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Geoderma 114 (2003) 389–400
GEODERMA
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Contributions of water supply from the weathered bedrock zone to forest soil quality

James H. Witty[a], Robert C. Graham[a,*], Kenneth R. Hubbert[b], James A. Doolittle[c], Jonathan A. Wald[d]

[a] *Soil and Water Sciences Program, Department of Environmental Sciences, University of California, Riverside, CA 92521-0424, USA*
[b] *Forest Fire Laboratory, Pacific Southwest Research Station, USDA Forest Service, 4955 Canyon Crest Drive, Riverside, CA 92507, USA*
[c] *USDA NRCS, 11 Campus Boulevard, Suite 11, Newtown Square, PA 19073, USA*
[d] *USDA NRCS, 210 N. Havana, Spokane, WA 99202, USA*

Abstract

One measure of forest soil quality is the ability of the soil to support tree growth. In mediterranean-type ecosystems, such as most of California's forests, there is virtually no rainfall during the summer growing season, so trees must rely on water stored within the substrate. Water is the primary limitation to productivity in these forests. Many forest soils in California are relatively thin, but are underlain by thick zones of weathered bedrock. Weathered granitic bedrock, the most prevalent lithology, has available water capacities (0.12-cm water/cm rock) that approach those of soils (0.2-cm water/cm soil) and, because the weathered rock zone is usually so much thicker (several meters) than the soil (< 1 m), it almost always constitutes the larger storage reservoir for plant-available water. The weathered bedrock retains the original rock fabric and is friable and easily excavated, but the primary minerals are not thoroughly altered to clay minerals, so it is not considered saprolite. Roots of ponderosa pine (*Pinus ponderosa*) seedlings penetrate through the soil and encounter weathered bedrock within the first 2 years on many sites. Thus, the influence of the weathered bedrock zone on plant growth begins early. Root access to the weathered bedrock is restricted to fractures, which are often spaced about 50 cm apart. Water is extracted from the intervening rock matrix through unsaturated flow toward the root mat in the fractures and by mycorrhizal fungal hyphae that penetrate the rock matrix. At one site in the Sierra Nevada, 30-year-old Jeffrey pine (*P. jeffreyi*) depleted the soil-held water by mid-June and relied on water stored in the weathered bedrock until the rainy season began in October. In this case, the weathered bedrock supplied at least 70% of the water used by the trees during the growing season. In the same area, we found that thin soils are not a detriment to pine productivity when they are underlain by a thick zone of weathered bedrock. In mediterranean-type ecosystems, the weathered bedrock zone is an essential

* Corresponding author. Tel.: +1-909-787-3751; fax: +1-909-787-3993.
E-mail address: graham@citrus.ucr.edu (R.C. Graham).

doi:10.1016/S0016-7061(03)00051-X

component of the plant water supply system and is thus an important contributor to forest soil quality.

Keywords: Ponderosa pine; Jeffrey pine; Site productivity; Regolith; Granitic rock; Roots

1. Introduction

The ability to promote biological activity is a major component of soil quality (Doran and Parkin, 1994). In this regard, an overriding soil quality issue for most forest lands in California is the capacity of soils to store water and make it available for plant growth (Powers and Ferrell, 1996). Most of California's forests receive insignificant rainfall from late spring to fall, therefore, trees and shrubs must rely heavily on water stored in the substrate. These forests are on upland sites where soils tend to be relatively thin and are underlain by thick zones of weathered bedrock.

Bedrock lithologies in California encompass a wide variety of types, including plutonic, volcanic, sedimentary, and metamorphic. Of these, granitic terrain makes up 20% of the state's land area. Fig. 1 shows the distribution of coniferous forest and where the landscape is dominated by weathered granitic bedrock within 1 m of the surface, thus well within the rooting zone of trees (Oliver and Ryker, 1990; Stone and Kalisz, 1991; Schenk and Jackson, 2002). There is a considerable overlap in northwestern California and in the Sierra Nevada, which runs along the east side of the state.

Weathered bedrock holds plant-available water, is host to plant roots, and can play a critical role in supporting conifers in summer dry environments (e.g., Arkley, 1981; Anderson et al., 1995; Zwieniecki and Newton, 1996; Hubbert et al., 2001a,b). However, the relationship of forest site productivity to the character of the underlying bedrock has not been investigated. As a result, timber and ecosystem site evaluations and productivity models generally incorporate information on soil characteristics, but not bedrock properties (Running, 1994; Runyon et al., 1994). We suggest that, to be realistic, forest substrates in summer dry environments must be considered to extend much deeper, and into weathered bedrock, rather than being limited to the solum or an artificial 2-m limit (Soil Survey Staff, 1999).

Our research addresses the deficiency in understanding how deep substrates contribute to forest soil quality in mediterranean-type ecosystems by focusing on the role of weathered granitic bedrock in supporting tree growth. Here, with respect to ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*P. jeffreyi*), and weathered granitic bedrock in California, we report on the age at which roots of seedlings reach and begin to utilize the bedrock, how roots of mature trees are distributed in it, the extent to which these trees rely on it for their water supply, and the effect it has on productivity.

2. Materials and methods

The Sierra Nevada is the major mountain range in California. It supports much of the commercial forest land and is predominantly underlain by granitic bedrock (SNEP, 1996).

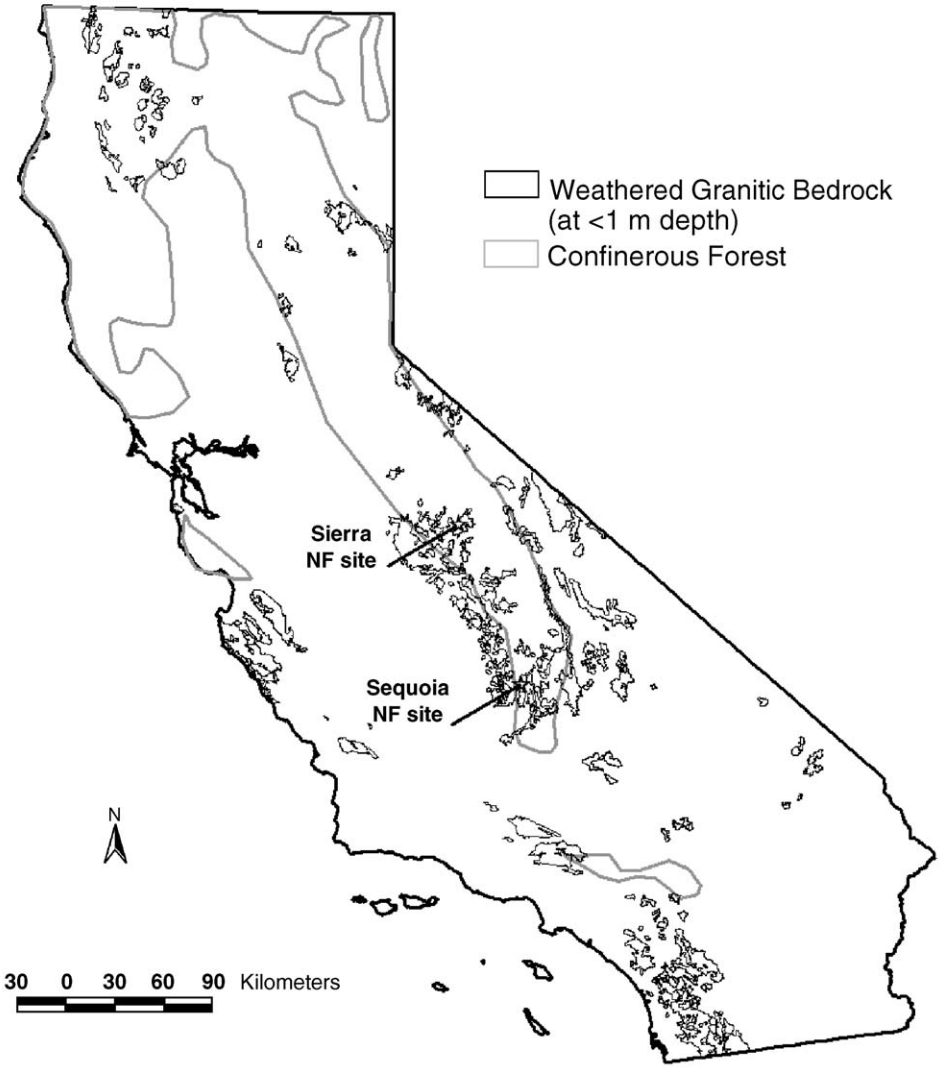

Fig. 1. Map of California showing distribution of coniferous forest, areas where weathered granitic bedrock within 1 m of the surface predominates, and the overlap of these two conditions. Study sites are indicated. Weathered bedrock distribution from Soil Survey Staff (1995). Coniferous forest distribution is from Davis et al. (1998).

Study sites on the Sierra and Sequoia National Forests were selected to represent these conditions (Fig. 1).

The site on the Sierra National Forest is at about 1580-m elevation, with a north aspect and gentle slope (3% to 8% gradient). Climatic data from a recording station at 1503-m elevation and 15 km south of the study site show a distinct dry season from May through September, a mean annual precipitation of 750 mm, and a mean annual temperature of

12.6 °C (Fig. 2a) (Big Creek PH1; Western Regional Climate Center, 2002). Winter precipitation occurs as both snow and rain. Soils are mapped as coarse-loamy, mixed, mesic Typic Dystroxerepts and are very deep (>150 cm) with a slight clay increase in the subsoil (Giger and Schmitt, 1983). The undisturbed vegetation of these sites consisted of ponderosa pine, sugar pine (*P. lambertiana*), white fir (*Abies concolor*), incense cedar (*Libocedrus decurrens*), greenleaf manzanita (*Arctostaphylos patula*), and a prostrate lupine (*Lupinus* sp.).

Trenches were excavated near seedlings ranging in age from 0.5 to 4 years old. Entire root systems were followed and excavated. The depth of the deepest root and the length of the longest root from the root surface were recorded.

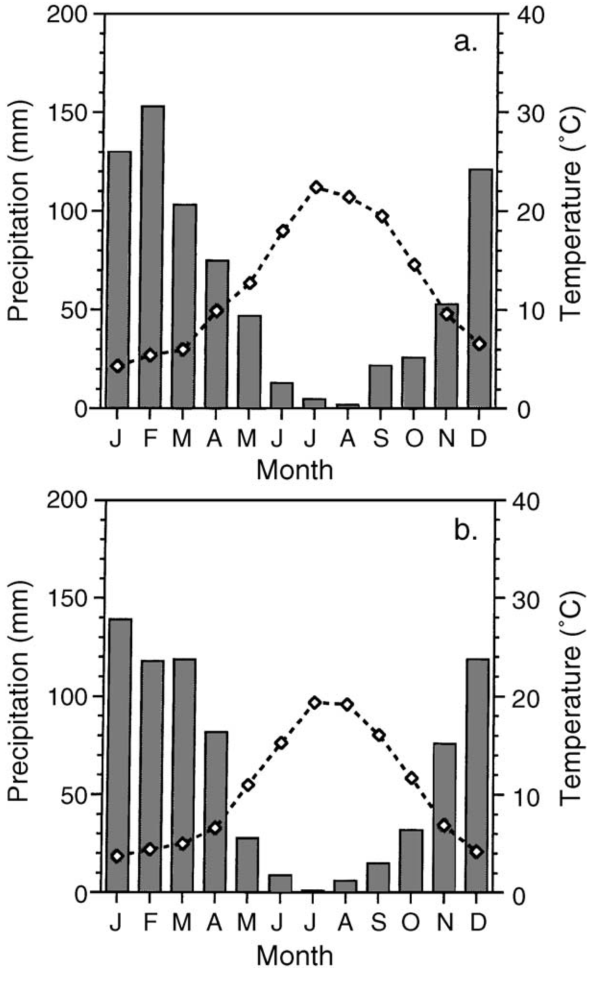

Fig. 2. Mean monthly precipitation and temperature at (a) Big Creek PH1, 15 km south of the Sierra N.F. site, and (b) Posey 3 E, 15 km south of the Sequioa N.F. site. The data for (a) are from 1948 to 2000, and the data for (b) are from 1954 to 1987.

On the Sequoia National Forest (Fig. 1), several sites within 3 km of each other were selected to examine the effect of variable soil and total regolith depths on the productivity of ponderosa pine, where weathered granitic bedrock is a regolith component. All sites were positioned on backslopes (6% to 30% gradient) with south-facing aspects. The vegetation of the area consists of an overstory of ponderosa pine, white fir, and incense cedar, and an understory of mountain whitethorn (*Ceanothus cordulatus*), greenleaf manzanita (*A. patula*), and mountain misery (*Chamaebatia foliolosa*). Tree basal areas at the sites ranged from 1 to 18 m^2 ha^{-1}, but were mostly (75%) <10 m^2 ha^{-1}. Tree ages ranged from 30 to 88 years. Elevation of the sites ranged from 1700 to 1950 m. An additional site amid those used for productivity assessments was used for intensive measurements of root distributions and regolith water dynamics in a stand of about 30-year-old Jeffrey pine and ponderosa pine. The trees were 8 to 10 m high and 0.25 to 0.30 m diameter. This site is at an elevation of 1950 m on a 10% slope facing northeast. The climate is similar to that at the Sierra National Forest site, as shown by data from a recording station at 1673-m elevation and 15 km south of the study area (Fig. 2b) (Posey 3 E; Western Regional Climate Center, 2002).

Soils at most of the sites, including the intensively studied site, were mapped as a Chawanakee (loamy, mixed, mesic, shallow Typic Dystroxerepts)–Rock outcrop–Chaix (coarse-loamy, mixed, mesic Typic Dystroxerepts) complex, while the deeper soils were mapped as a Holland (fine-loamy, mixed, mesic Ultic Haploxeralfs)–Dome (coarse-loamy, mixed, mesic Typic Dystroxerepts)–Chaix association (Hanes et al., 1981). The soils developed largely in quartz monzonite residuum. The weathered bedrock retained the original rock fabric, yet was friable and could be easily excavated with a spade or crushed to sand grains in one's hand. Nevertheless, the primary minerals in this regolith are not thoroughly altered to clay minerals, so it is not considered saprolite. The weathered rock mass was cut by joint sets that yielded fractures typically spaced 50 to 100 cm apart. At the productivity study sites, depth to weathered bedrock ranged from 20 to 300 cm, but was mostly (78%) between 40 and 120 cm. The soil and weathered bedrock characteristics at the intensively studied site are more completely described by Hubbert et al. (2001b).

Visual observations of rooting patterns were made in road cuts and in a trench 5 m long and 2.4 m deep excavated at the intensively studied site. The soil exposed in the trench was 80 cm deep to paralithic material (Cr horizon). Root length density (RLD) in the soil was measured using triplicate core samples (7.1 cm diameter and 10 cm long) taken in 15-cm depth increments to a depth of 60 cm immediately upslope from the trench. Within the bedrock, roots are restricted to fractures, so RLD was measured by taking triplicate samples from each root-containing fracture exposed in the trench. The samples were obtained by removing the material facing one side of the fracture, and cutting the roots out of an area of 10 by 15 cm from the fracture plane. The thickness of the fracture was represented by the diameter of the largest root confined in each fracture.

Water status at the intensively studied site was measured every 2 weeks during the dry season (April–October) in 1996 using a neutron probe. Measurements were made at 25-cm intervals in 10 hand-augered holes fitted with cellulose acetate butyrate access tubes and ranging in depth from 2.7 to 4.25 m, depending on depth to hard bedrock. Available water capacity (AWC) values for soil and weathered bedrock were determined using limits of -0.01 MPa (field capacity) and -2.2 MPa (permanent wilting point) as suggested for coarse-textured soils in natural systems (Cassel and Nielsen, 1986; Savage et al., 1996). Water retention curves were created using a pressure plate system to establish water potentials between -0.01 and -0.1 MPa (Klute, 1986) and the filter paper method to determine the potential of drier samples (Campbell and Gee, 1986). Gravimetric water contents were converted to volumetric using bulk densities determined by the paraffin-coated clod method (Blake and Hartge, 1986).

Several productivity indices were used on a single-tree basis. Thirty trees were measured for height, diameter at breast height, and age. These measurements were plotted against standard curves for site index (Dunning and Reinecke, 1933). Published equations were used to determine trunk volume (Wensel and Olsen, 1995) and total biomass (Little and Shainsky, 1995). These values were divided by age to determine mean annual increment in volume (MAI_{st}) and total biomass increment (TBI_{st}) on a single-tree basis.

At the productivity assessment sites, average soil depth was determined by augering at 1-m lateral distance from the trunk of the tree in the four cardinal directions. Depth to hard bedrock was determined using ground-penetrating radar. A Subsurface Interface Radar (SIR) System-2000 (Geophysical Survey Systems) with a 200-MHz antenna was used with scanning times of either 120 or 160 ns depending on depth of investigation. The instrument was calibrated in the field by burying a shovel blade at a known depth, and by augering to specific hard rock contacts appearing on radar records and calculating propagation velocity using the equation

$$V = 2D/T \quad (1)$$

where V is propagation velocity, D is depth, and T is the two-way pulse travel time. To predict depth to hard bedrock, a least square line was fitted to the data. The equation of this line

$$D = 0.06 + (0.088*T) \quad (2)$$

has a strong ($r = 0.961$; $p = 0.001$ level) relationship with the known data. The difference between predicted and measured depths ranged from -0.24 to 0.29 m. Data were gathered by making a radar survey in a complete circle around the tree of interest at a distance of 2 to 5 m from the trunk. When other trees prevented a complete circle, a semi-circle or two parallel traverses were surveyed around the tree.

The potential plant-available water (PPAW) was calculated by multiplying the thickness of soil and weathered bedrock by the appropriate AWC. The values calculated for the substrate around each tree were correlated with the productivity measurements of that tree. PAW values were also used to determine the percentage of PAW stored in the soil and weathered bedrock at various soil depths in a hypothetical 3-m regolith.

3. Results

3.1. Seedling root growth

The average length of the longest root of ponderosa pine seedlings increased from 0.5 to 1.3 m as age increased from 0.5 to 4 years (Table 1). Average seedling rooting depth

Table 1
Mean root length and depth of ponderosa pine seedlings growing in a soil derived from granitic rock

Age (years)	Root length (cm)	Root depth (cm)
0.5	52.1	47.2 (9.6)
1	80.4	65.2 (13.3)
2	101.2	76.0 (14.4)
3	135.8	102.1 (26.6)
4	125.8	90.8 (36.9)

Standard deviations are given in parentheses. $n=5$ for seedling ages 0.5 through 2 years and $n=4$ for seedling ages 3 and 4 years.

increased from 0.5 to 1.0 m over the same age group. The maximum root length and depth were exhibited by the 3-year-old seedlings.

3.2. Root distribution in established stands

Root length density averaged 2.5 cm cm^{-3} in the 0–60-cm depth of the soil and was higher in the bedrock fractures, averaging 4.3 cm cm^{-3} (Table 2). Even though we did not observe roots in the matrix of the weathered bedrock, the fracture RLD was recalculated to a whole rock basis for comparative purposes and was found to be <0.08 cm cm^{-3}. Those fractures with the highest RLD contained dense root mats. Many of the roots within the fractures were suberized. Pronounced heterorhizy of some roots within the joint fractures indicated mycorrhizal associations (Brundett et al., 1990). Pine roots were found in the deepest part of the trench (2.4 m), in material removed by augering to a depth of >4 m, and in nearby roadcuts to a depth of 6 m.

3.3. Water supplied by weathered bedrock

Because weathered bedrock in the Sierra Nevada is usually much thicker than the overlying soil, it has the potential to store much more plant-available water. The PPAW storage for the soil and weathered bedrock, assuming a combined regolith depth of 3 m, is shown in Table 3.

At the intensively studied site on the Sequoia National Forest, water held in the upper 75 cm of soil was depleted below the lower limit of plant availability by the end of June in 1996 (Fig. 3). Plant-available water was depleted from the 75- to 150-cm depth of weathered bedrock by August 19, but throughout the growing season (through October 10), there was still water available to plants in the 150- to 350-cm depth of the weathered

Table 2
Mean root length density for soil, fractures in weathered bedrock, and weathered bedrock as a whole

Rooting environment	Depth (cm)	Root length density (cm cm^{-3})
Soil	0–60	2.5 (1.19)
Joint fractures	80–240	4.3 (2.7)
Whole bedrock	80–240	<0.08 (nd)[a]

Standard deviations are given in parentheses. $n=12$ for soil and $n=21$ for joint fractures.
[a] nd = not determined.

Table 3
Amount of potential plant-available water (PPAW) that can be stored in the soil and weathered granitic bedrock components of a hypothetical 300-cm-thick regolith

Soil depth (cm)	PPAW	
	Soil (cm)	Bedrock (cm)
25	4.9	34.1
50	9.8	31.0
75	14.7	27.9
100	19.6	24.8
125	24.5	21.7
150	29.4	18.6
200	39.2	12.4
250	49.0	6.2

The assumed available water capacities are 0.196 m^3 m^{-3} for soils and 0.124 m^3 m^{-3} for weathered rock.

bedrock zone. The increase in soil moisture from May 17 to June 7 was due to a small (< 10 mm) rain event.

3.4. Productivity of established stands

Site index ranged from 40 to 70 (height in feet at 50 years) and MAI_{st} ranged from 7500 to 52,000 cm^3 $year^{-1}$. Site index of established stands of ponderosa pine was not affected

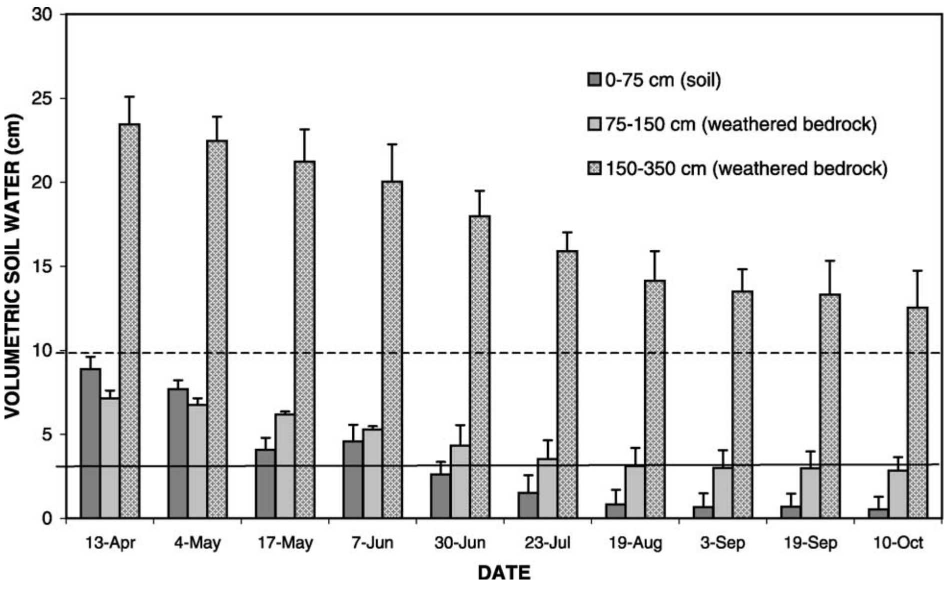

Fig. 3. Volumetric water content in soil and weathered granitic bedrock throughout the dry season in 1996 at the Sequoia National Forest site. Vegetation at the site is Jeffrey and ponderosa pine with an understory of greenleaf manzanita. Solid line at 3.75 cm represents the lower limit of plant-available water (matrix potential of − 2.2 MPa) in the 0–150-cm depth (soil and upper weathered bedrock zones). Dashed line at 10 cm represents the lower limit of plant-available water in the 150–350-cm zone of weathered bedrock.

Table 4
Relationships between substrate (soil, weathered bedrock, total regolith) thickness and productivity measurements

Y variable	Equation	95% CI		Standard error	*r*-value	*P*-value
		Slope	*Y*-intercept			
x = Soil depth (cm)						
Site index (m at 50 years)	$y = 0.002x + 17.5$	± 0.037	± 3.4	3.51	0.03	0.90
MAI_{st} (cm^3/year)	$y = 52.5x + 12{,}891$	± 124	± 11,464	11,927	0.20	0.39
TBI_{st} (kg/year)	$y = 902x + 153{,}260$	± 1075	± 99,232	103,243	0.37	0.10
x = Weathered bedrock thickness (m)						
Site index (m at 50 years)	$y = -0.57x + 19.1$	± 1.3	± 3.5	3.43	0.21	0.39
MAI_{st} (cm^3/year)	$y = 3255x + 9199$	± 4216	± 11,550	11,412	0.35	0.12
TBI_{st} (kg/year)	$y = 12{,}011x + 197{,}163$	± 40,719	± 111,547	110,208	0.14	0.54
x = Total regolith thickness (m)						
Site index (m at 50 years)	$y = -0.66x + 19.8$	± 1.4	± 4.8	0.22	0.22	0.34
MAI_{st} (cm^3/year)	$y = 4774x + 1608$	± 4403	± 15,166	0.46	0.46	0.04
TBI_{st} (kg/year)	$y = 28{,}485x + 133{,}746$	± 43,292	± 149,107	0.30	0.30	0.18

Mean annual increment (MAI_{st}) and total biomass increment (TBI_{st}) are reported on a single-tree basis. ($n = 21$).

by the thicknesses of soil, weathered bedrock, or total regolith (Table 4). The MAI_{st} was not significantly affected by soil thickness alone, but the increased thickness of including weathered bedrock (total regolith depth) seemed to improve the correlation coefficient. The TBI_{st} was slightly affected by soil depth, but was less affected by total regolith depth and weathered rock thickness. Except for TBI_{st}, the relationship between PPAW storage and the productivity measurements was stronger when the PPAW storage capacity included the weathered bedrock (Table 5).

Table 5
Relationships between productivity measurements and soil or total regolith potential plant-available water (PPAW)

Y variable	Equation	95% CI		Standard error	*r*-value	*P*-value
		Slope	*Y*-intercept			
x = Soil PPAW (cm)						
Site index (m at 50 years)	$y = 0.01x + 17.53$	± 0.19	± 3.4	3.5	0.03	0.90
MAI_{st} (cm^3/year)	$y = 268x + 12{,}891$	± 633	± 11,464	11,927	0.20	0.39
TBI_{st} (kg/year)	$y = 4601x + 153{,}260$	± 5483	± 99,232	103,243	0.37	0.10
x = Total regolith PPAW (cm)						
Site index (m at 50 years)	$y = -0.05x + 20$	± 0.11	± 5.4	3.4	0.21	0.36
MAI_{st} (cm^3/year)	$y = 417x - 2122$	± 343	± 16,593	10,515	0.50	0.02
TBI_{st} (kg/year)	$y = 2905 \times 92{,}195$	± 3358	± 162,208	102,791	0.38	0.09

$n = 21$.

4. Discussion

In shallow or moderately deep soils (< 1 m) of the Sierra Nevada, the roots of ponderosa pine seedlings will likely encounter weathered bedrock within 2 to 3 years of growth. Roots can penetrate deeper, into the bedrock zone, if they encounter fractures. Granitic bedrock holds very little water when it is hard and relatively unweathered (Jones and Graham, 1993), but when it is weathered to a friable state, it has an appreciable AWC (0.124 m^3 m^{-3}), although lower than that of the overlying soils (0.196 m^3 m^{-3}) (Hubbert et al., 2001b). So, while a very deep soil can hold more plant-available water, a thick zone of weathered bedrock underlying a thin soil can also supply a substantial amount of stored water, assuring survival of pine seedlings through the summer dry period that characterizes most of California's forests.

Roots of mature pine deeply penetrate the weathered bedrock zone, but are restricted to fractures because pores in the intervening weathered rock matrix tend to be too small for most to enter (< 100 μm) (Frazier and Graham, 2000). As a result, roots are concentrated as mats within fractures. Root length densities are commonly greater in the fracture environment than in the overlying soil, despite a low density in the bedrock as a whole. Ectomycorrhizal hyphae associated with the roots of oak (Bornyasz et al., 2002) and chaparral shrubs (Egerton-Warburton et al., in press) have been found to penetrate the matrix porosity of weathered granitic bedrock. Such hyphae have been shown to transport water to the host roots (Duddridge et al., 1980) and, we suspect, are critical to the ability of pine to exploit weathered bedrock as an effective rooting medium.

Since soils in the Sierra Nevada are often less than 1-m thick and the weathered bedrock zone is much thicker, plant-available water storage in the weathered bedrock is potentially a major contributor to forest water relations (Table 3). The water depletion pattern shown in Fig. 3 demonstrates that the 0–75-cm soil zone is insufficient to satisfy the water requirements of the forest during the summer dry season. Water was extracted from throughout the weathered bedrock thickness to a depth of at least 3.5 m, and even at the end of the dry season, some plant-available water remained. In this case, at least 70% of the water used by the forest during the growing season was extracted from the weathered bedrock. This bedrock-held water is essential to the survival and productivity of forests in much of California.

The relationships between productivity and the thicknesses and PPAW of the various regolith types were not strong. This is likely because a variety of site history and environmental factors, in addition to substrate, influence productivity (Powers and Oliver, 1978). While the influence of climate and parent material should be roughly constant among sites in this study, observed variations in understories and basal areas indicate that differences in site history are likely. In central Oregon, a 40% increase in diameter and 60% increase in height of pine saplings were observed 4 years after the removal of understory brush (Barret, 1965). Nevertheless, productivity as measured by mean annual increment is more completely explained by the inclusion of weathered bedrock than by soil alone (Tables 4 and 5). The presence of weathered granitic bedrock at a shallow depth is not a detriment to the survival and long-term productivity of ponderosa pine, instead it functions as an additional thickness of soil. The critical measurement relative to water supply is total regolith thickness (i.e., depth to hard bedrock).

5. Conclusions

When only a few years old, ponderosa pines in the Sierra Nevada have extended their roots into the subsoil weathered bedrock, from which they extract stored water. If the overlying soils are relatively thin (< 1 m), a thick zone of weathered bedrock will supply most of the water required by established stands of pine during the dry summer season. In this respect, weathered bedrock is an important contributor to forest soil quality in mediterranean ecosystems. It enhances site productivity and is, in fact, essential to the survival of the existing forest communities.

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