected from the catchment. The soil used in this study was sandy loam, classified according to the ISSS (International Society of Soil Science) system. The main physical properties of the soil are presented in Table 1. Field capacity was determined by the modified Wilcox method (Hanks et al., 1954). The size distribution of the rock fragments is presented in Table 2. Fragment sizes of 20–30 mm represented the largest proportion (>50%), followed by fragments >40 mm.

2.2. Experimental design and treatments

The experiment was conducted beneath a mobile plastic rain shelter from May to October 2014 and 2015 using PVC columns 1 m high and 20 cm in diameter. The fine (<2 mm) or stony soil was packed to a depth of 85–90 cm. Soil crusting was avoided by providing irrigation water through a tube (2 mm ID) inserted from the surface to the middle of the fine or stony soil in the columns. The korshinsk peashrub (*Caragana korshinskii* Kom.), a perennial shrub commonly used for vegetation recovery on the Loess Plateau, was chosen as a test plant for this study. Peashrub seeds were sown in the columns in August 2012, and seedlings were thinned to two plants per column.

Four rock-fragment contents were tested: 0, 10, 30 and 50% (gravimetric contents), abbreviated as A, B, C and D, respectively. Four water treatments were also tested. For the fine soil, the four water treatments were 15–19% (80–100% of field capacity), 11–15% (60–80% of field capacity), 9–11% (47–60% of field capacity, average water content in a wet year) and 6–9% (32–47% of field capacity, average water content in a dry year), abbreviated as W_1, W_2, W_3 and W_4, respectively. The corresponding gravimetric water contents were 11.3–14.3, 8.3–11.3, 6.8–8.3, and 4.5–6.8%, respectively. The bulk density of the packed fine soil was 1.33 g cm^{-3}, and the average bulk density of the rock fragments was 2.05 g cm^{-3}. The water content of the stony soil was determined by:

$$\theta_{mT} = R_m \theta_{mrf} + (1\text{-}R_m)\theta_{mfe} \tag{1}$$

where θ_{mT}, θ_{mfe} and θ_{mrf} are the water contents of the stony soil, fine soil and rock fragments, respectively; and R_m is the gravimetric rock-fragment content. θ_{mrf} was calculated by (Shao et al., 2009):

$$\theta_{mrf} = a(1\text{-}e^{-b\theta}{}_{mfe}) \tag{2}$$

where a and b are the empirical parameters. This equation expresses the relationship between the water contents of the fine soil and the rock fragments (calcium carbonate concretions) under stable conditions (i.e. no water is exchanged between the fine soil and the rock fragments). Shao et al. (2009) indicated that the rock-fragment content did not significantly affect the relationship between the water contents of the rock fragments and the fine soil. We thus used the same empirical parameters in the different