Plant Soil (2022) 473:369–387
https://doi.org/10.1007/s11104-021-05290-4

REGULAR ARTICLE

Do caliche nodules in loessial profiles affect root growth?

Mi Meixia · Chen Yupeng · Wu Xiaogang · Wang Yushen

Received: 6 June 2021 / Accepted: 26 December 2021 / Published online: 4 January 2022

Abstract
Background Caliche nodules, the product of the leaching and deposition of calcium carbonate in the soil, are widely distributed in loessial profiles on the Loess Plateau in China. Their presence leads to complex interactions between plant roots and the soil.
Aims and Methods We studied the interactions between caliche-nodule and water content and their effects on the biomass, morphology and vertical distribution of roots of Caragana (*Caragana korshinskii* Kom.) for two years using a soil-column experiment. Four root parameters (biomass, diameter, length density and surface-area density) in various diameter classes were compared and analyzed.
Results Water and caliche-nodule contents significantly affected root biomass and morphology. Both coarse- and fine-root biomasses were highest at a nodule content of 30%, did not differ significantly from those in fine earth (nodule-free) but were significantly higher than at the other two nodule contents. The nodules affected fine-root biomass when water content was <60% of field capacity. Higher water content corresponded to higher biomass. Roots become thick and short in loess containing nodules. High contents of nodules (50%) negatively affected root biomass at every depth and caused larger percentage of fine roots to concentrate in the shallower layers.
Conclusion Our results demonstrate that plants growing in the loess containing caliche nodules show some degree of adaptability in root morphology. High nodule content is adverse to accumulation of root biomass. Caliche nodules should be given more consideration when investigating the dynamics and habits of plant growth on the Loess Plateau.

Key words Rock fragments · root biomass and morphology · depth distribution · soil water · the Loess Plateau

Abbreviations

Four rock-fragment contents: R_1	fine earth (0% caliche-nodule content)
R_2	10% caliche-nodule content

Responsible Editor: Susan Schwinning.

M. Meixia (✉) · C. Yupeng
College of Urban and Rural Construction, Shanxi Agricultural University, Taigu 030801, China
e-mail: meixiami@126.com

W. Xiaogang
College of Forestry, Shanxi Agricultural University, Taigu 030801, China

W. Yushen
College of Agriculture, Shanxi Agricultural University, Taigu 030801, China

R_3	30% caliche-nodule content
R_4	50% caliche-nodule content
Four water treatments:	
W_1	80-100% of field capacity
W_2	60-80% of field capacity
W_3	47-60% of field capacity (average water content in a wet year)
W_4	32-47% of field capacity (average water content in a dry year)
RB	root biomass
AB	aboveground biomass
R/S	root-to-shoot ratio
RD	root diameter
RLD	root length density
RSAD	root surface-area density

Introduction

Many studies have reported that the presence of rock fragments in the soil influences plant growth and root elongation (Babalola and Lal, 1977a,b; Grewal et al., 1984; Danalatos et al., 1995; Heisner et al., 2004; Qin et al., 2015; Mi et al., 2016), because rock fragments affect the physical, chemical and biological conditions of the soil (e.g. porosity, mechanical resistance, nutrient content and composition, pH and microbial composition). Roots are organs connecting plants to soils, so they play an important role in the growth of plants. The morphology and distribution of roots in soil profiles are affected by soil properties, environmental factors and the genetic characteristics of the plants (Marshall and Waring, 1985; Gale and Grigal, 1987; Donnelly et al., 2016). Studying the effects of rock fragments on the characteristics of root systems, such as root growth and the uptake of water, is therefore important for fully understanding the habits and ecological adaptability of plant growth in stony soils, which is needed to design reasonable strategies for managing vegetation in areas where stony soils dominate.

Rock fragments affect root growth in both agricultural and forestry systems. Previous studies, however, have provided inconsistent conclusions (Table 1). Some studies have reported that the presence of rock fragments could improve the growth and development of root systems due to increases in root branching, nutrient content and populations of microbial species. For example, Jackson et al. (1972) demonstrated that blueberries (*Vaccinium angustilolium* Ait.) in stony soil germinated earlier and had more stems and root branches. Jongmans et al. (1997) found fungal hyphae in the pores of feldspars and hornblendes in podzol E soil horizons and granitic bedrock in European coniferous forests. The fungi exuded organic acids capable of dissolving minerals, which helped plants to use nutrients stored in the rock. Heisner et al. (2004) reported that rock fragments in the soils of the southern Black Forest in Germany had a cation exchange capacity (CEC) within the same order of magnitude as that of fine earth and that mycorrhizae and fine roots adhered to 70% of the fragments, which were conducive to the absorption of nutrients. Du et al. (2017) found that rock fragments embedded in the soil of the alpine steppe on the northern Tibetan Plateau promoted root growth, perhaps because most of the rock fragments in their study area were small (2-10 mm in diameter), providing many soil pores acting as water reservoirs for plants.

The unique thermal conditions of stony soil, with higher temperatures in high alpine ecosystems, and lower fine-earth bulk densities due to higher rock-fragment contents are conductive to root penetration. The presence of rock fragments therefore optimizes the environment for root growth.

Other studies, however, have indicated that roots developed abnormally due to the higher resistance to root growth in stony soils. Roots in regions with shallow soil layers based on the bedrock (such as karst areas) are mainly concentrated in the upper layers and in the pores or cavities of the bedrock (Schwinning, 2013; Estrada-medina et al., 2013). Roots that penetrate the bedrock play an important role in plant growth. About one quarter to one third of the total root length in 12-year-old forests in southwestern Oregon was in the rocky layer, where the roots could absorb sufficient water from the rock for satisfying the needs of the plants, even though the water content of the soil above the rocky layer was below the wilting coefficient (Zwieniecki et al., 1994). The roots in this study were morphologically adapted to the cracks in the rock, and the root cortex was flattened, with "wing-like" structures on the sides of the root stelae (Zwieniecki et al., 1995). Total nutrient and water

Table 1 Effects of rock fragments (mainly for type and content) on root growth for different types of soil, plants and climatic conditions

Effects	Rock fragment	Soil	Plant	Climate	Source
No	Unrecorded type 2.5 cm thick gravel layer 3-8 mm	Clayey loam	Hybrid forage sorghum	Semiarid steppe climate	Unger (1971)
Positive	Unrecorded type 16-43.2%	Loam, sandy loam and clayey loam	Blueberries	Greenhouse	Jackson et al. (1972)
Positive	Unrecorded type Depth to gravel from 5 to 10 cm	Sandy loam	Maize	Greenhouse	Babalola and Lal (1977a)
Positive Positive Negative Negative	Unrecorded type 10% 25% 50% 75%	Sandy loam and clay	Maize	Greenhouse	Babalola and Lal (1977b)
Positive	Limestone 10-20%	Terra Rossa, clay	Apple	Mediterranean climate	Magier and Ravina (1984)
Negative	Metasedimentary rock	Clayey loam	Forests	Mediterranean climate	Zwieniecki et al. (1994;1995)
Positive Positive Positive	Feldspars Hornblendes Granitic bedrock			Temperate continental climate	Jongmans et al. (1997)
Positive Positive Positive Positive	Granite Gneiss Sandstone Glacial deposits		Forests	Montane climate	Heisner et al. (2004)
Negative	Limestone bedrock	Leptosols , loam		Tropical climate	Estrada-medina et al. (2013)
Positive	Unrecorded type 15-35%	Cryosol, Sandy soil	Grass	Cold and semi-arid plateau monsoon climate	Du et al.(2017)
No No Negative Positive Positive Positive	Schist 25% 50% 75% 25% 50% 75%	Cinnamon, loam	*Artemisia vestita* *Bauhinia brachycarpa*	Subtropical monsoon climate	Hu et al.(2021)

contents also tend to decrease as the effective soil volume for root growth decreases (Ercoli et al., 2006; Qin et al., 2015).

Soil properties, the characteristics of the rock fragments (e.g. proportional mass or volume, size, degree of weathering, shape, lithology and position in the soil) , plant species and climatic conditions can potentially influence root growth in stony soils (Table 1). Unger (1971) reported that the presence of a band of gravel in the subsoil did not greatly significantly affect root distribution of hybrid forage sorghum (*Sorghum vulgare Pers.* × *Sorghum vulgare var. sudanense*). Babalola and Lal (1977a, b) found that root growth of maize depended on the content and position of rock fragments; the small number of rock fragments (<10%) in the clayey soil improved root growth, but the mechanical resistance to growth increased with gravel content, which led to extensive branching and the aberration of root-tip cells, and root length increased by 30% when the depth to the gravel increased from 5 to 10 cm. Babalola and Lal (1977b) also demonstrated that roots were longer in clayey soil with rock fragments than in sandy soil due to the better conditions of water and air, and that roots were shorter in soil with small rock fragments (4-8 and 8-15 mm in diameter) than in soil with larger rock fragments (15-40 mm). Magier and Ravina (1984) also found that the roots of fruit trees were more developed in stony soil under appropriate conditions of irrigation and fertilization; the number of roots was highest when the proportional volume of rock fragments was 10-20%. An optimal rock-fragment content within a moderate range can therefore benefit root growth. Optimal rock-fragment content, however, can vary with soil texture, fragment type and plant species. Grewal et al. (1984) demonstrated that yields of rainfed crops decreased as the rock-fragment content increased, but yields remained high for legumes with large fibrous roots when the proportional volume of rock fragments was 40%. Planting species with well-developed roots may therefore be more advantageous in stony soils, which could be one of the characteristics for selecting crops in stony areas. A recent study by Hu et al.(2021) demonstrated that rock fragments not only affected vertical root distribution and biomass accumulation, but also the relative allocation of biomass to roots. The R/S ratios for two shrubs (*Artemisia vestita* and *Bauhinia brachycarpa*) were highest at the highest rock-fragment content of 75%. Also, B. *brachycarpa* was likely better adapted to soil conditions associated with high contents of rock fragments compared with A. *vestita*.

Previous research has made important progress in determining the characteristics of root morphology and distribution in stony soils, which has helped us to understand the characteristics of plant growth and to clarify the relationships among plants, soils and rock fragments in stony areas. The factors of rock fragments influencing root growth, however, are complex. The effects of rock fragments on root growth are variable due to variations in the characteristics of rock fragments, soil properties and plant species among regions.

The thick loess widely distributed on the Loess Plateau of China differs from the soil in regions with shallow soil layers underlying bedrock. Caliche nodules are often present in loessial profiles due to the natural deposition and concretion of calcium carbonate. The spatial distribution of these nodules in surface soil and their effects on filtration, saturated water conductivity and soil erosion have been studied (Gong et al., 2018a,b; Ma et al., 2010; Zhou et al., 2009; Ma and Shao, 2008; Zhu and Shao, 2008). Gong et al. (2018a) reported a maximum coverage of caliche nodules in the surface soil near 20%, with ≥65% of all nodules 10-50 mm in diameter. Filtration and saturated water conductivity generally decrease as caliche-nodule content increases (Ma et al., 2010; Zhou et al., 2009; Ma and Shao, 2008). These studies of caliche nodules in the soils of the Loess Plateau, however, did not consider plant growth. Mi et al. (2016) reported that plants were negatively affected when caliche-nodule content was 50% but provided no details on root biomass or morphology. Clarifying whether or how caliche nodules in the soil profile affect root development is necessary. More details should be described and analyzed for roots in soil containing caliche nodules, such as diameter, length and proportion of total biomass. The objectives of this study were therefore to determine the effect of caliche-nodule content on root growth, identify interactive effects of nodule and water contents and determine whether and how caliche nodules and soil depth affect root biomass and root morphology. Based on existing research results, we hypothesized that (i) the effects of caliche nodules on root growth would vary with caliche-nodule content and would be positive at moderate nodule contents and negative at high nodule contents, (ii) the effects of nodule content on root growth would be stronger under conditions of water shortages than under conditions of sufficient water, and (iii) the presence of caliche nodules would affect the patterns of allocation of biomass of plants and the vertical distribution of roots.

Materials and methods

Plant materials and the sampling site

Caragana korshinskii Kom., a shrub belonging to the legume family, was selected as the experimental plant. *C. korshinskii* has been widely planted on the Loess Plateau to improve the local ecological environment and provide feed for animals due to its high tolerance to harsh environments (especially drought) and high ecological and economic value. *C. korshinskii* roots consist of a main root and developed and multistage lateral roots.

Caliche nodules and fine earth used in the experiments were collected from the topsoil nearly 30 cm thick in the Liudaogou catchment of the northern Loess Plateau (38°46′-38°51′N, 110°21′-110°23′E; 1081.0-1273.9 m a.s.l.), approximately 14 km west of Shenmu County, Shaanxi Province, China. This area has a semiarid continental climate with a mean annual temperature of 8.6 °C, accumulated temperature ≥10 °C of 3232 °C and mean annual precipitation of 412 mm, with a range of 251.3-693.7 mm. The daily relative humidity (RH), air temperature (AT) and solar radiation (SR) in 2014 and 2015 are shown in Fig. 5 of the Appendix. The average RH, AT and SR from May to September in 2014 and 2015 were 55.6 and 50.3%, 19.2 and 19.7 °C, 20.1 and 20.6 MJ m^{-2}, respectively. The ranges of RH, AT and SR in 2014 and 2015 were 14.5-97.3% and 14.4-97.9%, 6.8-26.3 and 9.0-27.7 °C, 2.5-31.7 and 1.7-31.3 MJ m^{-2}, respectively.

The fine earth in this area is an aeolian loess rich in carbonates, and the pH ranges from 8.5 to 8.8. The carbonates in wet years leach downward during rain. The carbonates in dry years are deposited in the soil and form caliche nodules or even a petrocalcic horizon (Fig. 1A). The petrocalcic horizons are broken into calcareous rock fragments by the combination of climatic conditions and human activity. Processes such as uplifting and cultivation have subsequently redistributed the nodules within the upper soil profile, where they may influence plant growth and root development. Caliche nodules in the Liudaogou catchment mainly develop and form on paleosols such as Wucheng and Lishi loess due to the wet paleoclimate and abundant vegetation (Zhu and Shao, 2008).

The fine earth and caliche nodules (Fig.1B) were transported to the laboratory and air-dried. All of the fine earth was then passed through a stainless steel sieve with a 2-mm mesh. Plant residues in the fine earth were removed. The fine earth and caliche nodules were sampled and used to measure the main physical properties before the experiment was conducted. The initial water contents of the fine soil and rock fragments were 0.0060 and 0.0056 m^3 m^{-3}, respectively. The average sand, silt and clay contents of the fine earth were 80.3, 13.6 and 6.1%, respectively (International Society of Soil Science System). The fine earth was a sandy loam classified as a Glossisol in the WRB classification. The nodules were mainly composed of particles with diameters of 20-30 mm and were capable of storing water (Table 2).

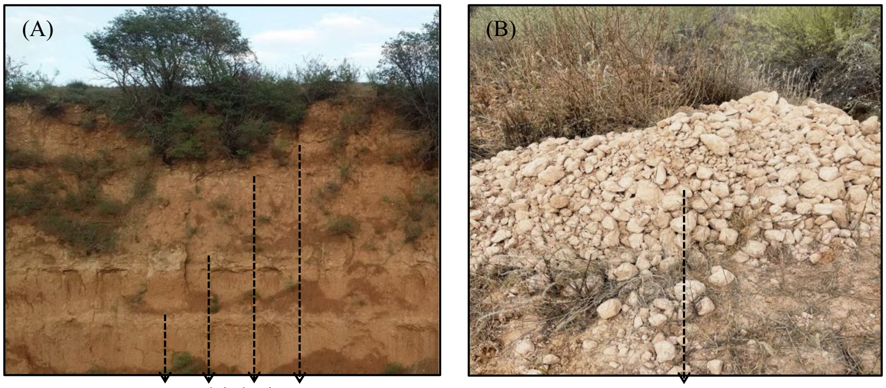

Fig. 1 Photographs of the loessial profile with petrocalcic horizons (**A**) and caliche nodules samples (**B**)

Table 2 Main physical properties of the caliche nodules

Size distribution (%)						Bulk density (g cm^{-3})	Saturated water content (m^3 m^{-3})	Shape
Particle size (mm)	2-10	10-20	20-30	30-40	>40	2.05	0.16	Ellipse or blocked
	2.15	6.69	52.92	11.38	26.86			

Soil composition and treatments

A soil-column experiment was conducted under natural conditions 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. We reconstituted soils with fine earth (particle diameter <2 mm) mixed with different gravimetric proportions of calichenodules of 10 (R_2), 30 (R_3) and 50% (R_4), representing low, medium and high rock-fragment contents, respectively. The fine earth (no nodules, R_1) was used as a control. The soils were then carefully mixed by hand, with air-dried fine earth and nodules placed in PVC columns (100 cm high and 20 cm in diameter). The bottoms of the columns were covered with corrosion-resistant plates. The small gap between the column wall and the corrosion-resistant plate was sealed with silicon sealant.

The amounts of nodules and fine earth necessary to fill the columns for each treatment were based on the average bulk density (2.05 g cm^{-3}) and proportion of the nodules and on the bulk density of the fine earth (fixed at 1.33 g cm^{-3}). The average bulk density for treatments R_2, R_3 and R_4 was 1.35, 1.42 and 1.45 g cm^{-3}, respectively. Nodules and fine earth were added to the columns from the bottom in layers (10 cm each). During the filling of the columns, a tube (2 mm ID) 50 cm in length was buried in each column to provide irrigation water during the stage of controlling water. The tube was buried in the soil at a depth of about 35 cm. The surfaces were covered with 2 cm of vermiculite to minimize evaporation. We ignored surface evaporation, so the loss of water was attributed to absorption by roots. Twelve replicate columns were prepared for each rock-fragment treatment, for a total of 48 columns. All columns were exposed to the environment except during rains, when a plastic shelter was placed above the columns to prevent rainwater from entering the columns.

Four water treatments were established for each treatment of rock-fragment content: 80-100% (W_1), 60-80% (W_2), 47-60% (W_3, average water content in a wet year) and 32-47% (W_4, average water content in a dry year) of field capacity. Each treatment had three replicates. All columns were randomly distributed among the four treatments of nodule content. The corresponding volumetric water contents of the fine earth for W_1, W_2, W_3 and W_4 were 15-19, 11-15, 9-11 and 6-9%, respectively. The gravimetric water content of the fine earth (θ_{mfe}, g g^{-1}) was calculated as the volumetric water content divided by the bulk density. The gravimetric water content of the rock fragments (θ_{mrf}, g g^{-1}) was calculated using the empirical equation under stable conditions:

$$\theta_{mrf} = a\left(1 - e^{-b\theta_{mfe}}\right) \quad (1)$$

where a and b are empirical parameters. The values of a and b were obtained by measuring a series of fine-earth and rock-fragment water contents under equilibrium conditions. a and b in our study were 0.082 and 14.429, respectively (N=35, R=0.88, SE=0.012; N is the number of samples, R is the correlation coefficient for the fit and SE is the standard error of the estimation).

The gravimetric water content of the stony soil was determined by:

$$\theta_{mT} = R_m\theta_{mrf} + \left(1 - R_m\right)\theta_{mfe} \quad (2)$$

where θ_{mT} (g g^{-1}), θ_{mfe} and θ_{mrf} are the water contents of the stony soil, fine earth and rock fragments, respectively, and R_m is the gravimetric rock-fragment content. The gravimetric water content of each treatment obtained using equation (2) is presented in Table 3.

The filled columns were left to subside naturally for two weeks. The height of the soil core in the PVC columns was 90 cm. The depth of subsidence was in the range of 0-5 cm. The first irrigation was performed from the surface of the columns to attain a water content of the soil columns of 50% of field capacity. The columns were sealed with plastic wrap and left for a week to balance the water. *C. korshinskii* seeds were sown in the columns in August 2012. Seedlings were thinned to two plants per column when the plants were about 10 cm tall. Before controlling water, water was added into the columns at regular intervals from the surface to attain a water content of 50% of field capacity to keep the plants alive and provide for healthy development. Water was controlled during the growing seasons (May to September) in 2014 and 2015. Water was added to the columns through the irrigation tube at the stage of controlling water.

Water content was controlled by weighing the columns regularly (2-4 d) using an electronic balance (1 g) and adding water to the columns through

Table 3 Treatments tested in the soil-column experiment

Rock-fragment treatment		Water treatment		
	Caliche-nodule content (%)		Calculated range of water content (%)	Actual average water content (%)
R_1	0	W_1	11.3-14.3	12.5±0.11
		W_2	8.3-11.3	9.7±0.08
		W_3	6.8-8.3	7.3±0.06
		W_4	4.5-6.8	6.1±0.03
R_2	10	W_1	10.8-13.6	12.0±0.12
		W_2	8.0-10.8	9.5±0.10
		W_3	6.6-8.0	7.2±0.06
		W_4	4.4-6.6	6.0±0.03
R_3	30	W_1	9.9-12.2	11.0±0.09
		W_2	7.5-9.9	8.7±0.06
		W_3	6.2-7.5	6.8±0.04
		W_4	4.3-6.2	5.8±0.03
R_4	50	W_1	8.9-10.8	9.5±0.07
		W_2	7.0-8.9	8.0±0.03
		W_3	5.9-7.0	6.5±0.05
		W_4	4.2-5.9	5.5±0.02

the water supply tube. The amount of water added to the columns after each weighing was determined by subtracting the residual amount of water in the columns from the upper limit of water amount in each water treatment. The changes in plant weight over the 2-4 d were ignored due to the low proportion of total water loss. The weight of the water in the column was calculated by subtracting the weight of an empty column, the fresh weight of the plant, the weights of the water supply tube and vermiculite layer and the dry weight of the reconstituted soils from the total weight. The fresh weight of the plant varied over time so was estimated using the double-factor allometric equation (H, cm; D, mm) (Sileshi 2014) $\mathrm{Ln}(B) = \mathrm{a} * Ln(D^2 * H) + \mathrm{b}$, where a and b are empirical coefficients and H, D and B (g) are the height, basal diameter and dry weight of the aboveground biomass (75 °C) for a single plant. a and b were obtained by measuring H, D and B for 106 plants in the study area. The ranges of H and D were 12-167 cm and 2.25-9.94 mm, respectively. The best curve fit was obtained at a=0.94 and =4.79, where R^2=0.98 and SE=0.20. The average water content during the study is presented in Table 3. The actual water content of all treatments was controlled within the calculated range, as expected.

Plant measurements and root analyses

Leaves and branches were collected at the end of September 2015. Each column was then carefully cut longitudinally to obtain an intact soil core with roots. The core was then cut transversely every 10 cm measured from the soil surface, and the sections were packed into numbered plastic bags. Nine samples with roots were collected from each column. We manually removed most roots from the fine earth and rock fragments from the stony soils. The residual samples of fine earth were then wet-sieved through a 0.3-mm mesh screen to obtain the residual fine roots. Fine roots adhering to the nodules were also manually removed. Roots in the nodules (if present) were also removed after destroying the nodules. All roots were washed to remove soil particles.

Root biomass (RB, g), diameter (RD, mm), length density (RLD, cm cm^{-3}) and surface-area density (RSAD, cm^2 cm^{-3}) were obtained by measuring and scanning the root samples. Individual root samples were separated into coarse roots (>2 mm) and fine roots (≤2 mm) and further dissected to facilitate scanning. Root length (RL) of the coarse roots was measured with a ruler to a precision of 1 mm. Coarse-root RD was measured with a digital caliper to a precision of 0.01 mm. Fine roots were further divided into four diameter categories (RD_1: 0-0.5, RD_2: 0.5-1.0, RD_3: 1.0-1.5 and RD_4: 1.5-2 mm) for a more detailed analysis of root morphology. All fine-root samples were placed on transparent Perspex plates, digitized at 300 dpi and measured using WinRHIZO Pro 2013d image-analysis software (Régent Instruments Inc., Quebec City, Canada) in conjunction with an Expression XL1000 flatbed scanner (Seiko Epson Corporation, Suwa, Japan) for determining RD, RLD and RSAD. Finally, the root samples were oven-dried (80 °C, 24 h), and root biomass was determined.

Data analysis

The root parameters (the means of the two plants in each PVC column) were compared among the rock-fragment treatments and water treatments using two-way ANOVAs. Pairwise multiple comparison tests of the least significant difference (LSD) were carried out to identify differences between treatments. The data were examined to ascertain whether the variables were normally distributed, and the variances were homogeneous. The multi-way ANOVAs were carried out using IBM SPSS Statistics 25 for Windows (IBM Inc., Stanford, USA). Differences at the 0.05 level were considered significant. Graphs were plotted using Origin 2018C software (OriginLab, Northampton, USA).

The root extinction coefficient (β) was used to analyze the relationship between the vertical distribution of the roots and soil depth using the vertical-distribution model of roots proposed by Gale and Grigal (1987):

$$Y = 1 - \beta^d \quad (3)$$

where Y represents the ratio of the number of roots in each transverse soil section to the total number of roots, and d represents the depth of the section. The value of β was obtained by simulating the vertical distribution of the root system for each treatment. A larger β indicates a larger percentage of the root system in the deeper sections, and a smaller β indicates that more of the root system is concentrated in the sections near the surface. The value of β is independent of root volume and density. The simulation was performed using Origin 2018C software. The fit of the vertical-distribution curves was always significant and quite good (R^2=0.892-0.998).

Results

Root-growth response

In the nodule treatments, the main roots bypassed the nodules and continued to grow in sub layers. The roots were twisted and bent in the stony soils, especially in the treatments with high nodule contents. Roots rarely grew into the nodules. Most roots were distributed in the fine earth and grew around the nodules. The roots were dense in the concave side of the fine earth when nodules were removed from the cross-section of the soil core. A small amount of fine roots were also attached to the surface of the nodules.

RB, RLD and RSAD in each diameter category (coarse roots and four categories of fine-root diameters, 0-0.5, 0.5-1.0, 1.0-1.5 and 1.5-2.0 mm) were all significantly affected by nodule and water content (Tables 4 and 5). The diameter of coarse roots also differed significantly among the water contents but not the nodule contents. In contrast, the diameter of fine roots differed significantly among the nodule contents but not the water contents. These results also indicated significant interactions between the nodule and water contents for fine-root biomass. The higher *F* and lower *p* for roots with smaller diameters indicated that nodule content affected the absolute values and proportions of thin roots more than thick roots (Tables 4 and 5). The impacts on RB, RLD and RSAD were weaker for nodule content (F=3.714-0.021, p=0.000) than water content (F=16.417-43.192, p=0.000).

Root biomass and R/S ratios

RB was highest in R_3 (36.6±3.99 g), followed by R_1 (33.5±9.68 g), R_2 (30.3±3.41 g) and R_4 (20.9±3.26 g). RB differed significantly between R_1 and R_4, R_3 and R_4 and R_2 and R_3. Variations in coarse-root biomass with nodule content were similar to the variations in total RB (Fig. 2A). Effects of nodule content on fine-root biomass varied with water content. In W_1, none of the four nodule treatments affected fine-root biomass. In W_2, fine-root biomass was significantly higher in R_3 than R_2 and R_4 but did not differ significantly between R_3 and R_1. In W_3 and W_4, fine-root biomass was significantly lower in R_4 than the other nodule treatments. High water content corresponded to high RB for both coarse and fine roots.

AB was also significantly affected by nodule and water contents (Table 4 and Fig. 2B). AB differed significantly between R_1 and R_4, R_3 and R_4. High water content corresponded to high AB. The R/S ratio did not vary with nodule or water content (Table 4 and Fig. 2C), indicating that the patterns of biomass allocation did not vary with the presence of caliche nodules and water stress.

Parameters of root morphology

Total RLD for R_1, R_2, R_3 and R_4 was 0.526±0.071, 0.341±0.051, 0.432±0.033 and 0.322±0.045 cm cm^{-3}, respectively. Total RASD for R_1, R_2, R_3 and R_4 was 0.110±0.015, 0.082±0.007, 0.101±0.011 and 0.070±0.010 cm^2 cm^{-3}, respectively. Increasing nodule content from 0 to 10, 30 and 50%, decreased total

Table 4 Effects of caliche-nodule and water contents on the root parameters

Root parameter		Caliche-nodule content		Water content		Water content × caliche-nodule content	
		F	*p*	*F*	*p*	*F*	*p*
RB	Total	**11.85**	**0.000**	**38.96**	**0.000**	0.760	0.653
	Coarse roots (RD≥2 mm)	**12.93**	**0.000**	**30.98**	**0.000**	1.051	0.424
	Fine roots (RD<2 mm)	**3.868**	**0.018**	**34.36**	**0.000**	**2.636**	**0.021**
AB		**13.01**	**0.000**	**69.56**	**0.000**	1.768	0.114
R/S ratio		1.454	.0.246	1.249	0.198	1.883	0.091
RD	Mean	0.382	0.767	0.738	0.537	1.504	0.189
	Coarse roots (RD≥2 mm)	0.936	0.435	**2.742**	**0.039**	1.180	0.340
	Fine roots (RD<2 mm)	**9.756**	**0.000**	0.458	0.713	0.411	0.920
RLD	Total	**7.963**	**0.000**	**22.36**	**0.000**	1.208	0.324
	Coarse roots (RD≥2 mm)	**7.939**	**0.000**	**43.19**	**0.000**	1.555	0.172
	Fine roots (RD<2 mm)	**8.234**	**0.000**	**21.92**	**0.000**	1.198	0.330
	(1.5≤RD<2 mm)	**4.345**	**0.011**	**22.77**	**0.000**	0.932	0.511
	(1≤RD<1.5 mm)	**6.116**	**0.002**	**25.52**	**0.000**	0.987	0.470
	(0.5≤RD<1 mm)	**7.596**	**0.001**	**27.22**	**0.000**	1.272	0.290
	(0≤RD<0.5 mm)	**8.787**	**0.000**	**16.42**	**0.000**	1.263	0.294
RASD	Total	**7.097**	**0.001**	**26.36**	**0.000**	1.370	0.242
	Coarse roots (RD≥2 mm)	**9.531**	**0.000**	**38.68**	**0.000**	0.849	0.578
	Fine roots (RD<2 mm)	**6.620**	**0.001**	**23.75**	**0.000**	1.361	0.246
	(1.5≤RD<2 mm)	**3.714**	**0.021**	**18.18**	**0.000**	1.208	0.324
	(1≤RD<1.5 mm)	**5.952**	**0.002**	**25.00**	**0.000**	1.239	0.307
	(0.5≤RD<1 mm)	**7.555**	**0.001**	**24.88**	**0.000**	1.446	0.210
	(0≤RD<0.5 mm)	**7.216**	**0.001**	**24.66**	**0.000**	1.431	0.216

These results were obtained using two-way ANOVAs. *F*, used for significance tests; *p*, probability associated with *F*. RB, RD, RLD and RASD represent root biomass, diameter, length density and surface-area density, respectively. AB and R/S represent aboveground biomass and the root-to-shoot ratio, respectively.

The bold type indicates that the impacts were significant at $p \leq 0.05$.

RLD by 35, 18 and 39% and RLD of fine roots by 35, 19 and 37%, respectively. Root elongation was therefore limited in the stony soils, especially those with high nodule contents (50% rock-fragment content in Fig. 3A). In contrast, the presence of nodules increased RD, especially for fine roots (Fig. 3B). Increasing nodule content from 0 to 10, 30 and 50% increased RD for fine roots by 10, 16 and 7%, respectively. Fine-root diameter was still higher at 50% nodule content, but the difference was smaller than for the treatments with lower nodule contents, indicating that root diameter would not increase, and could even decrease, if nodule content was sufficiently high. The parameters of root morphology excluding fine-root diameter, were not significantly affected by nodule content in W_4 (Figs. 3A, B and C).

Root classification

Roots were firstly divided into two groups: fine roots and coarse roots. We could not determine whether the coarse or fine roots were more easily affected by nodule content, because the root parameters responded differently. Nodule content significantly affected surface area and the production of root biomass more for the coarse than the fine roots (Table 4). Nodule content, however, significantly affected root diameter and length more for the fine than the coarse

Table 5 Effects of water and caliche-nodule contents on the proportions of the fine-root parameters for each diameter class for all roots

Root parameter		Caliche-nodule content		Water content		Water content ×caliche-nodule content	
		F	*p*	*F*	*p*	*F*	*p*
RB	Coarse roots (RD≥2 mm)	1.140	0.348	**4.002**	**0.016**	**2.239**	**0.046**
RLD	Coarse roots (RD≥2 mm)	**6.055**	**0.002**	2.679	0.064	0.849	0.578
	Fine roots (1.5≤RD<2 mm)	**7.122**	**0.001**	0.139	0.936	1.674	0.138
	(1≤RD<1.5 mm)	**6.341**	**0.002**	0.759	0.526	1.525	0.183
	(0.5≤RD<1 mm)	**9.935**	**0.000**	**5.627**	**0.003**	1.581	0.164
	(0≤RD<0.5 mm)	**10.407**	**0.000**	2.310	0.096	1.654	0.143
RASD	Coarse roots (RD≥2 mm)	1.681	0.191	2.682	0.064	1.156	0.356
	Fine roots (1.5≤RD<2 mm)	**9.597**	**0.000**	0.358	0.783	1.674	0.138
	(1≤RD<1.5 mm)	**3.319**	**0.033**	1.516	0.230	1.525	0.183
	(0.5≤RD<1 mm)	**4.417**	**0.011**	**3.697**	**0.022**	1.581	0.164
	(0≤RD<0.5 mm)	**9.097**	**0.000**	1.491	0.236	1.654	0.143

These results were obtained using two-way ANOVAs. *F*, used for significance tests; *p*, probability associated with *F*. RB, RLD and RASD represent root biomass, length density and surface area density, respectively. The bold type indicates that the impacts were significant at $p \leq 0.05$.

roots, particularly the finest roots (Table 4). Root length and surface area were further divided into four diameter categories for analysis. Mean fine-root RLD and RASD in the RD_1 diameter class (0-0.5 mm) were significantly higher in R_1 than the other three nodule treatments, indicating that the presence

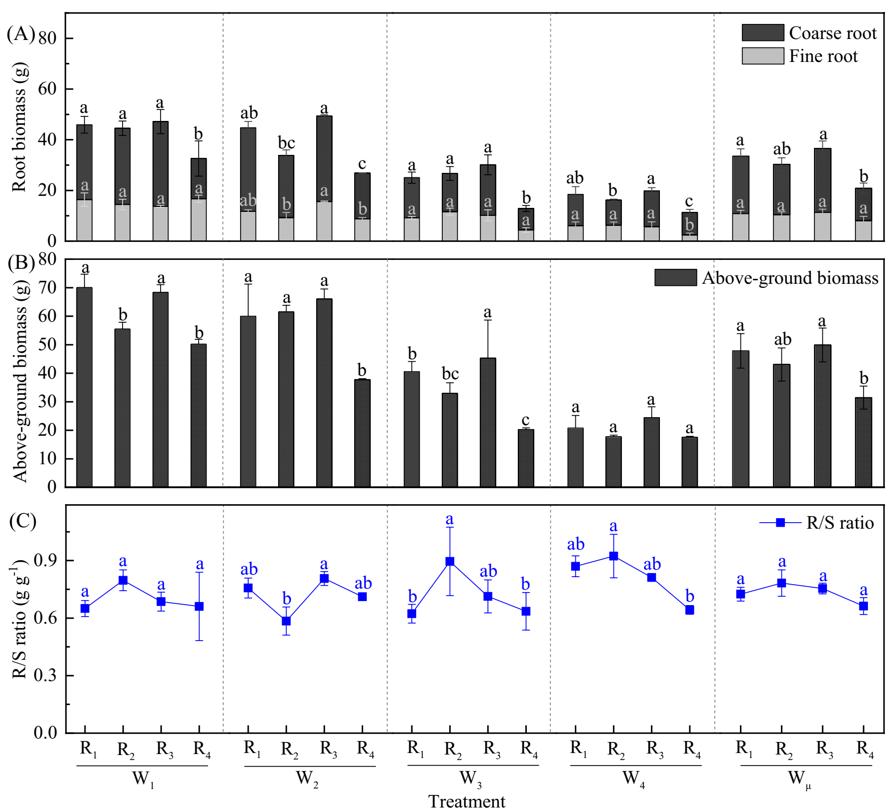

Fig. 2 Root biomass, aboveground biomass and the root-to-shoot (R/S) ratio of coarse and fine roots for three replicates. Different letters indicate significant differences between caliche-nodule contents at $p \leq 0.05$ (one-way ANOVA). The error bars represent standard errors, and W_μ represents the overall mean for the set of water contents

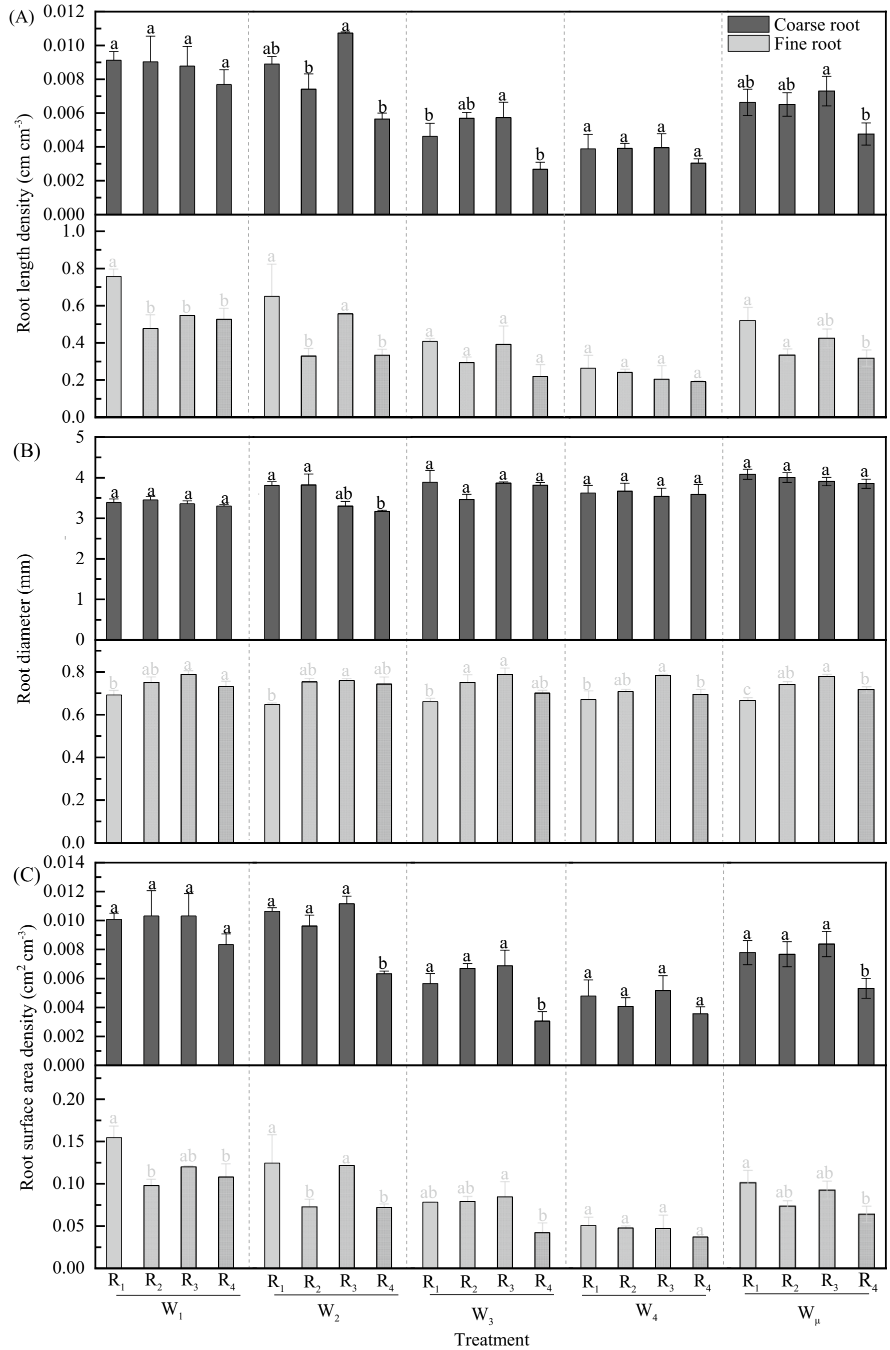

Fig. 3 Mean root length density (RLD, cm cm^{-3}), diameter (RD, mm) and surface-area density (RSAD, cm^2 cm^{-3}) for three replicates. Different letters indicate significant differences between rock-fragment contents at $p \leq 0.05$ (one-way ANOVA). The error bars represent standard errors, and Wμ represents the overall mean for the set of water contents

of nodules negatively affected the growth of the finest roots. Mean RLD and RASD in RD_2 (0.5-1 mm), RD_3 (1-1.5 mm) and RD_4 (1.5-2 mm) were highest in R_1 and R_3 and significantly higher than in R_2 and R_4 (Table 7 in the Appendix), which were similar to the total values of RLD and RASD. RLD and RASD were lower in all diameter classes as water content decreased, also similar to total RLD and RASD. Mean RLD and RASD in RD_1 did not differ significantly between W_1 and W_2.

The percentage of RLD or RASD was equal to RLD and RASD in each diameter class divided by the total for each treatment. Fine-root length and surface area were represented mainly by finer roots (Tables 7 and 8 in the Appendix). Approximately 80-85% of fine-root length was represented by roots with diameters <1.0 mm for all treatments, and approximately 50% were <0.5 mm. More than 60% of fine-root surface area was represented by roots with diameters <1.0 mm for all treatments. R_1 and R_4 had the highest percentages of roots in RD_1, significantly more than for R_2 and R_3 (Table 8 in the Appendix). The variation in the percentages of the other diameter classes, however, was the opposite (i.e. lower in R_1 and R_4 than R_2 and R_3).

Vertical root distribution

RB was used to analyze the vertical distribution of roots to give sufficient consideration to the interactive effects between nodule and water contents. RB for the coarse and fine roots varied with depth (Fig. 4).

The coarse-root profiles for R_1, R_2, R_3 and R_4 indicated that 93.9, 94.6, 94.5 and 89.0% of the coarse roots were concentrated in the 0-50 cm sections, respectively. The fine-root profiles for R_1, R_2, R_3 and R_4 indicated that 65.3, 68.6, 67.4 and 75.1% of fine roots were concentrated in the 0-50 cm sections, respectively. β for the coarse-root distribution did not differ significantly between rock-fragment

Fig. 4 Variations in root biomass with soil depth and its response to caliche-nodule content and water content (*). The error bars represent standard errors for the set of water contents (W_μ) and caliche-nodule contents (R_μ)**.** R, W and R×W represents caliche-nodule contents, water contents and the interaction between nodule and water contents, respectively. *, p<0.05; **, p<0.01.

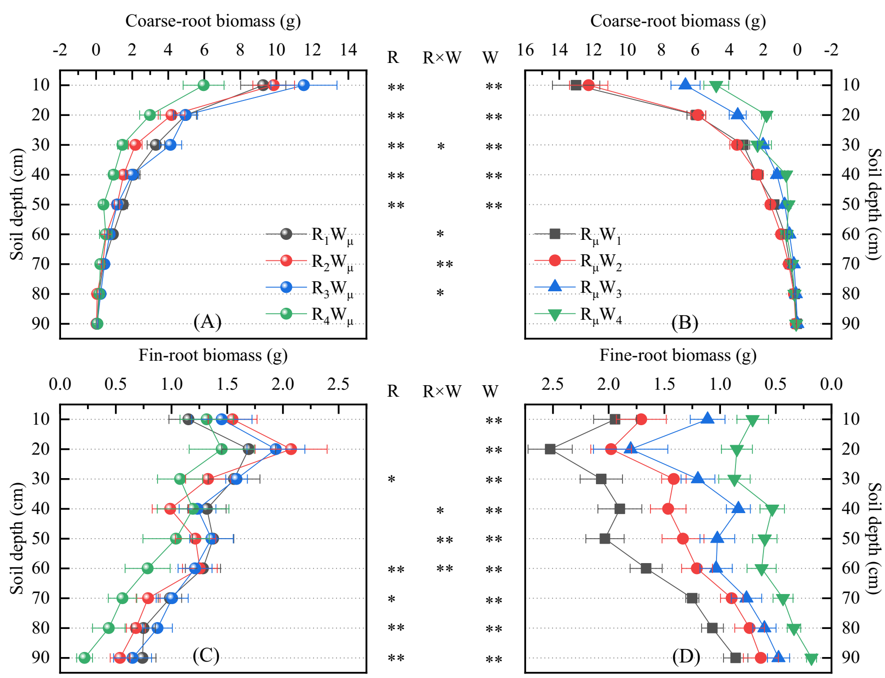

Fig. 5 Daily relative humidity (RH), air temperature (AT) and solar radiation (SR) from May to September in (A) 2014 and (B) 2015

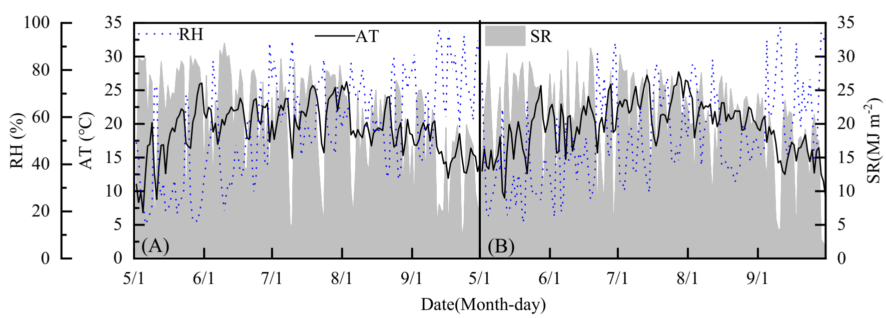

Table 6 Extinction coefficients (β) of the distribution of root biomass for the rock-fragment and water contents

β for the caliche-nodule contents				β for the water contents		
Treatment W_{μ}	Coarse roots (RD>2 mm)	Fine roots (RD≤2 mm)		Treatment R_{μ}	Coarse roots (RD>2 mm)	Fine roots (RD≤2 mm)
	R_1	0.946±0.013a	0.978±0.002a	W_1	0.939±0.011a	0.977±0.006a
	R_2	0.936±0.020a	0.975±0.003a	W_2	0.942±0.015a	0.975±0.005a
	R_3	0.943±0.012a	0.976±0.004a	W_3	0.935±0.023a	0.975±0.004a
	R_4	0.961±0.020a	0.972±0.005b	W_4	0.946±0.017a	0.975±0.003a

contents (F=1.297, p=0.292, Table 6) or the water contents (F=1.083, p=0.370). β for the fine-root distribution differ significantly between the nodule contents (F=6.322, p=0.002) but not the water contents (F=1.341, p=0.297). No interactive effects were identified. Mean β for the fine-root distribution was lower in R_4 than R_1, R_2 and R_3, indicating that the profile of fine roots was shallower in R_4.

RB for the coarse and fine roots in each soil layer was analyzed using a two-way ANOVA, with nodule and water contents as fixed factors (Fig. 4). The results indicated that nodule content mainly affected coarse-root biomass above 50 cm and fine-root biomass below 50 cm.

Discussion

Effects of caliche nodules on root biomass and morphology

The mechanical strength of soil restricts root growth more in stony soil than fine earth (Unger and Kaspar, 1994; Merotto and Mundstock, 1999; Schneider and Don, 2019), and the total amount of available water decreases as rock-fragment content increases (Cousin et al., 2003; Tetegan et al., 2011). The presence of rock fragments should therefore adversely affect plant growth and root development. Our results for the effects of caliche nodules, however, did not support these expectations. Root biomass was lower only at the highest nodule content. Our result was consistent with the study by Hu et al. (2021) for *A. vestita, a* fast-growing subshrub where root biomass was significantly lower in a treatment with the highest rock-fragment content than in fine earth. The highest rock-fragment content in the study by Hu et al. (2021) was 75% by volume, which was higher than that in our experiment (50% by mass ≈ 40% by volume). Our result differed from the study by Hu et al. (2021) for another plant, *B. brachycarpa*, a slow-growing shrub where all treatments with rock fragments had higher root biomass than fine earth. Plants of different species therefore responded differently to rock-fragment content, indicating the need for individualized management for different plants species in stony areas.

According to the analysis by Mi et al. (2016), water-use efficiency (WUE) was highest in soil containing 30% caliche nodule, similar to the finding by Ceacero et al. (2020) that WUE in Mediterranean ecosystems was highest at a rock-fragment content of 17% (by volume). We speculated that WUE, not the total amount of water available to plants, may have been the more important factor affecting root production. As reported by Babalola and Lal (1977a,b), Magier and Ravina(1984) and Poesen and Lavee (1994), root growth was optimal at the moderate content of rock fragments (the common range of 10-20%). Rock-fragment content beyond the optimal may thus begin to negatively affect root growth because of poor growing conditions, such as restricted availabilities of water and nutrients, excessive temperature and resistance to growth. We therefore proposed a similar hypothesis. However, optimal nodule content did not appear in this study, further demonstrating that the effects of rock fragments on plant growth were complex. A more elaborate experimental design for nodule content is therefore needed to verify whether the optimal nodule content exists.

Caliche nodules affect aboveground biomass and root biomass similarly. The nodules in our study did not significantly affect the ratio of aboveground to root biomass, indicating that the pattern of biomass distribution was not influenced by the nodules. This finding differed from the results reported by Du et al.

(2017), where the ratio of aboveground to root biomass in grassland on the northern Tibetan Plateau decreased as the rock-fragment content increased, because aboveground biomass decreased, and root biomass increased. R/S between the fine earth and the soil containing rock fragments did not differ significantly for *A. vestita* but differed significantly only when the rock-fragment content reached 75% for *B. brachycarpa* in the study by Hu et al.(2021) in Minjiang Arid Valley in southwestern China. These conflicting results were probably due to the different soils, rock fragments, plants and natural conditions between the study areas. The fine earth, rock fragments and plant samples were taken from the natural grassland by Du et al.(2017) and the establishing experimental plots under naturally climatic conditions by Hu et al.(2021). Hu et al.(2021) irrigated water into the plots at the seedling stage of the plant. Frequent irrigation and vermiculite mulch carried out in our soil-column experiment, which could weaken effects of nodules on root growth. The frequent watering led to different soil moisture fluctuations from the natural precipitation. Tetegan et al. (2015) considered that rock fragments could serve as water reservoirs during periods when the fine earth dried and could reduce plant-water stress during a moderate drought. The frequent watering weakened this effect of the nodules. Vermiculite mulch (a common way to minimize soil evaporation for obtaining data for plant evaporation based on water loss) could effectively inhibit soil evaporation in order to make ensure water loss by roots uptake in our original consideration, however, did not consider the effects of the nodules on soil evaporation.

Roots become thick and short in loess containing caliche nodules. Our results for the effects of rock fragments on root morphology were partly consistent with the effects of soil compaction. The mechanical resistance to root penetration is higher in compacted soils (Colombi et al., 2017; Ramos et al., 2010), similar to stony soils where roots have difficulty penetrating when they encounter rock fragments. Root thickening is a common response of roots to mechanical impedance, which is the adjustment of the roots to soil strength to reduce the risk of buckling and to the decrease in mechanical stress acting on the roots during penetration. This adjustment is associated with cell turnover and rate of cell detachment at the root cap and in root mucilage (Colombi et al., 2017). Unlike the trend of root shortening and thickening with the degree of soil compaction (Colombi et al., 2017; Ramos et al., 2010), root diameter and length in our study increased at nodule contents of 10 and 30% and then decreased at a content of 50%. The presence of rock fragments creates macropores between rock fragments and fine earth (Babalola and Lal, 1977a, b; Meng et al., 2018), which is conducive to root penetration and the conservation of water and may have contributed to the longer roots in the soil containing 30% nodules relative to the soil containing 10% nodules.

Effects of water content on root growth and the interaction of water content with caliche-nodule content

The behavior was similar between the fine earth and the stony soils, where the higher water content led to longer roots and higher surface-area density and biomass (Figs. 2A, 3A and 3C). High water content stimulates root growth, and low water content may induce withering. Our results were consistent with the conclusion by Cai et al. (2018), who compared plant growth in stony soil with rock-fragment contents up to 60% with homogeneous silty soil under different water conditions. Cui et al. (2021) also reported a positive relationship between the vertical distribution of root density and water content for *C. korshinskii*.

The coarse-root biomass in our study was affected by the nodules at all water contents, and nodule content and water content did not interact. Fine roots behaved differently from coarse roots. The effects of nodule content on fine-root biomass varied with water content. The results of the fine-root responses to the nodules supported our second hypothesis, that the effects of the nodules on root growth were more significant under low-than high-water conditions. In the two high-water treatments, fine-root biomass in each nodule treatment did not differ from that in the fine earth. In the two low-water treatments, fine-root biomass in the treatment of 50% nodule content significantly reduced (reduced by 52 and 60% in W_3 and W_4 treatment, respectively). Water deficiency exacerbated the negative effects of nodules on fine-root growth in the soil with high content of nodules. Available water content was lowest in the lowest water and highest nodule content treatment. Available water content is possibly too low to meet the need for plant growth. Interactive effects of nodule and water content on the responses to the response of plants to soil water availability were also considered to be one of the evidences to explain interactive effects on fine-root growth and need to be further studied.

Variation of impacts of caliche nodules with root diameter and soil depth

The division of roots into fine and coarse categories are considered to be too arbitrary for identifying the difference of physiological function between different root sizes (Donnelly et al., 2016; Yu et al., 2017; McCormack et al., 2015). Studies of fine roots have confirmed that thin fine roots are more responsive to soil environmental changes than are thicker fine roots. For example, King et al. (2002), Baddeley and Watson (2005) and Montagnoli et al. (2014) indicated that the lifespans of fine roots were shorter for smaller roots with higher turnover rates compared to larger roots. Materechera et al. (1992) reported that roots with large diameters also tended to have higher percentages of penetration, Montagnoli et al. (2014) found that finer roots (RD <0.5 mm) were more responsive than larger roots (0.5< RD <2 mm) to soil temperature and water content. The length and surface area of fine roots easily obtained using a root scanner in our study were divided into four diameter categories to provide an opportunity for a detailed analysis of root morphology. The resulted demonstrated that the presence of nodules resulted in morphological adaptations and altered fine root distribution. The thinner the fine roots, the more they were affected by the nodules, indicating that finer roots were more sensitively responsive to the presence of nodules than were the thicker roots. The fine-root systems of *C. korshinskii* are mostly comprised of very fine roots (≤1 mm). These were the longest and largest surface-area root type and play important role in root water and nutrient uptake. These results emphasize the need to divide fine roots into categories. Evaluating the structural and morphological attributes of roots of each diameter category and how they respond to caliche nodules and water content would provide more detailed information about how plants regulate themselves to adapt to the presence of caliche nodules and changes in water content.

Zhang et al. (2009) reported that the roots of mature *C. korshinskii* (twenty years old) were distributed vertically in the uppermost portion of the 3-m soil profile in the Tengger Desert in China, with coarse roots concentrated in the upper 0.4 m and >60% of fine roots distributed in the upper 1.0 m. Bi et al. (2006) also reported that >80% of root biomass of young *C. korshinskii* (three years old) was distributed in the 0-60 cm layer. The roots in our study were obtained after three years of plant growth, and the control of water content began in the second year. By the end of the study, >90% of the coarse roots were concentrated above 50 cm and >90% of the fine roots were concentrated above 80 cm, indicating that the depth of the soil column was satisfactory. Vertical distribution of roots for *C. korshinskii* in this study was consistent with the previous studies, i.e. roots (especially for coarse roots) mainly distributed in the upper soil layers. In the treatment of 50% nodule content, nodules negatively affected coarse-root biomass at the shallower depths (-10 to -50 cm) and fine-root biomass at the deeper sections (-60 to -90 cm), respectively. In the entire profile, more fine roots were at shallower depths in the stony soils (lower β in Table 6), especially at the highest nodule content. The presence of caliche nodules therefore affected the pattern of the vertical distribution of the roots. High levels of caliche nodules prevented roots from extending downward due to negative effects such as high penetration resistance, relative few soils and water resources.

Implications and limitations of this study

Caliche nodules in the soil profile are common and natural on the Loess Plateau of China. We designed a soil-column experiment under semi natural conditions to simulate the loessial environments that had different nodule and water contents. The nodules are heterogeneously distributed in the soil or on the soil surface due to the influence of a combination of terrain, climate, pedogenesis and human activity. Zhu and Shao (2008) reported that the mass percentage of caliche in topsoil ranged from 3 to 50% in the study area. We designed different caliche nodule contents by referring the range found by Zhu and Shao (2008) to represent low, medium and high levels of nodules. The nodules in the columns were uniformly distributed throughout the entire depth of nearly 1 m where plant roots are concentrated. The scenario of the topsoil containing nodules is also common in the northern Loess Plateau.

Caliche nodules are characterized of lower water holding capacity and harder material than the fine earth. According to the study by Ma et al.(2010) and Zhou et al.(2009), nodule content was 30% and 50%, saturated hydraulic conductivity of the stony soils was significantly lower than the fine earth. Nodule content was about 10% (8% by volume), the stony soil displayed a greater saturated hydraulic conductivity compared to the fine earth (Ma et al., 2010). Water movement and porosity structure are different in the soil containing nodules from the fine earth. The presence of nodules therefore results in complicated soil circumstance for plant growth. In this soil column experiment, slow water transport and formation of large porosity would be helpful for efficient water absorption for plants and roots penetration. However, low ability of water retention and hard material would limit root growth. In the regions with high caliche nodule coverage (the top of mountain, mountain ridge, roadsides, edges of ravines, and other high elevation regions in the study by Gong et al. (2018a) and where the soil containing high nodule content, caliche nodules deserve serious consideration to develop appropriate plant management measures.

Soil water, a significant water source for plant on the Loess Plateau of China, was as another factor to explore whether effect of nodules on root growth varied with soil water condition. The results indicated that both water and nodule contents influenced root growth and the distribution of root parameters into fine and coarse roots, but interactions were rare, except in fine-root biomass. The dominant driver of root biomass and morphology was the watering level, and only the highest nodule content (50%) consistently reduced root production. Our study preliminarily and explicitly focused on the effects of caliche nodules on root development on the Loess Plateau and can provide a practical reference for developing measures of vegetation cultivation and management by predicting plant growth based on the abundance of caliche nodules.

Soil and plant undergoes a natural cycle of wetting and drying in the field. Our soil columns experiment, however, could not meet the completely natural conditions. Frequent irrigation mentioned above was different from the natural precipitation. Effects of nodules on soil evaporation were not considered. Finally, caliche nodules may affect the lateral growth of roots in the soil, which cannot be understood using soil-column experiments. Extending the study to field plots in situ or simulated under a completely natural environment will be necessary to obtain more precise and detailed information on root growth in loess containing caliche nodules.

Conclusions

Studying roots in different diameter categories and soil depths under different water conditions in response to caliche-nodule content is necessary for understanding and predicting plant dynamics in soil containing caliche nodules on the Loess Plateau. The soil containing a moderate mass content of nodules (30%), similar to fine earth, was generally more favorable to root growth than soil with low (10%) or high (50%) mass contents of nodules. High contents of nodules negatively affected root growth. Nodules also affected root morphology. Root length density was 35, 18 and 39% lower, and fine-root diameter was 10, 16 and 7% higher, in the soils with nodule contents of 10, 30 and 50%, respectively, relative to fine earth. Higher water content led to higher root production, longer roots and larger surface areas in both the fine earth and the stony soils. Fine-root biomass varied significantly and interactively with nodule and water contents and was not affected by the presence of the nodules until the water content was <60% of field capacity. Classifying the roots based on the length and surface area of fine roots indicated that roots with smaller diameters were more significantly affected by the nodules. Coarse roots were significantly affected by nodules in the 10-50 cm soil layer, but fine roots were significantly affected by nodules in the 60-90 cm layer. A larger percentage of the fine roots were concentrated in the shallower layers in the stony soils, especially in the treatment with the highest nodule content.

Acknowledgements This study was supported by the National Science Foundation of China (No. 41907012), the Scientific and Technological Innovation Programs of Shanxi Agricultural University (Nos. 2017YJ02, 2017YJ01 and 2017ZZ12) and the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi Province of China (No. 2020L0169). We are indebted to the editors and reviewers for their constructive comments and suggestions on this work during review.

Appendix

Table 7 Fine-root length density ($cm\ cm^{-3}$) and root surface-area density ($cm^2\ cm^{-3}$) in diameter classes from 0 to 2 mm in increments of 0.5 mm. Values are means ± standard errors for the set of water contents (W_μ) and caliche-nodule contents (R_μ). Different letters indicate significant differences at $p \leq 0.05$ (one-way ANOVA).

Treatment		Root length density × 10^2 ($cm\ cm^{-3}$) Root diameter (mm)				Root surface-area density × 10^2 ($cm^2\ cm^{-3}$) Root diameter (mm)			
		0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0
W_μ	R_1	27.19±3.60a	14.48±2.12a	4.58±0.71a	1.73±0.29a	3.47±0.47a	3.66±0.54a	2.00±0.31a	1.07±0.17a
	R_2	16.18±1.47b	10.04±1.15b	3.40±0.37b	1.34±0.14b	2.33±0.19bc	2.65±0.24b	1.56±0.14b	0.89±0.09b
	R_3	20.04±2.48b	12.85±1.55a	4.56±0.49a	1.79±0.19a	2.82±0.34b	3.34±0.40a	2.03±0.22a	1.14±0.12a
	R_4	16.42±2.00b	8.66±1.48b	3.01±0.51b	1.26±0.18b	2.13±0.27c	2.19±0.37b	1.34±0.22b	0.82±0.11b
R_μ	W_1	27.60±1.98a	17.57±1.21a	5.84±0.40a	2.24±0.16a	3.70±0.26a	4.38±0.32a	2.52±0.18a	1.40±0.09a
	W_2	23.61±3.11a	13.29±1.63b	4.48±0.49b	1.80±0.18b	3.18±0.38a	3.42±0.40b	2.01±0.21b	1.16±0.11b
	W_3	16.80±1.90b	9.05±1.01c	3.19±0.34c	1.24±0.12c	2.33±0.25b	2.45±0.26c	1.48±0.15c	0.82±0.08c
	W_4	11.82±1.35b	6.12±0.63c	2.03±0.23d	0.83±0.08c	1.54±0.16c	1.58±0.16d	0.90±0.10d	0.52±0.05d

Table 8 Proportions of fine-root length density and surface-area density of each diameter class to total densities. Values are means ± standard errors for the set of water contents (W_μ) and caliche-nodule contents (R_μ). Different letters indicate significant differences at $p \leq 0.05$ (one-way ANOVA).

Treatment		Proportion of root length density (%)@@Root diameter (mm)				Proportion of root surface-area density (%)@@Root diameter (mm)			
		0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0
W_μ	R_1	55.9±1.5a	29.7±0.9b	9.5±0.5b	3.5±0.2c	31.6±0.9a	33.1±0.6a	18.2±0.6b	9.6±0.3c
	R_2	51.9±1.3b	31.3±0.6ab	10.7±0.5b	4.2±0.2b	28.8±0.9b	32.2±0.3a	18.8±0.5b	10.8±0.4b
	R_3	49.7±0.7b	32.1±0.4a	11.7±0.4a	4.7±0.2a	27.2±0.5b	32.3±0.5a	20.1±0.4a	11.4±0.2a
	R_4	56.6±1.3a	28.0±0.9c	9.7±0.4b	4.2±0.2b	31.2±0.8a	30.5±0.68b	18.6±0.4b	11.4±0.4a
R_μ	W_1	50.9±0.8b	32.5±0.4a	10.8±0.3a	4.2±0.2a	28.5±0.5b	33.5±0.5a	19.4±0.3a	10.9±0.3a
	W_2	53.5±1.3ab	30.1±0.9b	10.4±0.4a	4.2±0.2a	29.4±0.8ab	31.4±0.7b	18.8±0.4a	11.0±0.5a
	W_3	54.6±1.5ab	29.3±0.7b	10.5±0.6a	4.1±0.2a	32.5±1.0a	31.5±0.4b	19.4±0.6a	11.0±0.5a
	W_4	55.1±1.8a	29.3±1.0b	9.9±0.6a	4.1±0.2a	30.6±1.2ab	31.5±0.67b	18.1±0.6a	10.6±0.3a

References

Bi JQ, Du F, Liang ZS, Ran LG (2006) Research on root system of caragana korshinskii at different site conditions in the hilly regions of loess plateau. Forest research 19(2):225–230. https://doi.org/10.3321/j.issn:1001-1498.2006.02.018

Baddeley JA, Watson CA (2005) Influences of root diameter, tree age, soil depth and season on fine root survivorship in *Prunus avium*. Plant and Soil 1-2:15–22. https://doi.org/10.1007/s11104-005-0263-6

Babalola O, Lal R (1977a) Subsoil gravel horizon and maize root growth. I. Gravel concentration and bulk density effects. Plant Soil 46:337–346. https://doi.org/10.1007/BF00010090

Babalola O, Lal R (1977b) Subsoil gravel horizon and maize root growth. II. Effects of gravel size, inter-gravel texture and natural gravel horizon. Plant Soil 46:347–357. https://doi.org/10.1007/BF00010091

Cui X, Zhang Z, Guo L, Liu X, Chen X (2021) The root-soil water relationship is spatially anisotropic in shrub-encroached grassland in north china: evidence from GPR investigation. Remote Sensing 13(6):1137. https://doi.org/10.3390/rs13061137

Ceacero CJ, Díaz-Hernández JL, Campo ADD, Navarro-Cerrillo RM (2020) Soil rock fragment is stronger driver of spatio-temporal soil water dynamics and efficiency of water use than cultural management in holm oak plantations. Soil and Tillage Research 197(C):104495. https://doi.org/10.1016/j.still.2019.104495

Cousin I, Nicoullaud B, Coutadeur C (2003) Influence of rock fragments on the water retention and water percolation in a calcareous soil. Catena 53(2):97–114. https://doi.org/10.1016/S0341-8162(03)00037-7

Cai GC, Vanderborght J, Langensiepen M, Andrea S, Hüging H, Vereecken H (2018) Root growth, water uptake, and sap flow of winter wheat in response to different soil water conditions. Hydrology and Earth System Sciences 22(4):2449–2470. https://doi.org/10.5194/hess-22-2449-2018

Colombi T, Kirchgessner N, Walter A, Keller T (2017) Root tip shape governs root elongation rate under increased soil strength. Plant Physiology 174(4):2289–2301. https://doi.org/10.1104/pp.17.00357

Danalatos NG, Kosmas CS, Moustakas NC, Yassoglou N (1995) Rock fragments II. Their impact on soil physical properties and biomass production under mediterranean conditions. Soil Use and Management 11(3):121–126. https://doi.org/10.1016/0148-9062(96)85003-0

Donnelly L, Jagodziński AM, Grant OM, Reilly CO (2016) Above- and below-ground biomass partitioning and fine root morphology in juvenile Sitka spruce clones in monoclonal and polyclonal mixtures. Forest Ecology & Management 373:17–25. https://doi.org/10.1016/j.foreco.2016.04.029

Du ZY, Cai YJ, Yan Y, Wang XD (2017) Embedded rock fragments affect alpine steppe plant growth, soil carbon and nitrogen in the northern Tibetan Plateau. Plant and Soil 420(1-2):79–92. https://doi.org/10.1007/s11104-017-3376-9

Estrada-Medina H, Graham RC, Michael F et al (2013) The importance of limestone bedrock and dissolution karst features on tree root distribution in northern yucatán, méxico. Plant and soil 362(1-2):37–50. https://doi.org/10.1007/s11104-012-1175-x

Ercoli L, Masoni A, Mariotti M, Arduini I (2006) Dry matter accumulation and remobilization of durum wheat as affected by soil gravel content. Cereal Research Communications 34(4):1299–1306. https://doi.org/10.1556/CRC.34.2006.4.272

Gong TX, Zhu YZ, Shao MA (2018a) Spatial distribution of caliche nodules in surface soil and their influencing factors in the Liudaogou catchment of the northern Loess Plateau, China. Geoderma 329:11–19. https://doi.org/10.1016/j.geoderma.2018.05.012

Gong TX, Zhu YZ, Shao MA (2018b) Effect of embedded-rock fragments on slope soil erosion during rainfall events under simulated laboratory conditions. Journal of Hydrology 563:811–817. https://doi.org/10.1016/j.jhydrol.2018.06.054

Gale MR, Grigal DF (1987) Vertical root distributions of northern tree species in relation to successional status. Canadian Journal of Forest Research 17(8):829–834. https://doi.org/10.1139/x87-131

Grewal SS, Singh K, Dyal S (1984) Soil profile gravel concentration and its effect on rainfed crop yields. Plant and soil 81(1):75–83. https://doi.org/10.1007/bf02206896

Hu H, Li FL, McCormack ML, Huang L, Bao WK (2021) Functionally divergent growth, biomass allocation and root distribution of two xerophytic species in response to varying soil rock fragment content. Plant and Soil 463(1-2):265–277. https://doi.org/10.1007/s11104-021-04906-z

Heisner U, Raber B, Hildebrand EE (2004) The importance of the soil skeleton for plant-available nutrients in sites of the southern black forest, Germany. Eur. J. Forest Res 123:249–257. https://doi.org/10.1007/s10342-004-0041-7

Jongmans AG, van Breemen N, Lundström U, van Hees PAW, Finlay RD, Srinivasan M, Unestam T, Giesler R, Melkerud PA, Olsson M (1997) Rock-eating fungi. Nature 389(6652):682–683. https://doi.org/10.1038/39493

Jackson LP, Hall IV, Aalders LE (1972) Lowbush blueberry seedling growth as affected by soil type. Canadian Journal of Soil Science 52(1):113–115. https://doi.org/10.4141/cjss72-012

King JS, Albaugh TJ, Allen HL, Buford M, Strain BR, Dougherty P (2002) Seasonal dynamics of fine roots relative to foliage and stem growth in loblolly pine (*Pinus taeda* L.) as affected by water and nutrient availability. New Phytologist 154:389–398. https://doi.org/10.1046/j.1469-8137.2002.00393.x

Meng C, Niu JZ, Yin ZC, Luo ZT, Lin XN, Jia JJ (2018) Characteristics of rock fragments in different forest stony soil and its relationship with macropore characteristics in mountain area, northern China. Journal of Mountain Science 15(3):519–531. https://doi.org/10.1007/s11629-017-4638-y

Mi MX, Liu BX, Shao MA (2016) Effect of rock fragments content on water consumption, biomass and water-use efficiency of plants under different water conditions. Ecological engineering 94:574–582. https://doi.org/10.1016/j.ecoleng.2016.06.044

McCormack ML, Dickie IA, Eissenstat DM, Fahey TJ, Fernandez CW, Guo D, Helmisaari HS, Hobbie EA, Iversen CM, Jackson RB, Leppälammi-Kujansuu J, Norby RJ, Phillips RP, Pregitzer KS, Pritchard SG, Rewald B, Zadworny M

(2015) Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes. New Phytologist 207(3):505–518. https://doi.org/10.1111/nph.13363

Montagnoli A, Di Iorio A, Terzaghi M, Trupiano D, Scippa GS, Chiatante D (2014) Influence of soil temperature and water content on fine-root seasonal growth of European beech natural forest in Southern Alps. Italy. European Journal of Forest Research 133(5):957–968. https://doi.org/10.1007/s10342-014-0814-6

Ma DH, Shao MA, Zhang JB, Wang QJ (2010) Validation of an analytical method for determining soil hydraulic properties of stony soils using experimental data. Geoderma 159(3-4):262–269. https://doi.org/10.1016/j.geoderma.2010.08.001

Ma DH, Shao MA (2008) Simulating infiltration into stony soils with a dual-porosity model. Eur J Soil Sci 59(5):950–959. https://doi.org/10.1111/j.1365-2389.2008.01055.x

Merotto JA, Mundstock C (1999) Wheat root growth as affected by soil strength. Rev. Bras. Cienc. Solo 23:197–202. https://doi.org/10.1590/S0100-06831999000200002

Materechera SA, Alston AM, Kirby JM, Dexter AR (1992) Influence of root diameter on the penetration of seminal roots into a compacted subsoil. Plant Soil 144:297–303. https://doi.org/10.1007/BF00012888

Marshall JD, Waring RH (1985) Predicting fine root production and turnover by monitoring root starch and soil temperature. Canadian Journal of Forest Research 15(5):791–800. https://doi.org/10.1139/x85-129

Magier J, Ravina I (1984) Rock fragments and soil depth as factors in land evaluation of Terra Rossa. Soil Science Society of America, Special Publication 13:13–30. https://doi.org/10.2136/sssaspecpub13.c3

Poesen J, Lavee H (1994) Rock fragments in top soils: significance and processes. Catena 23(1-2):1–28. https://doi.org/10.1016/0341-8162(94)90050-7

Qin Y, Yi S, Chen J, Ren S, Ding Y (2015) Effects of gravel on soil and vegetation properties of alpine grassland on the Qinghai-Tibetan plateau. Ecological Engineering 74:351–355. https://doi.org/10.1016/j.ecoleng.2014.10.008

Ramos JC, Imhoff SDC, Pilatti MÁ, Vegetti AC (2010) Morphological characteristics of soybean root apexes as indicators of soil compaction. Scientia Agricola 67(6):707–712. https://doi.org/10.1590/S0103-90162010000600013

Schneider F, Don A (2019) Root-restricting layers in German agricultural soils. Part II: Adaptation and melioration strategies. Plant and Soil 442:419–432. https://doi.org/10.1007/s11104-019-04186-8

Schwinning S (2013) Do we need new rhizosphere models for rock-dominated landscapes? Plant and soil 362(1-2):25–31. https://doi.org/10.1007/s11104-012-1482-2

Sileshi GW (2014) A critical review of forest biomass estimation models, common mistakes and corrective measures. For Ecol Manag 329(1):237–254. https://doi.org/10.1016/j.foreco.2014.06.026

Tetegan M, Korboulewsky N, Bouthier A, Samouëlian A, Cousin I (2015) The role of pebbles in the water dynamics of a stony soil cultivated with young poplars. Plant and Soil 391(1-2):307–320. https://doi.org/10.1007/s11104-015-2429-1

Tetegan M, Nicoullaud B, Baize D, Bouthier A, Cousin I (2011) The contribution of rock fragments to the available water content of stony soils: proposition of new pedotransfer functions. Geoderma 165:40–49. https://doi.org/10.1016/j.geoderma.2011.07.001

Unger PW, Kaspar TC (1994) Soil Compaction and Root Growth: A Review. Agronomy Journal 86(5):759–766. https://doi.org/10.2134/agronj1994.00021962008600050004x

Unger PW (1971) Soil Profile Gravel Layers: II. Effect on Growth and Water Use by a Hybrid Forage Sorghum. Soil Science Society of America Journal 35(6):980–983. https://doi.org/10.2136/sssaj1971.03615995003500060035x

Yu RG, Xia SL, Liu CF, Zhang Z, Shi GR (2017) Variations in root morphology among 18 herbaceous species and their relationship with cadmium accumulation. Environmental Science and Pollution Research 24(5):4731–4740. https://doi.org/10.1007/s11356-016-8210-z

Zhang ZS, Li XR, Liu LC, Jia RL, Zhang JG, Wang T (2009) Distribution, biomass, and dynamics of roots in a revegetated stand of Caragana korshinskii in the Tengger Desert, northwestern China. Journal of Plant Research 122(1):109–119. https://doi.org/10.1007/s10265-008-0196-2

Zhou BB, Shao MA, Shao HB (2009) Effects of rock fragments on water movement and solute transport in a loess plateau soil. Comptes Rendus Geoscience 341(6):462–472. https://doi.org/10.1016/j.crte.2009.03.009

Zhu YJ, Shao MA (2008) Spatial distribution of surface rock fragment on hill-slopes in a small catchment in wind-water erosion crisscross region of the loess plateau. Science in China Series D: Earth Sciences 051(006):862–870. https://doi.org/10.1007/s11430-008-0056-x

Zwieniecki MA, Newton M (1995) Roots growing in rock fissures: Their morphological adaptation. Plant and Soil 172(2):181–187. https://doi.org/10.1007/BF00011320

Zwieniecki MA, Newton M (1994) Root distribution of 12-year-old forests at rocky sites in southwestern oregon: effects of rock physical properties. Canadian Journal of Forest Research 24(9):1791–1796. https://doi.org/10.1139/x94-231