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Root distribution and seasonal water status in weathered granitic bedrock under chaparral

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Abstract

Soils in mountainous terrain are often thin and unable to store sufficient water to support existing vegetation through dry seasons. This observation has led to speculation about the role of bedrock in supporting plant growth in natural ecosystems, since weathered bedrocks often have appreciable porosity and, like soil, can store and transmit water. This study, within a chaparral ecosystem in southern California, was designed to determine the extent of rooting within weathered granitic bedrock and to measure the relative contributions of soil and weathered bedrock to water-use by chaparral shrubs (*Adenostoma fasciculatum* Hook and Arn., *Arctostaphylos glandulosa* Eastw., and *Ceanothus greggii* A. Gray). The rooting pattern was mapped from the wall of a trench excavated into the weathered bedrock. Water contents of soil-weathered bedrock profiles were measured at one to four week intervals for two years using a neutron probe. Chaparral roots penetrate deeply (≥ 4 m) into the weathered bedrock and are largely confined to joint traces. During summer dry seasons, the shrubs extracted 39.4 cm of water from a 2.9-m-thick zone of weathered bedrock — accessing nearly ten times as much water as from the 0.35-m-thick soil (Typic Xerorthents). Although it is commonly neglected in ecological inventories and analyses, weathered bedrock can be an essential ecosystem component, particularly where soils are thin and seasonal drought occurs.

1. Introduction

Weathered bedrock is the interface between soil, in which earth materials have been reorganized by pedologic processes, and the underlying unaltered bedrock. While it

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retains the fabric and general appearance of rock, this zone is significantly altered by in situ weathering and may be tens of meters thick (Wahrhaftig, 1965; Graham et al., 1994). A fundamental aspect of this alteration is the production of porosity throughout the rock matrix, resulting in a medium that transmits and stores water (Brimhall et al., 1992; Graham et al., 1994). In mountainous areas where the soil cover is kept thin by mass wasting, roots of woody plants have been observed penetrating many meters into bedrock along joints and fracture planes (Hellmers et al., 1955; Scholl, 1976; Stone and Kalisz, 1991; Jones and Graham, 1993; Zwieniecki and Newton, 1994; Canadell and Zedler, 1995). This is particularly significant in ecosystems that experience seasonal drought, because during extended dry periods plants must rely on water stored within the substrate (Canadell and Zedler, 1995). Wildland scientists have noted that at many sites the soil mantle is far too thin to store enough water to support existing vegetation (Megahan, 1974; Arkley, 1981; Jones and Graham, 1993; Running, 1994); nevertheless, the underlying weathered bedrock is usually not acknowledged in textbooks on woody plants as an important water storage zone (Wenger, 1984; Waring and Schlesinger, 1985; Kozlowski et al., 1991) and is generally neglected in resource inventories and under-appreciated as an ecosystem component (Megahan, 1974; Graham et al., 1994).

Jones and Graham (1993) demonstrated that weathered granitic rock can hold an appreciable amount of water at matric potentials that make it accessible to plants. Our goal in this research was to more directly examine the edaphic role of weathered bedrock in chaparral ecosystems where soils are thin. More specifically, our objectives were to determine the rooting patterns within weathered granitic bedrock and to measure the relative contributions of soil and weathered bedrock to chaparral water-use during the summer dry season.

2. Materials and methods

We established an experimental site on a nearly level hill summit in the foothills (1150 m elevation) of the San Jacinto Mountains in southern California, about 130 km east of Los Angeles. The climate is mediterranean with a mean annual precipitation (MAP) estimated to be about 550 mm, based on records (NOAA, 1992) at the cities of Banning (792 m elevation, 12 km to the northwest, MAP = 432 mm) and Idyllwild (1640 m elevation, 20 km to the southeast, MAP = 645 mm). Precipitation occurs mainly as rain during the cool months of November through April. The remaining six months are usually dry and hot. Vegetation on the site consists of a dense cover of woody shrubs, known as chaparral, dominated by chamise (*Adenostoma fasciculatum* Hook and Arn.), Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.), and cupleaf ceanothus (*Ceanothus greggii* A. Gray). The bedrock is tonalite of the late Mesozoic Peninsular Ranges batholith, one of the larger bodies of granitic rock in the United States. In general, the rock contains 50 to 55% plagioclase (An_{30-40}), 20 to 30% quartz, 1 to 8% K-feldspar, 10 to 15% biotite, and 0 to 5% hornblende (Hill, 1988). The rock at the study site contains about 10% biotite and $< 1\%$ hornblende. It is weathered to several meters depth, yielding a substrate with up to 30% porosity through which water flows at rates of up to 5 cm h^{-1} under saturated conditions (Johnson-Maynard et al., 1994). The weathered rock holds at least 0.10 m^3 m^{-3} plant-extractable water, as estimated by water retention between matric potentials of −0.01 and −1.5 MPa (Jones and Graham, 1993). This is similar to the water-holding capacities of the overlying soils, which are coarse-loamy, mixed, mesic Typic Xerorthents. The bedrock, typically encountered at about the 35 cm depth, is generally friable such that it can be chopped and dug using a pick and shovel, and chunks of it can be broken or crumbled by hand. For the most part, it matches the criteria for weathering classes 5 or 6 of Clayton and Arnold (1972), but is not sufficiently weathered to be considered saprolite (weathering class 7).

Water contents of soil-weathered bedrock profiles were monitored at one to four week intervals under a 15 × 15-m plot that was mechanically cleared of chaparral, and under the adjacent undisturbed, natural chaparral vegetation. The cleared site was maintained free of living vegetation for the duration of the experiment, but was covered with cut brush to reduce direct incidence of solar radiation on the bare ground. Water content of soil and bedrock was measured with a neutron probe (Gardner, 1986). At both cleared and natural sites, five access holes, spaced at least 3 m apart, were excavated with a power auger fitted with a 60-mm diameter bit. Variable subsurface weathering patterns, which could not be predicted from surface conditions, governed the depth to which the holes could be augered. Only two holes at each site reached the 3-m depth, while the others were restricted by hard bedrock encountered within the 2 to 3 m depth range. Neutron probe access tubes, each consisting of PVC pipe (60-mm o.d., 54-mm i.d.) with the lower end sealed, were inserted into the auger holes. The free space between the tube and the hole wall was filled with material excavated from the hole. The protruding ends of the access tubes were covered between readings to exclude rain and debris. Neutron probe readings were made at 25-cm depth increments to the bottom of each access tube. The neutron probe was calibrated for each hole using gravimetric water contents and neutron probe readings obtained for corresponding depths during the establishment of the access tubes. Since samples with very low water contents were not available from these initial samplings, gravimetric water contents were also measured for samples taken near the access tubes at the end of the dry season. These data were incorporated into calibration curves relating neutron probe readings to gravimetric water content. Predawn water potential of plants, an assumed indicator of plant equilibrium with substrate moisture, was measured with a pressure chamber (Scholander et al., 1965).

Roots were mapped from a 2.4-m-long, 2.1-m-deep section of a trench wall at the boundary between the cleared and natural areas using a portable frame grid comprising 10 × 10-cm cells. Root abundance (measured as numbers of root intersections with the trench wall) was quantified for 10-cm-depth increments from this mapping. The soil–bedrock morphology was described and sampled in this same trench. Bulk density was determined using paraffin-coated clods (Blake and Hartge, 1986). Porosity was calculated from these bulk density values and particle densities measured for each horizon using a gas pycnometer (Blake and Hartge, 1986). Particle size distribution was measured by pipette and sieving (Gee and Bauder, 1986) using samples that had been previously air-dried and sieved to remove rock fragments > 2 mm in diameter. Total C was measured by dry combustion (Nelson and Summers, 1982) and assumed equal to organic C, since no carbonates are present in these soil and rock materials.

3. Results and discussion

The soil horizons have sandy loam textures (≤ 8% clay) and weak structure (Table 1). Organic C content decreases from 50.1 g kg^{-1} in the A horizon to 5.6 g kg^{-1} in the C horizon (Table 1). The bedrock mass is divided into blocks by joints spaced 10 to 80 cm apart. The joint traces themselves range from 0.1 to 15 cm wide (mostly ≤ 2 cm) and are not open fissures, but are filled with a sandy loam material apparently produced by weathering in situ. The average joint trace width decreases from 6 cm in the Cr/C horizon (35–85 cm) to 2 cm in the Cr horizon (85–220 cm). The blocks of weathered rock (Cr material) contain between 2 and 6% clay, whereas the joint trace material (C material) has a somewhat finer texture (5–7% clay).

While chaparral roots are most abundant within the soil, they penetrate deeply into the weathered bedrock (Fig. 1) and were recovered from auger borings as deep as 4 m at the site. Roots within the bedrock are largely confined to joint traces, resulting in distinct linear patterns in the cross-sectional map presented in Fig. 2. The irregular changes in root abundance with depth in the bedrock, shown in Fig. 1, are the result of variations in the density and orientation of joints exposed in the trench wall (Fig. 2) and the occurrence of root mats (Graham et al., 1994) within some joint planes. By exploiting the weathered bedrock, the shrubs have increased their bulk rooting volume at least ten-fold beyond what the soil alone would provide. In the Cr horizon, where the roots are narrowly confined within joint traces, the organic C content is considerably higher in the joints (4.0 g kg^{-1}) than in the matrix blocks of weathered rock (0.85 g kg^{-1}) (Table 1).

Initial water contents at all depths were similar for both cleared and natural sites (Fig. 3), but, as the 1993 dry season progressed, the chaparral plants depleted water from throughout the monitored depth at the natural site, while losses were minimal under the

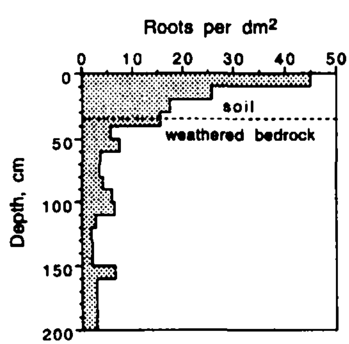


Fig. 1. Chaparral root density with depth in the soil-weathered bedrock profile. Root concentrations are from counts of root intersections with a vertical trench wall (Fig. 2). Dashed horizontal line shows approximate boundary between soil and weathered granitic bedrock.

Table 1
Selected properties of the soil and weathered granitic bedrock

Horizon	Depth (cm)	Dry color	Texture [a]	Gravel (%)	Sand (% < 2 mm)	Silt (% < 2 mm)	Clay (% < 2 mm)	Structure [b]	Dry consistence [c]	Roots [d]	Organic carbon ($g\ kg^{-1}$)	Bulk density ($Mg\ m^{-3}$)	Porosity ($m^3\ m^{-3}$)	Other features
O	3–0	Loose chamise and manzanita leaves and twigs.												
A	0–5	10YR 4/2	sl	18	75	17	8	1cgr	so	2vf,f,1m,1c	50.1	ND [e]	ND	
AC	5–20	10YR 6/3	sl	20	75	19	6	1fsbk	so	2vf,f,1m,1c	10.5	1.35	0.49	
C	20–35	10YR 6/2	sl	38	72	20	8	1fsbk	sh	2vf,f,1m,1c	5.60	1.48	0.44	
Cr/C	35–85	Cr: variegated	sl	51	76	18	6	rock structure	h		2.70	1.72 (Cr/C combined)	0.35	
		C: 10YR 7/2	sl	32	73	20	7	massive	sh	2vf,1f,1m	2.70			Joint trace width 2–10 cm, frequency ~ 30 cm
Cr	85–220	Blocks: variegated	ls	50	84	14	2	rock structure	h–vh	0–1 vf	0.85	2.34	0.12	Few thin & moderately thick clay films
		Joints: 10YR 7/2	ls	46	77	18	5	massive		2vf,f,2m,1c	4.00	2.08	0.21	Joint width mostly 2 cm, frequency ~ 40 cm

[a] sl = sandy loam; ls = loamy sand.
[b] 1 = weak; f = fine; c = coarse; gr = granular; sbk = subangular blocky.
[c] so = soft; sh = slightly hard; h = hard; vh = very hard.
[d] 1 = few; 2 = common; vf = very fine (< 1 mm); f = fine (1–2 mm); m = medium (2–5 mm); c = coarse (> 5 mm).
[e] ND = not determined.

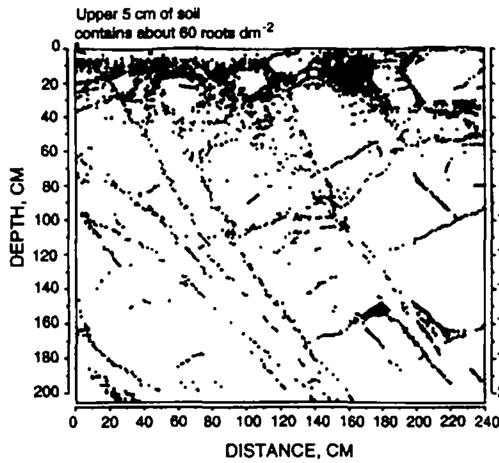


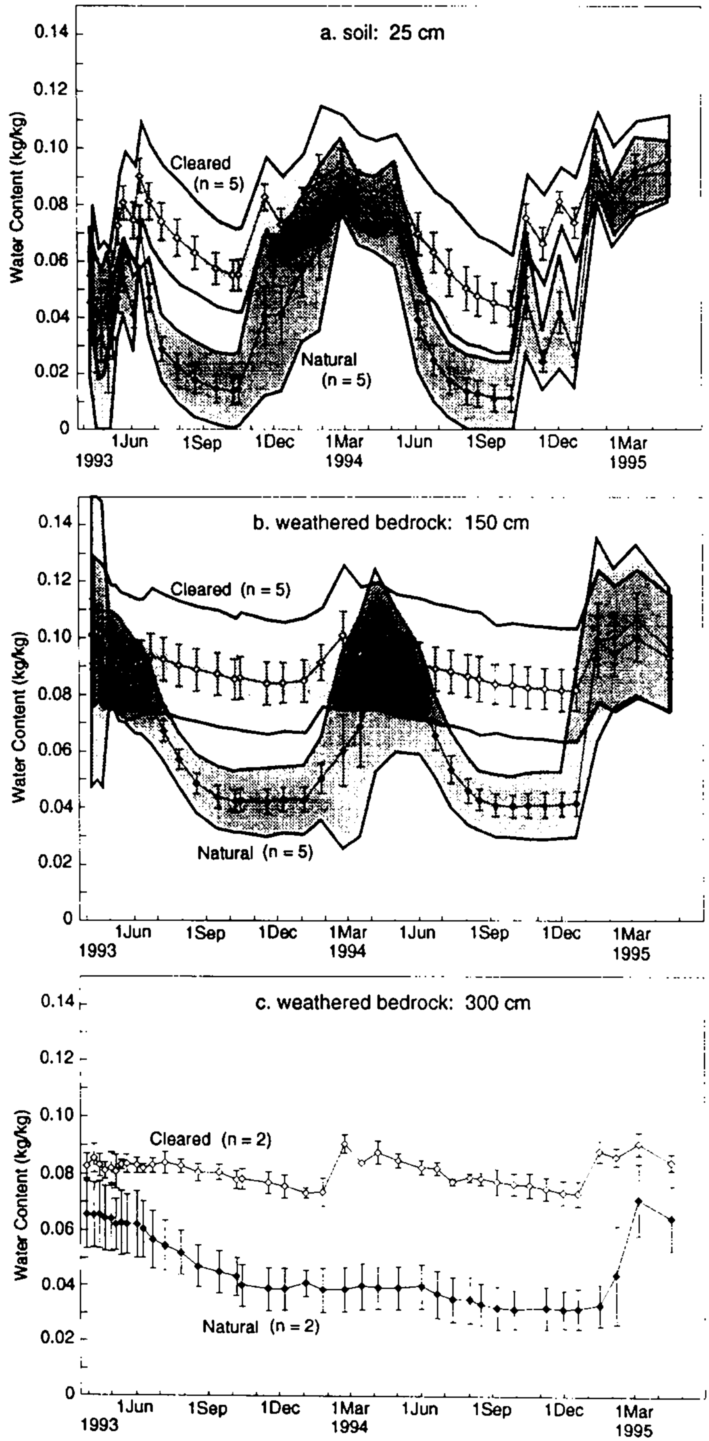
Fig. 2. Map of chaparral root distribution in weathered granitic bedrock. The soil–bedrock boundary is within the 20–40 cm depth. Each point represents a single root intersecting the trench wall.

cleared site below 25 cm (Fig. 3b, c). The onset of warm, sunny weather in early summer stimulated plant transpiration, resulting in rapid water loss from the soil and bedrock under natural vegetation until early fall (Fig. 3), when predawn plant water potentials reached lows of −5.5 (chamise) to −7.0 MPa (ceanothus). Such low potentials indicate that the small amount of water remaining in the rock (0.04 kg kg^{-1} at the 150-cm depth; Fig. 3b) was largely inaccessible to the plants. In contrast, the cleared site lacked plants, so the primary mechanism of water loss was evaporation, the effect of which was greatly diminished with depth (Hillel, 1982). The minor losses observed at the greatest depths may be due to a few wide-ranging roots from surrounding active plants, but in general the cleared site served as a control to demonstrate the effectiveness of water depletion by vegetation on the natural site.

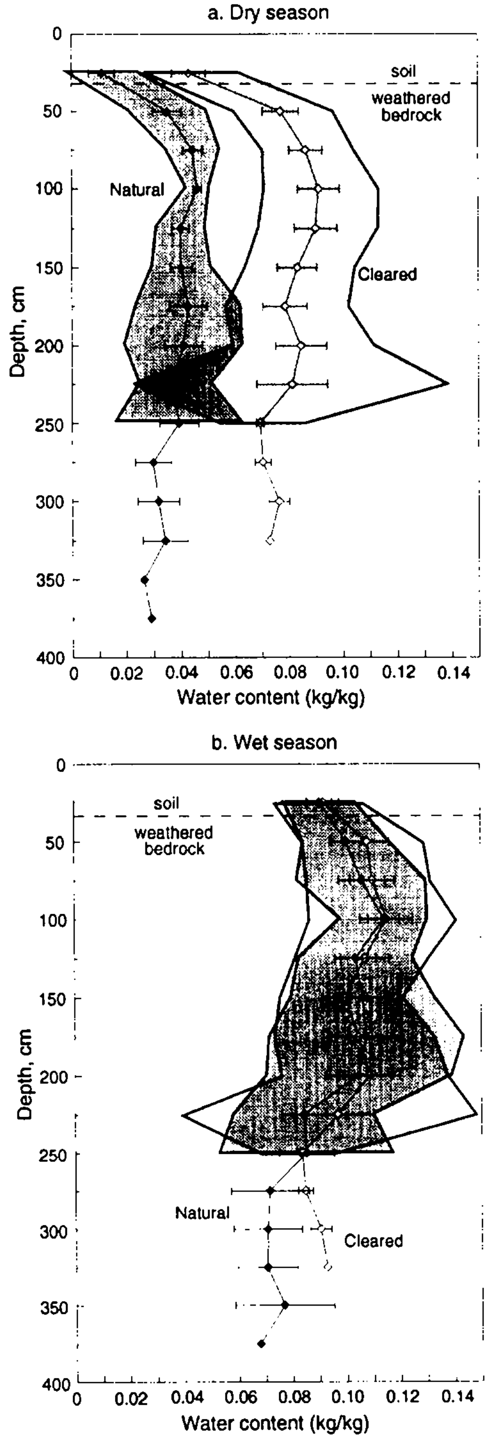
Water content data for full soil-weathered bedrock profiles further illustrate seasonal water content trends under the cleared and naturally vegetated sites (Fig. 4). In the second dry season (1994), vegetation greatly depleted water throughout the substrate depth (> 300 cm) compared to the cleared site (Fig. 4a), but, in the following wet season, the profiles recharged and showed virtually no difference in water content between treatments at a given depth (Fig. 4b).

Based on the maximum and minimum water contents recorded at each depth, and appropriate bulk densities to convert gravimetric water content to a volumetric basis (Gardner, 1986), the soil (0–35 cm depth) stored and supplied 3.9 cm of water for plant use during the dry season, whereas the upper 2.9 meters of weathered rock contributed 39.4 cm of water. The available water capacities calculated from these values are 0.11

Fig. 3. Seasonal changes in gravimetric water contents (kg water per kg soil or rock) under mechanically cleared and natural chaparral vegetation sites. On the x-axis, the first day of each month is indicated by a tick mark. Error bars indicate one standard error of the mean. Shaded regions delimit the 95% confidence regions for each curve (not given for the 300 cm depth due to small sample size).



a. soil: 25 cm
Cleared (n = 5)
Natural (n = 5)
b. weathered bedrock: 150 cm
Cleared (n = 5)
Natural (n = 5)
c. weathered bedrock: 300 cm
Cleared (n = 2)
Natural (n = 2)
Water Content (kg/kg)
0 0.02 0.04 0.06 0.08 0.10 0.12 0.14
1Jun 1Sep 1Dec 1Mar 1Jun 1Sep 1Dec 1Mar
1993 1994 1995


a. Dry season
soil
weathered bedrock
Natural
Cleared
Depth, cm
Water content (kg/kg)
b. Wet season
soil
weathered bedrock
Natural
Cleared
Depth, cm
Water content (kg/kg)

$m^3\ m^{-3}$ for the soil and 0.14 $m^3\ m^{-3}$ for the weathered rock. The available water capacity of the weathered granitic rock is in close agreement with the results of Jones and Graham (1993) and Anderson et al. (1995). The soil may supply additional water if rainfall replenishes it during the growing season. This occurred in June 1993 (Fig. 3a), but it is a relatively uncommon phenomenon, particularly later in the summer. The chaparral plants in this study were able to extract water from much deeper than 2.9 m into weathered bedrock (the value used in the comparison above), since we observed roots and measured water depletion even below the 3.5 m depth in 1993. During dry years, like 1994, rainfall is insufficient to replenish water storage deep within the bedrock (Fig. 3c, under natural vegetation).

4. Conclusions

This study shows that weathered bedrock vastly increases the storage of plant-available water beyond that held by thin soils. This reservoir of water within the bedrock is thoroughly exploited by chaparral shrubs as their roots penetrate several meters into the rock, allowing the plants to tap the water stored within it to survive the summer drought. Without the additional rooting volume and water provided by the bedrock, the ecosystems would have a much more arid character in that the biomass would be greatly reduced and more drought-adapted species would be favored. Predictive models of plant growth potential that ignore weathered bedrock will seriously underestimate the capabilities of these ecosystems (Running, 1994; Runyon et al., 1994).

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Fig. 4. Gravimetric water content as a function of depth in soil-weathered bedrock profiles under mechanically cleared and natural chaparral vegetation sites near the end of (a) a dry season (29 September 1994) and (b) a wet season (3 March 1995). Error bars represent one standard error of the mean; $n = 5$ for all treatments through the 200 cm depth, but is variable (< 5) below that. Where no error bars are shown, $n = 1$. Shaded regions delimit the 95% confidence regions for each curve (not shown when $n < 3$). Dashed horizontal line shows approximate boundary between soil and weathered granitic bedrock.

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