

AN ABSTRACT OF THE THESIS OF

Maciej A. Zwieniecki for the degree of Doctor of Philosophy in Forest Science presented on June 21, 1995. Title: Meta-Sedimentary Bedrock as an Alternative Source of Water for Forest Ecosystems in a Mediterranean Climate.

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Michael Newton

Evaluation of meta-sedimentary bedrock as a source of stored water available to plants in a mediterranean climate is presented based on: root length distribution (RLD), root morphology, rock water holding capacity and seasonal pattern of water depletion. Studies were performed in southwestern Oregon under young stands of whiteleaf manzanita, ponderosa pine, Douglas-fir and Pacific madrone. RLD analysis shows that more then one quarter of the total root length of ericaceous plants is located in the rock layer. Stepwise procedures identified the best fitting multiple-regression model for relating RLD to depth, bulk density of rock and the space penetrable by roots (SPR). Linear expressions of SPR and depth were found to be significant explanatory variables.

Roots of manzanita and madrone occupy rock fissures as small as 100 um. The root stele remains cylindrical in shape without visible mechanical stress, the cortex became flat, creating "wing-like" structures on each side of the stele. Fine particles

that fill the space between root cortex and rock matrices create a continuous conduit for water flow.

Pore volume distribution of rock was measured in four functional ranges of pore size: gravitational water, available water content (AWC), slowly available water (SAW) and unavailable water (UW). An appreciable amount of pore volume is present within the AWC and SAW, ranging downward from 20% of total rock volume in rock at a density of 2.1 to negligible at density 2.67 grams per cubic centimeters. End-of-summer water content measured in-site in the field and bio-assay results shows that plants extract this water from the rock matrix during the typical water stress of a mediterranean type summer.

Water depletion from soil/rock profile follows distinct patterns according to vegetation type, based on neutron probe measurements from aluminum access tubes 3.2 m deep. Measurements were taken during two growing seasons (1993 and 1994) under pure cover of the above species. Both conifers show very limited ability to utilize water from bedrock. Ericaceous plants were very efficient in depletion of water from the rock layers, using all available water measured by the access tubes. Water resources used by both types of plants overlaps considerably and competition will be very strong in species mixtures. Ability to utilize bedrock water by ericaceous plants appears to offer a major competitive advantage.

**Meta-Sedimentary Bedrock as an Alternative Source of Water for Forest Ecosystems  
in a Mediterranean Climate**

by

**Maciej A. Zwieniecki**

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Maciej A. Zwieniecki, Author

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# Meta-Sedimentary Bedrock as an Alternative Source of Water for Forest Ecosystems in a Mediterranean Climate.

## 1. Introduction

Plants growing in Mediterranean climate experience prolonged summer drought leading to severe water stress. Shallow soils, being very common in this climate, significantly contribute xeric condition of sites. In search for water many plants of shrubland communities developed root system being able to utilize deep water resource. A few of those grow roots into the fractured bedrock.

Following I present four papers describing basic features of the Mediterranean sclerophyll forest sites in terms of possible utilization of bedrock as an alternative source of water.

In chapter one root length distribution (RLD) in soil/rock profile under woody vegetation in southwestern Oregon is presented. Distribution pattern is associated with depth bulk density and space available to root growth.

In chapter two basic morphological features of roots growing in rock fissures are described with their implication to water uptake facilitation.

In chapter three meta-sedimentary rock is characterized in terms of its water holding capacity. Total water holding capacity is divided into four basic ranges gravitational water, available water content (AWC), slowly available water (SAW) and unavailable water (UW).

In chapter four quantitative analysis of water depletion from soil/rock profile under four type of woody communities in southwester Oregon is presented. Measurements were taken during two following vegetation season down to 3.25 m into the bedrock layer.

All four papers present a complete picture of meta-sedimentary rock as a potential alternative source of water by compiling knowledge about rooting pattern,

morphological adaptation potential amount of water stored in bedrock and direct measurements of water depletion.

## 2. Root distribution of 12-year-old forests at rocky sites in southwestern Oregon: Effects thereon of rock physical properties

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### 2.1 Abstract

Distribution of root length density (in terms of cm of fine and large roots per cm<sup>3</sup> of soil and bedrock) was analyzed at harsh forest sites supporting 12-year-old stands of pure whiteleaf manzanita (Arctostaphylos viscida Parry), pure ponderosa pine (Pinus ponderosa Dougl. ex Laws.), or mixtures of Pacific madrone (Arbutus menziesii Pursh) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) in southwest Oregon. On such sites, soil (usually <50 cm deep) dries below the wilting point of plants before the middle of the growing season. Bedrock there contains enough water to support a dense stand of woody plants. The study shows that about 1/4 to 1/3 of the total root length is located in the rock layer. Stepwise procedures were applied to find the best-fitting multiple regression model for relating root length density to depth, bulk density of the soil and rock, and SPR (space penetrable by roots). Linear expressions of SPR and depth were found to be the only significant explanatory variables. Bulk density had very limited explanatory power, reflecting high general density of the bedrock containing the water but lower density of the fine material in minuscule fissures in which roots were found.

## 2.2 Introduction

Studies of root distribution show that root growth is strongly influenced by physical properties of the soil, such as bulk density or soil impedance (Bennie 1991; Ares and Peinemann 1992; Wang *et al.* 1994). Compacted soil with high bulk density creates high mechanical resistance to root growth, and penetrability of such soil by roots is very small (Glinski and Lipiec 1990; Laryea *et al.* 1991). Distribution of roots in soil profiles is usually shown as a function of depth and mechanical resistance or bulk density (Menzel *et al.* 1990; Bennie 1991). Root-impeding layers close to the soil surface will restrict downward root growth and rooting depth will be shallow (Ehlers *et al.* 1983; Chaudhary *et al.* 1985; Bennie and Botha 1986; Balneares and de la Mare 1989). However, measurements also show that transpiration at such sites does not stop even when soil water potential drops below the wilting point during the summer (M. Newton, unpublished data).

We report here on the question of whether deeper strata are occupied by roots and whether the rock is a substrate that provides plants with water and nutrients. The main objectives of this study were to determine root distributions in soil/rock profiles and to determine which physical properties of the bedrock possibly explain the observed distributions.

## 2.3 Methods

Two sites in southwestern Oregon were selected on the basis of proximity to above-ground studies. In both areas, 85% of the total annual precipitation (600 mm on one area and 1040 mm on the other) occurs during winter. In both, the residual clay loam soil is very shallow, 20–50 cm deep, and the underlying rock material is described as slightly to moderately weathered meta-sedimentary rock. Detailed descriptions of the areas are given in Wang *et al.* (1994) and White and Newton (1989).

At each site, two soil/rock profiles 4 m deep were blasted with dynamite and excavated with a small backhoe. Loose rubble was removed by shovel until only the intact rock profile remained, unaffected by the excavation or blasting.

At one site, both of the profiles (hereafter referred to as S1 and S2) supported a 12-year-old mixed forest of Pacific madrone (Arbutus menziesii Pursh) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). At the other site, one of the profiles supported a cover of pure 12-year-old ponderosa pine (Pinus ponderosa Dougl. ex Laws.) and the other supported a cover of 12-year-old pure whiteleaf manzanita (Arctostaphylos viscida Parry). The four forest covers are described in Table 2.1. Soil/rock samples were taken from seven depths, at intervals of 50 cm. Each sample represented a layer 10 cm thick. Three samples per layer were randomly collected. However, at one location, additional samples were collected because material of unusually low density was present; these samples are shown as separate points and were not used in statistical analyses. Volume of each sample was about 2 dm<sup>3</sup> for rock and 0.5 dm<sup>3</sup> for soil.

Table 2.1. Stand characteristics of the forest covers supported by the four soil profiles sampled.

| Species composition                     | Trees/ha<br>(thousand) | Basal area | Average height |
|---|------------------------|------------|----------------|
| whiteleaf manzanita<br>100%             | 4.6                    | 29.8       | 1.11           |
| Ponderosa pine 100%                     | 12.0                   | 25.9       | 3.27           |
| Douglas-fir 8%;<br>Pacific madrone 92%  | 18.0                   | 39.6       | 4.05           |
| Douglas-fir 14%;<br>Pacific madrone 86% | 20.0                   | 40.6       | 4.43           |

Root length density (RLD) of both live and dead roots in terms of cm of fine and large roots per cm<sup>3</sup> of soil and bedrock was determined for each sample. (All rocks were crushed gently to permit collection of all roots present in minute cracks.) All

roots were separated by hand into two categories according to diameter:  $< 1$  mm (fine) and  $> 1$  mm (large). Because the roots growing in cracks had unusual morphology, they were separated on the basis of observable function: dark, suberized roots providing transport were classed as large; light-colored roots providing uptake were classed as fine.

While root length was being determined by hand measurements, fine material filling the rock cracks was removed and put through a 1-mm sieve. The sampled rock and fine material were then dried and weighed. The ratio of fine material ( $< 1$  mm) to rock (in terms of g of crack-filling medium/g of rock) was determined and was considered to be representative of the space penetrable by roots (SPR). In all rock samples, the volume of fine material was  $< 1\%$  of the total.

Rock/soil samples, each 100–200 cm<sup>3</sup>, were used to determine bulk density. These samples were dried in an oven at 110°C for 3 days, then weighed. Exact volume was measured by submerging each sample in distilled water (at 20°C); weight of the displaced water was recorded and volume was calculated. This method was used to avoid dissolving and removing fine material from the surface and cracks of the rock. The same method was used for soil samples because such samples were compacted in the form of large aggregates. Before being submerged, each sample was coated with waterproof seal to prevent water-absorption.

The statistical design concentrated on collection of rock/root samples encompassing an appropriate range of depth, bulk density, and SPR. Analyses were performed separately for each profile. Simple linear regressions of RLD on each of five variables were first run; then backward stepwise procedures were used to derive the best-fitting model (incorporating all five variables) for each profile (Sokal and Rohlf 1981). The five variables used were depth, depth squared, bulk density of soil and rock, SPR, and SPR squared. Square root transformation was used for RLD; residuals did not show any evident patterns.

## 2.4 Results

Rock type in all four profiles was similar. Bulk density varied from 2.0 to 2.7 g/cm<sup>3</sup> and increased with depth. (Unweathered meta-sedimentary rock normally ranges from 2.65 to 2.75 g/cm<sup>3</sup>.) Rock matrices were cracked. Crack size varied from less than 100  $\mu$ m to 1 cm. Cracks were usually filled with fine material (clay, silt, fine sand). Occasionally, cracks < 1 mm wide were filled with mats of roots, mostly below the madrone and manzanita cover.

Distribution of root length density (RLD) of fine and large roots in rock samples is shown in Fig. 2.1. Separate scales were used for the top layer of soil and the lower rocky strata. In each profile, the top layer (0–10 cm) had about 10 times more RLD than did any other layer. RLD in the rock zone was highly variable, suggesting that depth, as well as other variables, should be used to explain root distribution. There were no obvious differences among vertical RLD distributions in the various profiles except that RLD was highest in the top layers at the two madrone/Douglas-fir sites, which also had the highest aboveground biomass. Total root lengths (in both soil and rock) per m<sup>2</sup> of surface area are shown in Table 2.2. In all cases, nearly 1/4 to 1/3 of all fine roots were located in bedrock medium.

Table 2.2. Total length of fine and large roots in relation to surface area and soil medium at the four sites.

| Root type | Medium | Root length (m) per m <sup>2</sup> of surface area |                     |                         |      |
|-----------|--------|--|---------------------|-------------------------|------|
|           |        | Pure manzanita                                     | Pure ponderosa pine | Madrone and Douglas-fir |      |
|           |        |  |                     | S1                      | S2   |
| Fine      | Soil   | 1325   | 630                 | 1486                    | 2128 |
|           | Rock   | 301  | 204                 | 390                     | 441  |
| Large     | Soil   | 12   | 20                  | 36                      | 52   |
|           | Rock   | 7  | 26                  | 11                      | 10   |

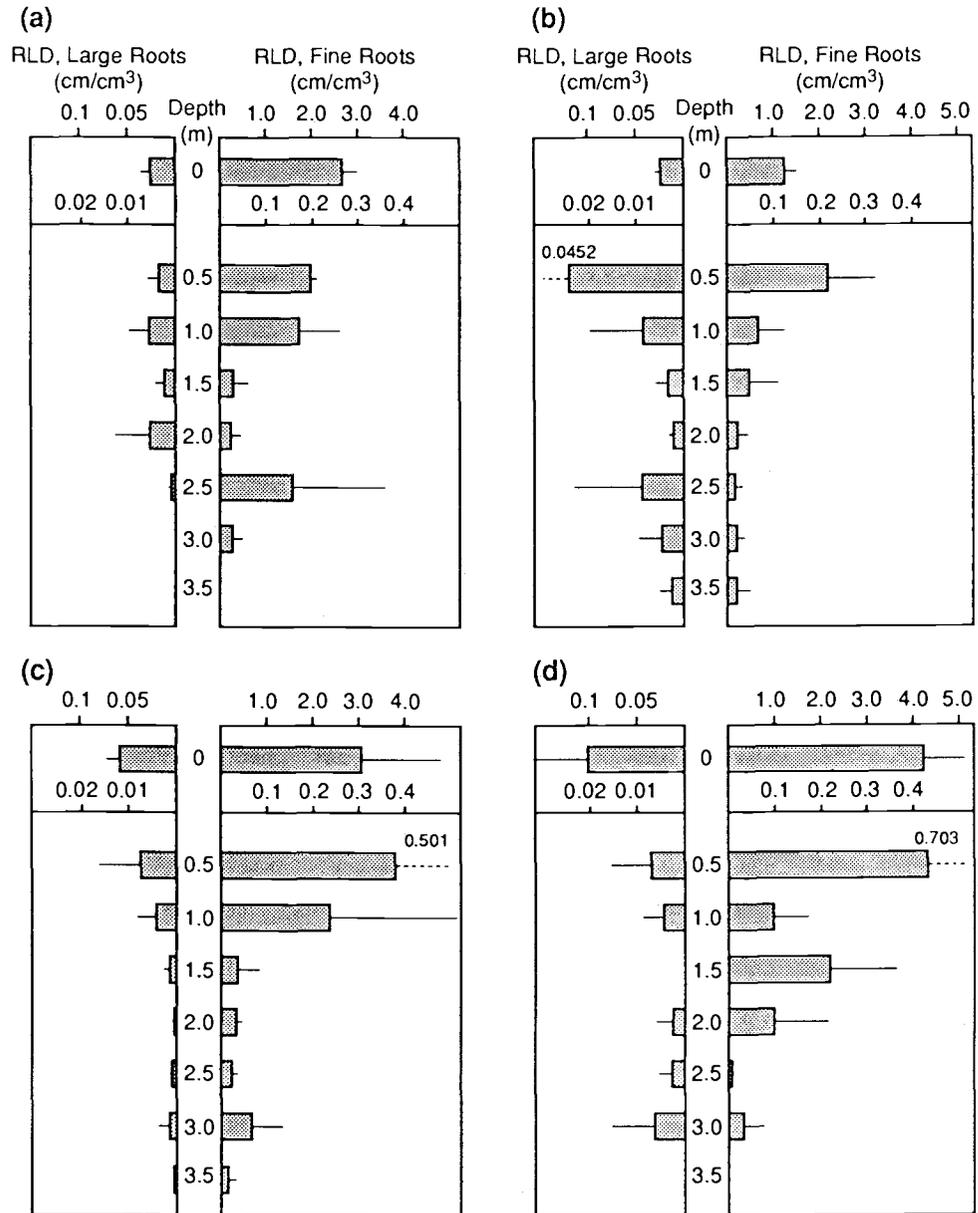


Figure 2.1. Distribution of root length density in soil profiles supporting (a) pure manzanita, (b) pure ponderosa pine, and mixtures of madrone and Douglas-fir (profile S1 shown in c and profile S2 in d). Horizontal lines indicate SD. In a few cases, SD was too large to show on graph and is indicated by a broken line and a value. Note change in scale below soil/rock interface.

Scatter plots (Fig. 2.2) show the relationships between RLD of fine roots and both bulk density and SPR (space penetrable by roots). They demonstrate continuity with SPR regardless of the medium in which roots are found. The change in RLD at the transition from rock to soil does not illustrate any shift in responsiveness to SPR with depth or bulk density.

For each profile, the backward stepwise procedure was used to find the best-fitting multiple-regression model for relating RLD of fine roots to the five tested variables (Table 2.3). In each case, SPR emerged as one of the best explanatory variables. In one case, the model included depth and depth squared, and in two cases it included SPR squared. Bulk density was not chosen by this procedure as a useful explanatory variable in any model. All fitted models were significant ( $P < 0.02$ ) (see breakdown of variation in Table 2.4), with  $R^2$  adjusted between 0.26 and 0.73. Forcing bulk density into the model did not further explain the RLD variation and seemed unnecessary for predictive purposes.

Table 2.3. Partial coefficients for the variables chosen by the backward stepwise procedure to be included in the model describing the association between RLD and the chosen variables, by soil profile supporting a cover type a,b.

| Variable                    | Partial coefficient in model for profile |                     |                         |                |
|-----------------------------|--|---------------------|-------------------------|----------------|
|                             | Pure manzanita                           | Pure ponderosa pine | Madrone and Douglas-fir |                |
|                             |  |                     | S1                      | S2             |
| $b_0$ (constant)            | -0.01 (0.7450)                           | 0.40 (0.0041)       | 0.12 (0.0041)           | 0.41 (0.0001)  |
| $b_1$ (SPR)                 | 7.12 (0.0001)                            | 2.29 (0.0016)       | 4.08 (0.0179)           | 7.48(0.0134)   |
| $b_2$ (SPR <sup>2</sup> )   | -24.53 (0.0075)                          | N/A                 | N/A                     | -48.8 (0.0189) |
| $b_3$ (depth)               | N/A                                      | -0.29 (0.0084)      | N/A                     | N/A            |
| $b_4$ (depth <sup>2</sup> ) | N/A                                      | 0.06 (0.0220)       | N/A                     | N/A            |

Note: The generalized model was of the form  $RLD = b_0 + b_1(\text{SPR}) + b_2(\text{SPR}^2) + b_3(\text{depth}) + b_4(\text{depth}^2) + b_5(\text{bulk density})$ . Bulk density was never selected by stepwise procedure for inclusion in the model. N/A, variable was not selected by stepwise procedure for inclusion in the model. Parenthetical values are the  $\alpha$ -levels of the parameters.

Table 2.4. Results of tests of significance in multiple-regression models chosen by backward stepwise procedure, by soil profile supporting a cover type.

| Cover type supported by soil profile         | Source of variation | Sum of squares | df | Mean square | Adjusted |                |         |
|--|---------------------|----------------|----|-------------|----------|----------------|---------|
|  |                     |                |    |             | F        | R <sup>2</sup> | P       |
| Pure manzanita                               | Model               | 0.53663        | 2  | 0.26832     | 26.4016  | 0.72           | <0.0001 |
|  | Error               | 0.17277        | 17 | 0.01016     |          |                |         |
|  | Total               | 0.70940        | 19 |             |          |                |         |
| Pure ponderosa pine                          | Model               | 0.17216        | 3  | 0.05739     | 6.854    | 0.48           | 0.0094  |
|  | Error               | 0.13396        | 16 | 0.01001     |          |                |         |
|  | Total               | 0.30612        | 19 |             |          |                |         |
| Madrone and Douglas-fir (S1 profile beneath) | Model               | 0.07803        | 1  | 0.07803     | 6.959    | 0.26           | 0.0179  |
|  | Error               | 0.17941        | 16 | 0.01121     |          |                |         |
|  | Total               | 0.25745        | 17 |             |          |                |         |
| Madrone and Douglas-fir (S2 profile beneath) | Model               | 0.74024        | 3  | 0.24675     | 14.7733  | 0.63           | <0.0001 |
|  | Error               | 0.35075        | 21 | 0.01670     |          |                |         |
|  | Total               | 1.09098        | 24 |             |          |                |         |

## 2.5 Discussion

Our data show that partly weathered meta-sedimentary rock beneath a shallow soil is a substantial medium for root growth. The volume of fine material in fissures is so small as to contribute negligible storage capacity, but this volume is adequate to provide access by fine roots to the rock in which considerable water is stored (Wange *et al.* 1994). In fact, about 25–33% of the total root length beneath the sampled sites is located there. Indeed, this percentage may be even higher because there was some evidence of deeper root penetration. Hellmers *et al.* (1955) found that many chaparral and conifer species in southwestern California have root systems that penetrate far

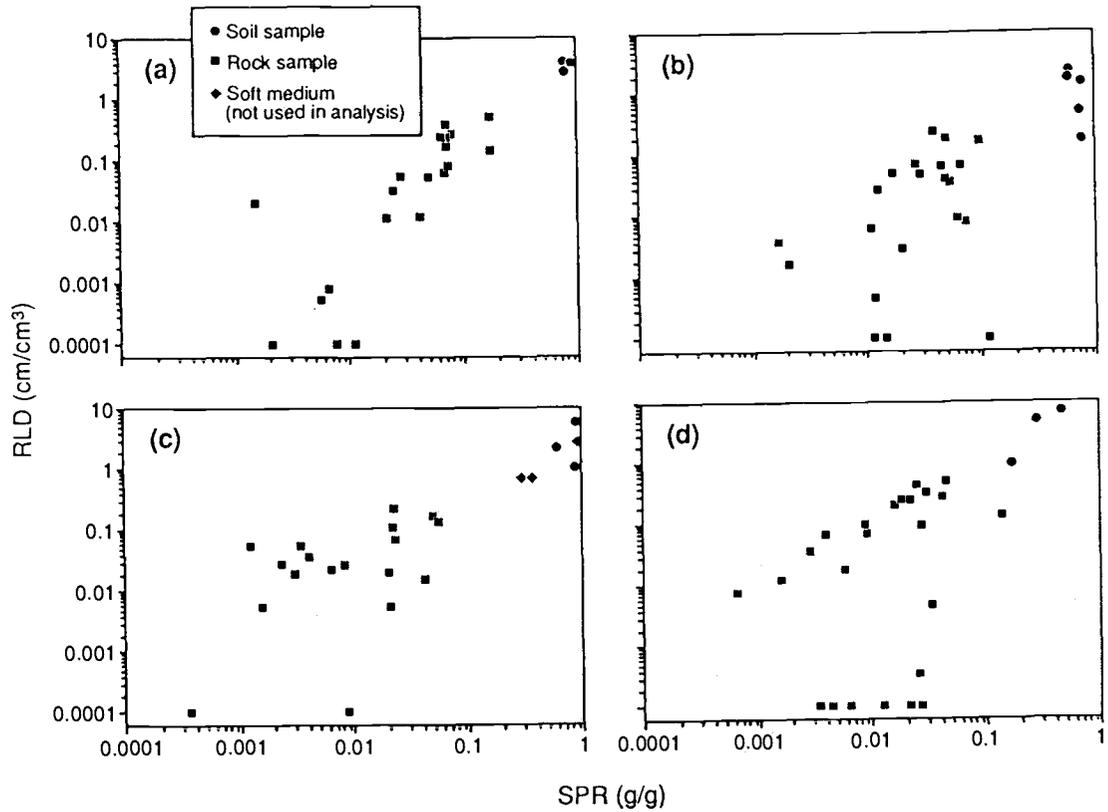


Figure. 2.2. Root length density of fine roots regressed against the space penetrable by roots (SPR) in soil profiles supporting (a) pure manzanita, (b) pure ponderosa pine, and mixtures of madrone and Douglas-fir (profile S1 shown in c and profile S2 in d).

below the lower boundary of the soil and extend  $> 8.5$  m into the bedrock. Stone and Kalisz (1991) tabulate information about 29 species from around the world whose roots extend into the bedrock to a depth of 60 m.

Even a modest fraction of roots present in bedrock can support plant growth if water and solutes are adequate. It has already been noted that chaparral and, to some extent, trees at the sampled sites continue to transpire long after water in the top shallow soil has dropped below the wilting point of plants. Nevertheless, many authors restrict their analysis of the vertical distribution of roots to only the top layers of soil  $< 50$  cm deep (Ares and Peinemann 1992; Ehrenfeld *et al.* 1992), reporting that 60–80% of the total root weight is located in this layer (as, indeed, it is in our findings also). However, in our case these shallower roots function as absorbers only during the wet season; after the soil dries to the wilting point, the deeper roots become the main source of water and nutrients, as has been recently noted by Wang *et al.* (1993). Thus, the usual convention of presenting distribution of vertical root biomass can be misleading at rocky sites. In our study, examination of the morphology of roots in the rock matrix showed that the roots from small fissures were usually very flat and that the ratio of length to mass was very high. These relationships would obviously influence the efficiency of root uptake per gram of biomass and thus increase the relative role of the deeper roots.

One of the main objectives of this study was to determine the factors influencing RLD distribution. Depth was considered as one of these factors. Menzel *et al.* (1990) reported that 62% of the lychee tree's root density variation in soil can be explained as a curvilinear function of depth. Similar results were reported by Ares and Peinemann (1992) for some conifer species growing on shallow soil. Both of these studies restrict their analysis to the top 50 cm; hence, behavior in rock cannot be ascertained. Our study shows that, in the rock layer, only about 8% to 30% of the total variation in RLD distribution was explained by depth (when depth was used as the only variable in the initial linear regression model).

Soil impedance, which is associated mainly with bulk density, has been used to explain RLD distribution for several crop plants: maize (Shibusawa and Araki 1990),

corn (Vepraskas and Wagger 1990), wheat (Huang and Liu 1989), and trees like the banana (Dorel 1990). However, if we consider that the water-holding characteristics of rock are inversely correlated with its bulk density (Jones and Graham 1993; Wang et al. 1993) and that root distribution on forested sites is largely determined by the total availability of water (Nizinski and Saugier 1989), then the explanatory power of bulk density in our study ( $r^2$  adjusted values range from 5% to 25%) is much below expectation. In our study, bulk density of rock ranged from 2.0 to 2.7; rocks of such high densities are usually considered impenetrable by roots. Roots do not grow in solid rock matrices; however, they form mats of feeder roots in large fissures (Hellmers et al. 1955). Such mats were found in some of the shallower cracks in this study. Thus, rock bulk density has less explanatory power than does soil bulk density, but the presence of fissures penetrable by roots is a very important rock property in terms of creating space for root growth. This important variable—calculated as the ratio of the dry weight of fine material filling rock fissures to the total weight of rock in the sample—was incorporated into our model as space penetrable by roots (SPR). The explanatory power of SPR in the separate models was about double that of any other variable. The backward stepwise procedure always resulted in SPR being chosen as the variable with the most explanatory power.

## 2.6 Conclusions

On rocky sites with relatively shallow soils, tree roots present in the rock layer can tap water and nutrients held there and thus support the trees during a prolonged drought. Currently used methods that restrict the investigation of vertical root distribution to the top 50–90 cm of soil should be modified to include any bedrock with measurable fissures.

Instead of rock bulk density, space penetrable by roots (in terms of the ratio of the weight of fine material in fissures to the total weight of the rock sample) should be used to explain the distribution of root length density in rock.

## 2.7 Acknowledgements

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### 3. Roots growing in rock fissures: Their morphological adaptation

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#### 3.1 Abstract

On sites with shallow soil in semi-arid climate conditions, whiteleaf manzanita (Arctostaphylos viscida) and Pacific madrone (Arbutus menziesii) utilize water from the bedrock. Roots of these plants occupy rock fissures as small as 100  $\mu$ m. Although the root stele remains cylindrical in shape without visible mechanical stress, the cortex may become flat, creating "wing-like" structures on the sides of the stele. Fine particles of soil and rock that fill the space between root cortex and rock matrices create good contact for water flow.

#### 3.2 Introduction

Little is known about the growth and function of roots growing in rock fissures. These roots can be critically important for plants growing in semi-arid conditions in Mediterranean climates where soil is shallow and summer water needs must be met from deep in bedrock.

More than 80 years ago, Cannon (1911) described the "intimate" association between rock and roots of the cactus Opuntia discata. He also suggested that rock can retain and conduct water better than bare soil. Other early work showed that many of

the dominant woody species growing in arid and semi-arid conditions have dual root systems. Shallow, superficial roots operate during spring, and the deep penetrating part of the root, usually located in relatively unweathered bedrock, operates during dry summers (Cannon, 1924; Cooper, 1922). Cooper also suggested that the role of deep roots is limited to supplying plants with some minimum amount of water to tide them over the critical dry summer period. Later, Zohary and Orhansky (1951) and Oppenheimer (1956, 1957) described the phenomenon of summer-long transpiration by deep-rooted plants growing on shallow residual soil or even on bare rock in Israeli maquis. They concluded that roots growing in fissures are the major water supplier.

More recent work has evaluated the significance of bedrock for water storage. Jones and Graham (1993) observed that available water content (AWC) in weathered granite rock can be 12–14% of total rock volume; for some sedimentary rock, it can be 8–22% (Kummerow, 1981), and AWC varies with the bulk density of the rock (Wang *et al.*, 1995). Wang *et al.* also showed that water depletion from bedrock caused by woody vegetation in southern Oregon is approximately 200 mm/year. Similar results were obtained in vineyards in France (Duteau, 1987).

This paper describes some morphological features of roots that grow in rock fissures and take up water. Moreshet and Huck (1989) state that understanding the cellular anatomy of root tissue is critically important for describing water movement into and through the roots. We explore the morphology of roots in fissures, where roots of *Arctostaphylos viscida* Parry (whiteleaf manzanita) and *Arbutus menziesii* Pursh (Pacific madrone)—woody species of the USA's Pacific Northwest—depleted water from subsurface rock.

### 3.3 Methods

Four 4-m-deep soil/rock profiles were opened up by drilling and blasting with low-velocity dynamite. The use of low-velocity dynamite prevented major changes in rock structure on the vertical 2-m-wide profile headwalls (Fig. 3.1).

Profiles were located on experimental sites under cover of 12-year-old *A. viscida*, *A. menziesii*, and *Pinus ponderosa* Dougl. ex Laws. (ponderosa pine). Sites were characterized by soil less than 40 cm deep—gravelly or clayey loams of the Vermisa and Beekman series. Beneath the soil was a lightly to moderately weathered sedimentary rock layer with density ranging from 2.05 to 2.67 g/cm<sup>3</sup> (Fig. 1). Sites were located in southwestern Oregon (USA), where a Mediterranean climate includes hot summers, mild winters, and precipitation of 600–1200 mm/year; 87% of this precipitation falls during the winter months. Detailed description of sites and vegetation complex is given in Pabst *et al.* (1990), Wang *et al.* (in press), and White and Newton (1989).

Rock samples (2–4 dm<sup>3</sup>) were collected from headwalls at 0.5-m depth intervals and immediately transported to the laboratory. Crack sizes were estimated under the microscope, and then the samples were broken along the lines of the cracks by hand or with a hammer and chisel. After breaking, surfaces of the rock showing evidence of weathering were investigated microscopically for roots. This procedure was repeated with progressively finer division of samples until no roots were found in newly opened fissures. The roots were collected, and free-hand transverse sections were cut for investigation of radial morphology.

### 3.4 Results

An important feature of root systems, as we found them, is their non-uniform distribution within the profile. Roots were concentrated in the large fissures and low-

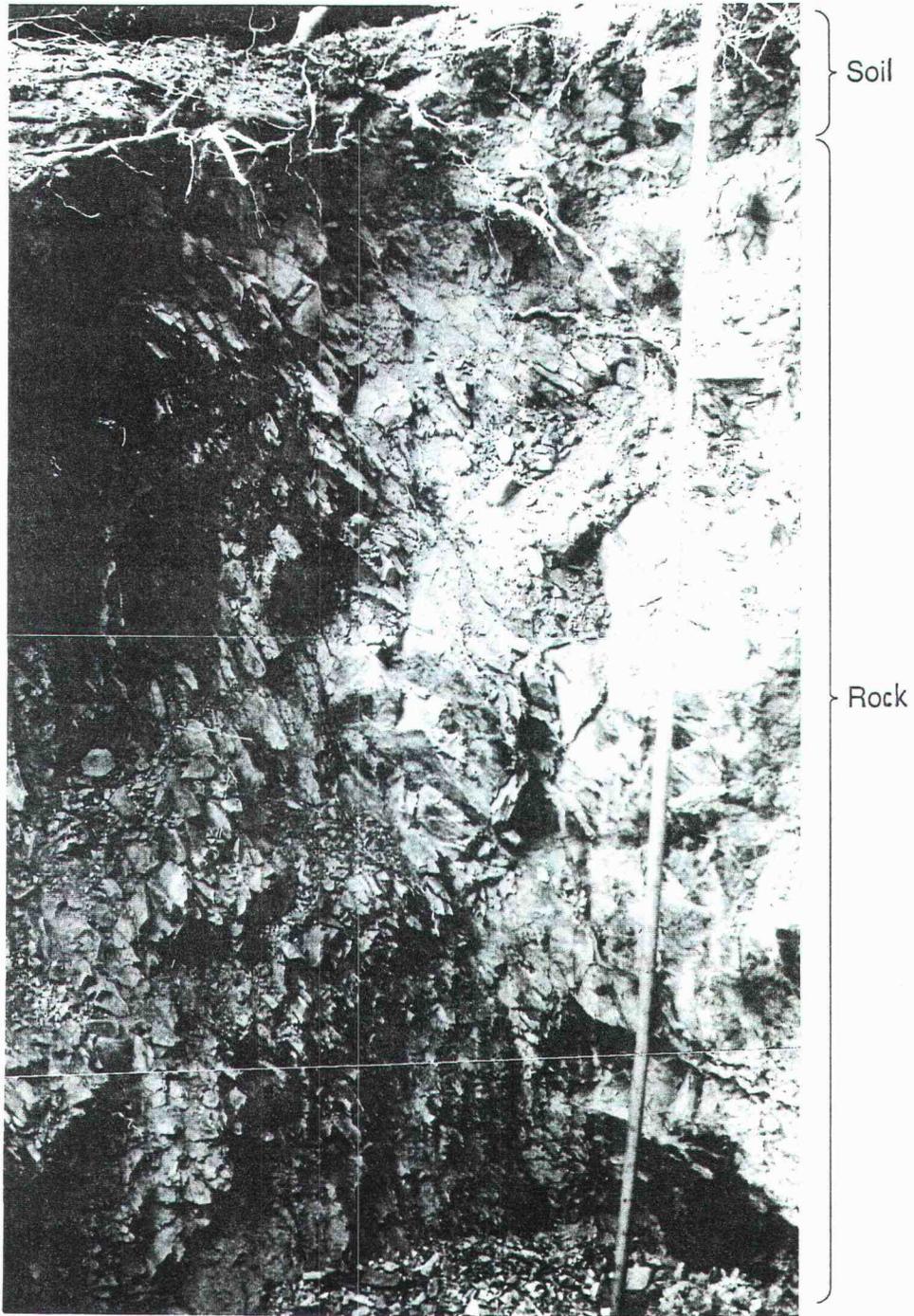


Figure 3.1. Soil/rock profile. Soil cover is 40 cm deep.

density layers of rock, some of which were vertically oriented. The network of fissures on the site of interest was very well developed, forming a continuous space penetrable by roots. No roots grew into the intact rock matrix; therefore, root development was limited by the distance between the two parallel surfaces forming rock fissures (Fig. 3.2). Fissures, unlike soil, create little more space than a wrinkled plane; in the absence of longitudinal stress, pressure from only the two sides is involved.

Roots of *A. viscida* and *A. menziesii* were found in fissures as small as 100 mm, as estimated by root thickness. In such an environment, only very fine roots were found. Density of these roots was sometimes very high, with total root length of up to 20 cm per cm<sup>2</sup> of fissure surface. Root steles were always approximately cylindrical (Fig. 3.3a and b). The stele structure did not show any particular deformation related to the growing environment. Cross-sectioned views of *A. viscida* show "wing-like" structures (Fig. 3.3a and b); with these extensions, a root 0.1 mm thick was up to 0.75 mm across. Similar structures were found for *A. menziesii*. Fig. 3.4 shows diagrams of roots developed in rock fissures (3.4a) and in soil (3.4b). The flat cortex tissue in Fig. 4a is the major difference between the two. This cortex structure extended back more than 20 cm from the root tip, and even in older suberized roots it was visible as remnant tissue (Fig. 3.5); later, older roots adjusted their shape to the fissures in intricate sculptures. All old large roots were ribbon shaped except when they were growing in soil. No normal root hairs were observed. If root hairs developed, they were never found on the surface of the cortex, but only on the edges of the "wing-like" structures (Fig. 3.2).

Roots of the coniferous species growing on this site, *P. ponderosa* and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), did not occupy the smallest fissures. They were limited to cracks >0.5 mm wide. Thus, no morphological adaptation to a narrow fissure environment was observed in coniferous roots. Nevertheless, *P. ponderosa* did penetrate deeply (>4 m) down large fissures, whereas *P. menziesii* did not appear to do so (see also Wang *et al.*, in press).

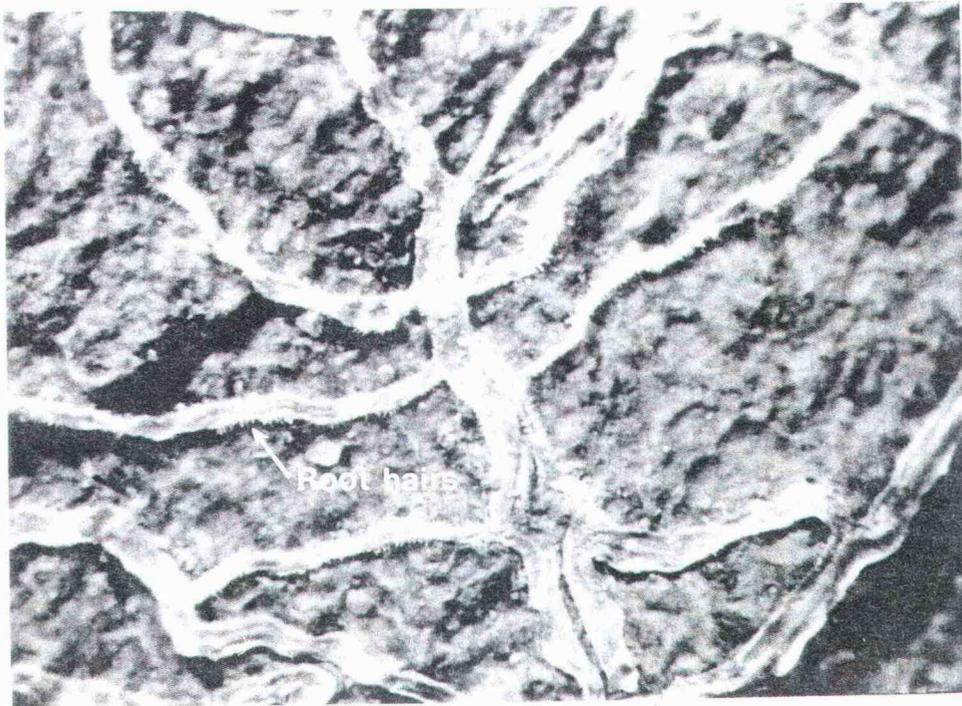


Figure 3.2. Roots of *Arctostaphylos viscida* (whiteleaf manzanita) tightly pressed to the rock surface have a two-dimensional distribution in fissures.

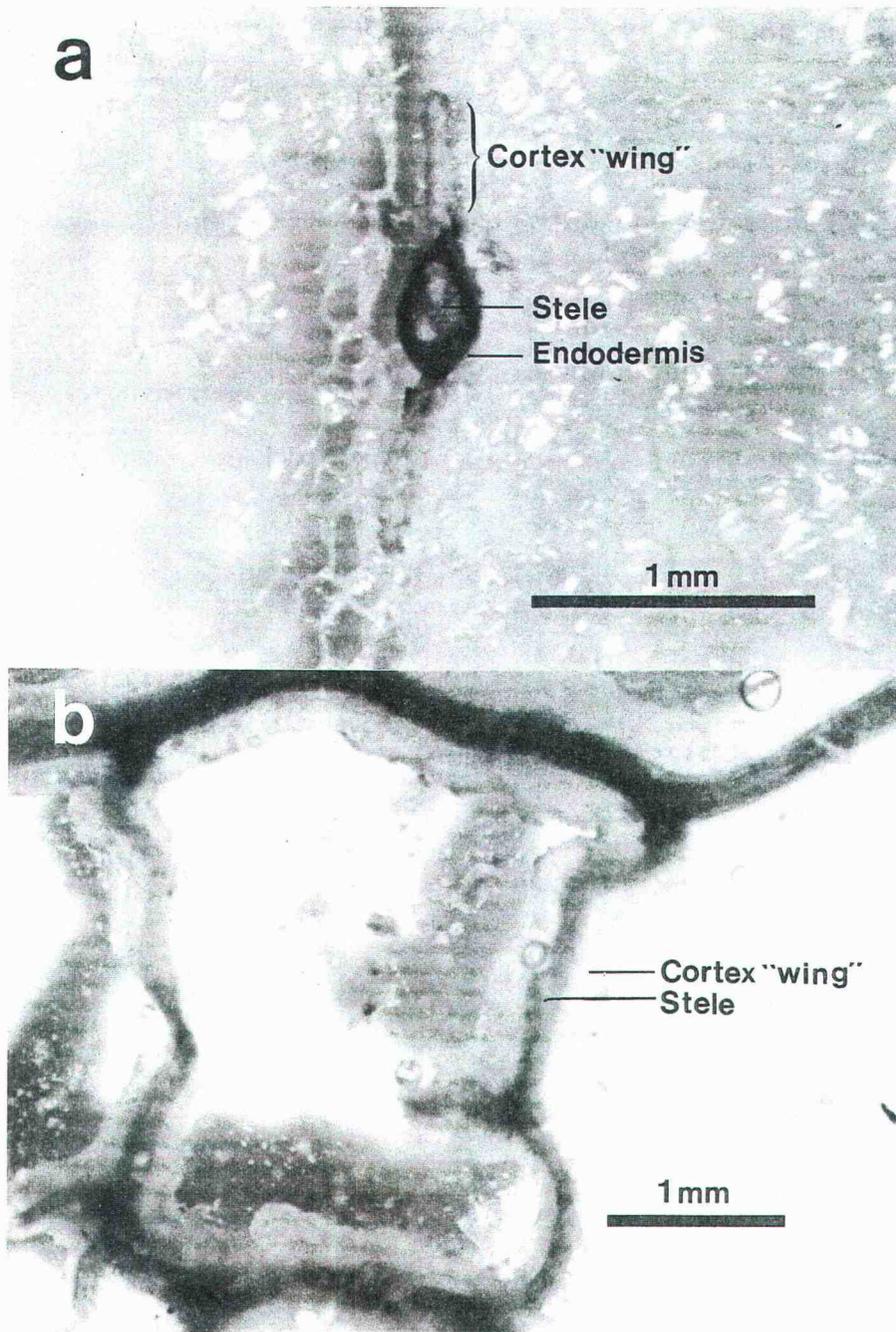


Figure 3.3. (a) Cross-section of a root of *A. viscida* (whiteleaf manzanita), 5 cm from the root tip, (b) root surface; cortex wings are visible as half transparent structures. In these narrow fissures, roots developed a severely flattened cortex, the same thickness as the fissure width.

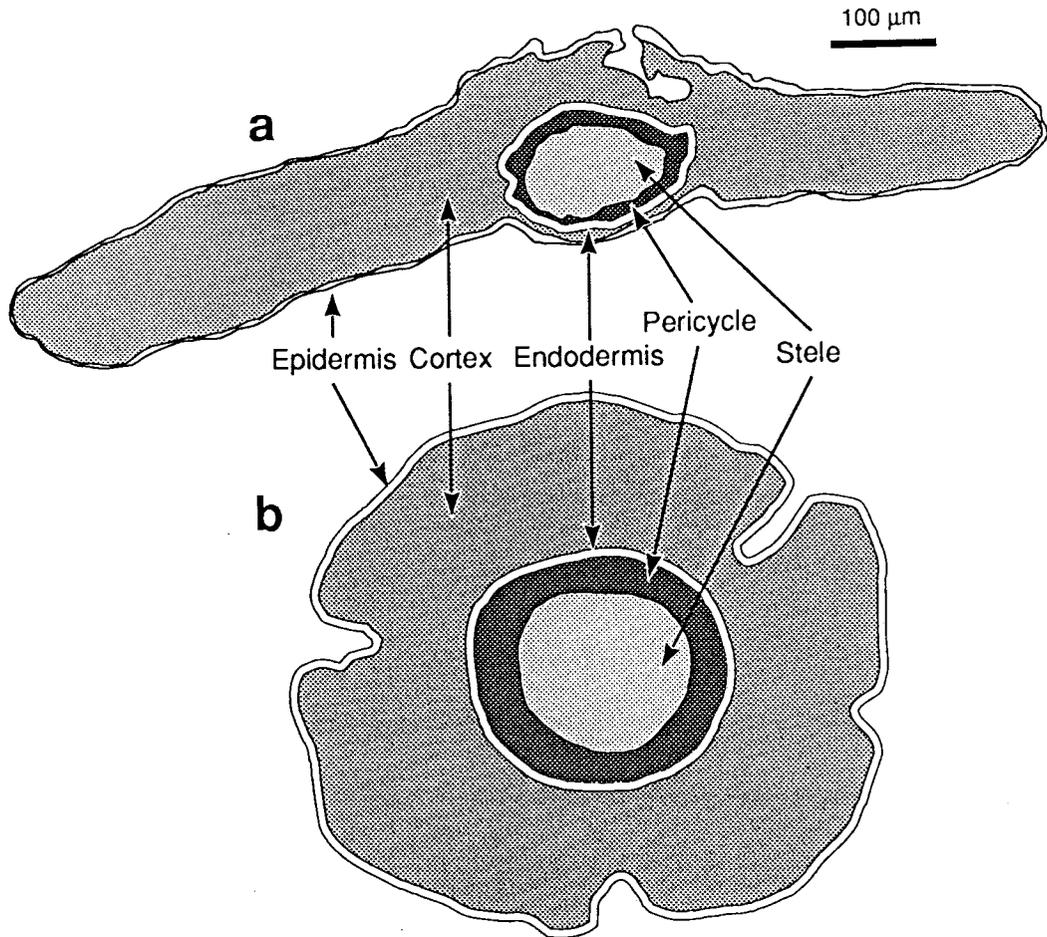


Figure 3.4. Comparison of cross-section of roots (a) growing in rock cracks (microscopic investigation), and (b) normal roots (based on Esau, 1965). The cross-section was taken at the stage when the pericycle increased in width and the cortex was starting to break down. In (a), the vascular cambium takes the shape of available space, and in (b) it is circular.

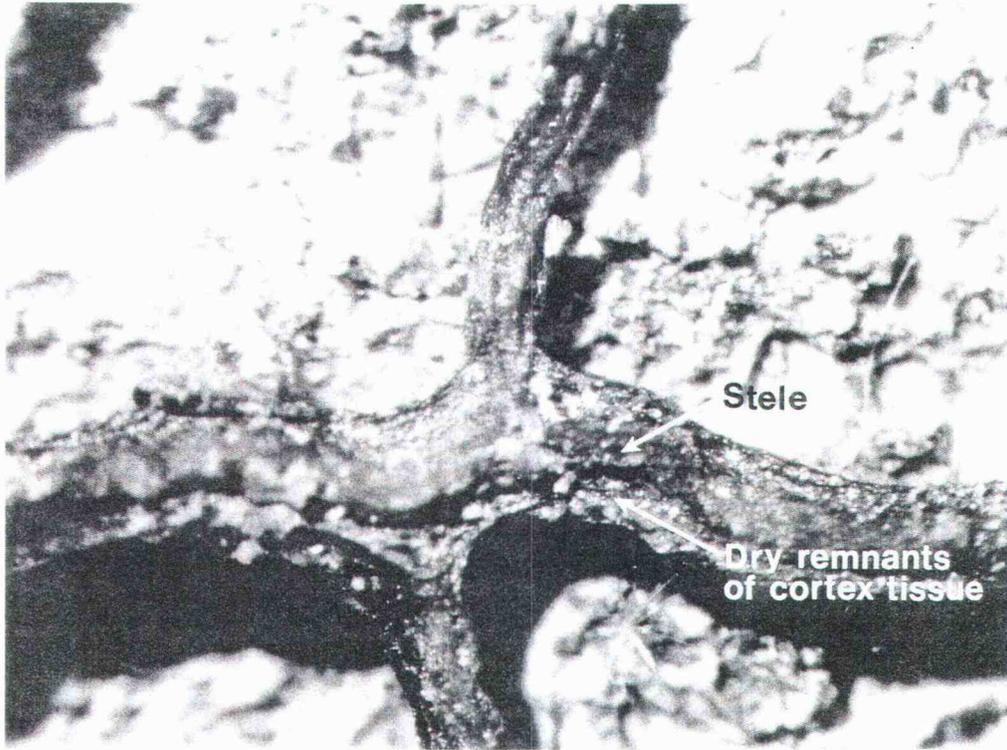


Figure 3.5. Old suberized root. Flat cortex structures are still visible on the sides of the stele.

### 3.5 Discussion

Morphology of roots is related to their environment. In compacted clayey soils denser than  $1.6 \text{ g/cm}^3$ , roots become thick and short, without root hairs (Baligar *et al.*, 1975; Bennie, 1991). Rock density is far greater than  $1.6 \text{ g/cm}^3$ , but in rock, roots do not show the changes described above. In rock, roots apparently grow only in fissures, which evidently do not cause high resistance to longitudinal growth as long as the stele can remain cylindrical. However, the narrow fissures provide strong resistance to radial growth of the roots. Because in one direction there is no space for expansion, the roots become flat, and cortex tissue fills all available space between rock surfaces. Our observations demonstrate that only some of the higher plants present are able to tolerate such deformation, and these are the most adaptive and competitive species in Mediterranean-climate shrublands. Conifers do not show adaptation to small rock fissures, and thus they suffer under competition from *A. viscida* and *A. menziesii* (Pabst *et al.*, 1990; Wang *et al.*, in press; White and Newton, 1989). Even when *P. ponderosa* locates some of its roots in the rock, they do not readily penetrate the small fissures.

Although the observed flat morphology may be an effect of physical confinement, it has several attributes that can improve the efficiency of water uptake. Intimate contact between roots and rock surface because of pressure on pads of fine material can create continuity of micro-pores for water flow. By analogy, in the measurement of rock water pressure potential, kaolinite silt is used to establish connections between a pressure plate and the rock samples (Jones and Graham, 1993). Cross-sections of roots growing in fissures indicate that the roots act as connecting bridges between two discontinuous rock matrices. Fissures typically contain a film of fine-textured mineral material that also is likely to provide capillary conductivity between rock surfaces. From theoretical modeling of water flow in unsaturated fractured material, we know that all water flow is likely to be concentrated through such bridges if there are no connections in the form of fine-textured material (Pruess

and Wang, 1987). Lack of root hairs evidently is also an adaptation to fissure environment. Root hairs can penetrate only fissure space or the fine contents of fissures, where there are limited resources available except from adjacent rock. Thus there could be little functional role for root hairs in rock fissures except to extend the functional surface of the pad described above.

Our data suggest that the smallest rock fissure size to be occupied is about 100 mm. This is the average minimum stele diameter of the described roots. No visible deformation such as strong elliptical shape occurred in the root stele, nor was there cell flattening or similar evidence of physical pressure. The root tip is approximately the same diameter as the stele, and it cannot extend growth where there is not enough space (Wiersun, 1957). Thus 100 mm may be considered as the smallest fissure size that plants can occupy, and it can also explain the lack of stele deformation. Conversely, when fissures appear that are  $\geq 100$  mm, the probability is good that they will be occupied, and that the bedrock will substantially affect woody plant domination.

### 3.6 Acknowledgements

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#### 4. Water-Holding Characteristics of Metasedimentary Rock in Selected Forest Ecosystems in Southwestern Oregon

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Submitted to Soil Science Society of America Journal

##### 4.1 Abstract

On sites characterized by shallow soil in semi-arid climates, lack of bedrock description may lead to underestimates of total storage capacity of water available for plants, and therefore of potential site productivity. Sample rocks from southwestern Oregon soil-rock profiles excavated beneath typical forest plant communities were examined for pore volume distribution by means of mercury intrusion porosimetry and oversolution equilibrium. Four ranges of pore size were distinguished: gravitational water, available water content (AWC), slowly available water (SAW), and unavailable water (UW). Pore volume for AWC and SAW was associated with bulk density and in low density rock was 20% of volume. Results suggest that metasedimentary rock has potential to be a major reservoir of plant available water in semi-arid climates.

##### 4.2 Introduction

The lack of description of bedrock in soil surveys may lead to underestimation of available water content (AWC), and therefore of site productivity, if the rock should have significant water-storage capacity. Indeed, Joffre and Rambal (1993) found that evapotranspiration computed from the water balance equation was low when compared

to measured transpiration, a result associated with underestimation of root extension into the soil-rock profile. Plants of many families are able to penetrate fractured rock layers (Cannon, 1911; Stone and Kalisz, 1991). Some of the Ericaceae family develop the considerable root length density of  $0.3 \text{ cm/cm}^3$  rock and locate one-third of their total root length in the bedrock (Zwieniecki and Newton, 1994). Root morphology suggests that roots found in bedrock are acquiring water and possibly nutrients from the rock (Zwieniecki and Newton, 1995).

Analysis of water depletion from the soil-rock profile under plant cover shows that  $>200$  mm of transpired water can come from the bedrock. This water may constitute more than 50% of all water-use by the plants during the growing season in such different ecosystems as Israeli maqui (Shachori et al., 1967, French vineyards (Detau, 1987), and southern-Oregon chaparrals (M. Zwieniecki and M. Newton, 1995, unpublished data). Recent reports evaluate AWC at less than 1% and more than 12%, respectively, for unweathered and highly weathered granite rock (Jones and Graham, 1993). Montagne et al. (1992) report that some siltstone has more than 15% AWC. Capacity varies with the bulk density of the rock, and in sedimentary rock can be from 8% to 22% (Kummerow, 1981; Wang et al., 1995).

The objective of this study was to determine water-holding characteristics of sedimentary rock relative to its bulk density. Four ranges of water matrix potential were of interest: i) gravitational water, which plays a major role in buffering surface water flow, temporarily held in the range from 0 to  $-0.01$  Mpa; ii) available water capacity (AWC), which is crucial to plant life, nominally ranging from  $-0.01$  to  $-1.5$  Mpa; iii) slowly available water (SAW), which may support some sclerophyllous woody plants that transpire water with leaf water potential as low as  $-10.0$  MPa; and iv) unavailable (hygroscopic) water (NAW), which is unavailable to plants but removable by oven drying, in this study held at  $-4.0$  MPa (Jones and Graham, 1993).

### 4.3 Methods

Rock samples were collected in two locations in southwestern Oregon. Annual precipitation there ranges from 600 to 1200 mm per year, 87% during the six winter months. Sites were characterized by 40- to 70-cm-deep gravelly loams or clay loams of the Vermisa and Beekman series, with pockets of fine loams of the Kerby series (Bureau of Land Management, 1977). Underlying rock material is slightly to moderately weathered metasedimentary rock. Detailed descriptions of the sites are given in Wang et al. (1995) and Pabst et al. (1990).

At the end of summer 1992, four 4-m-deep profiles of soil and rock were opened by drilling and blasting with medium velocity dynamite, which permitted examination of the structure of the vertical 2-m-wide headwalls with minimum damage. On one site, two profiles were located under mixed Pacific madrone [*Arbutus menziesii* (Pursh)] and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]. The site had been burned previously and was occupied by regenerating madrone sprout clumps and planted Douglas-fir (90% and 10% basal diameter, respectively). On another site, where whiteleaf manzanita [*Arctostaphylos viscida* (Parry)] had been cleared mechanically and planted with conifers, one profile was excavated under a pure stand of newly germinating manzanita and one under a pure stand of ponderosa pine [*Pinus ponderosa* (Dougl. ex Laws.)]. All stands were 12 years old. Immediately after removal of the loose blasted material, three samples of soil/rock were collected from seven depths at 0.5 m intervals. The volume of intact soil/rock samples was from 2 to 4 dm<sup>3</sup>. Subsamples of approximately 300-400 cm<sup>3</sup> of cleaned wall rock were sealed in plastic bags and later used to evaluate end-of-summer water content (by drying at 110 °C for 72 hours). In total, 100 samples were collected.

Dry rock or soil subsamples were coated with a sealant for determination of bulk density. The volume of the rock was determined by displacement according to Archimedes' Principle (Jones and Graham, 1993).

Porosity and water-holding capacity were determined by mercury intrusion porosimetry and oversolution equilibrium. Mercury intrusion porosimetry gives volumetric distribution of pore diameters in the range of 50 to 0.036  $\mu\text{m}$ . It was applied on 0.5 to 1.5 g of soil or rock particles that were first oven-dried at 110 °C for 72 hours. Samples were placed in a small, prevacuated chamber and submerged in liquid Hg; then as pressure was increased, the volume of Hg penetrating the sample and the corresponding pore diameter were recorded (AMINCO porosimeter model 5,000 psi). Water matrix potential was obtained by applying the capillary principle to calculated pore diameter with the assumption of 100% wetness of capillary walls and a water surface tension of 0.0728 Pa/m at 20 °C. Calculated ranges of the water matrix potential and the equivalent ranges of pore diameter are shown in Table 4.1. Density of minerals was assumed to be 2.75 g/cm<sup>3</sup>, based on the average of five measured randomly chosen rock particles (pycnometer).

Table 4.1. The ranges of water matrix potential, calculated with assumptions of 100% wetness of capillary walls and 0.0728 Pa/m water surface tension, and equivalent pore diameters.

| Water availability      | Water matrix potential | Pore diameter                 |
|-------------------------|------------------------|-------------------------------|
| Gravitational water     | 0 to -0.01 MPa         | More than 14 $\mu\text{m}$    |
| Available water content | -0.01 to -1.5 MPa      | 0.097 to 14 $\mu\text{m}$     |
| Slowly available water  | -1.5 to -4.0 MPa       | 0.036 to 0.097 $\mu\text{m}$  |
| Unavailable water       | Less than -4.0 MPa     | Less than 0.036 $\mu\text{m}$ |

Oversolution equilibrium measurement of pore size and volume entails a series of six glass desiccators in which water vapor pressure is regulated by NaCl solutions to the water potentials -0.5 MPa, -1.0 MPa, -1.5 MPa, -2.0 MPa, -3.0 MPa and -4.0 MPa as calculated for 23 °C. Three soil or rock particles (1-2 cm<sup>3</sup>) of each sample were placed in each desiccator. During equilibration, desiccators were kept in a thermoregulated chamber at a constant 23 °C. For additional protection against

temperature oscillation, desiccators were in a styrofoam box. Solutions were replaced every 2 months, at which time net weight gain due to water absorption of all rock in the regulated humidity was recorded. When no changes in weight were observed in two consecutive 2-month periods, the equilibration process was terminated. After 12 months, samples were weighed and oven-dried at 110 °C for 72 hours for estimation of water content.

Water extractable from the rock particles by living plants was determined by a grass bioassay. Rock particles ranging in volume from 1 cm<sup>3</sup> to 40 cm<sup>3</sup>, were placed in each of 99 small pots (200 cm<sup>3</sup> volume). Space between the rocks was filled with coarse sand, and the pots were watered daily to near field water capacity. Grass was allowed to grow in the pots for one month. One third of all pots were then randomly collected and water content in the rock was determined. The remaining pots were split into two equal groups, one in which the grass was killed with glyphosphate herbicide and one in which it was left alive. There was no additional watering. After 3 weeks, when approximately 50% of the untreated grass was dead from dehydration, the rocks in the remaining pots were collected and rock water content was determined for each particle.

Data were analyzed by multiple regression with polynomials of bulk density providing all independent variables.

#### 4.4 Results

Bulk density of soil from the study sites ranged from 1.49 to 1.82 g/cm<sup>3</sup>, bulk density of rock from 1.97 to 2.68 g/cm<sup>3</sup>. Association of rock bulk density with the depth of origin was weak and varied substantially within layers.

Mercury intrusion porosimetry and oversolution equilibrium gave similar patterns of pore size distribution over the range of bulk densities, although results calculated from mercury intrusion were slightly lower (Fig. 4.1). An analysis of pore

sizes showed that more than 20% of total soil volume was in pores of the AWC range, 5% in the SAW range, and 18% in the gravitational water range when density is 1.5 g/cm<sup>3</sup>. Total pore volume decreased in proportion to the increase in soil bulk density. In rock, volume in pores of smaller diameter increased slightly, especially within the UW range, which more than doubled from 3% volume at 1.5 g/cm<sup>3</sup> (soil) to 8% at 2.1 g/cm<sup>3</sup> (rock). Pore volume in the AWC and gravitational ranges decreased markedly with an increase in bulk density (Fig. 4.1). Above 2.1 g/cm<sup>3</sup>, volumes in pores of all sizes decreased with increasing density. Soil and rock show well-fitting continuity of pore volume distribution within measured ranges.

Along with the general decline in pore volume with increasing bulk density, the distribution changed among the ranges of interest. Figure 4.2 illustrates that as density of soil-rock increased from 1.5 to 2.5 g/cm<sup>3</sup>, pore volume for gravitational-water decreased from 36 to 10% and volume for the AWC decreased from 44% to 6% of total pore volume. At 2.5 g/cm<sup>3</sup> density, 15% of the pore volume was in the SAW range and 53% in UW range.

A good relationship appeared between bulk density and AWC ( $R^2$  adj. = 0.77,  $p < 0.0001$ ) and between bulk density and AWC plus SAW ( $R^2$  adj. = 0.80,  $p < 0.0001$ ). In general, AWC plus SAW is 3% to 5% higher than AWC alone, which could contribute 12 to 21 mm of water in the 40 to 70 cm of soil found on the sites of interest, and more than 90 mm of water in the 3.5-m-deep rock layer penetrated by roots (Fig. 4.3).

The grass bioassay showed the volume of water in fully watered pots to be slightly higher than the percentage represented by the -0.01 matrix potential line. Depletion of water from rocks in pots with herbicide-treated grass reflected the evaporation process and local diffusion or unsaturated movement. It must be acknowledged that an unknown quantity of transpiration occurred in the treated grass before its death terminated the process. Water content of high-density rocks under dead grass was no different than that under living grass, but more water was depleted from low-density rocks beneath living grass than from beneath dead grass,

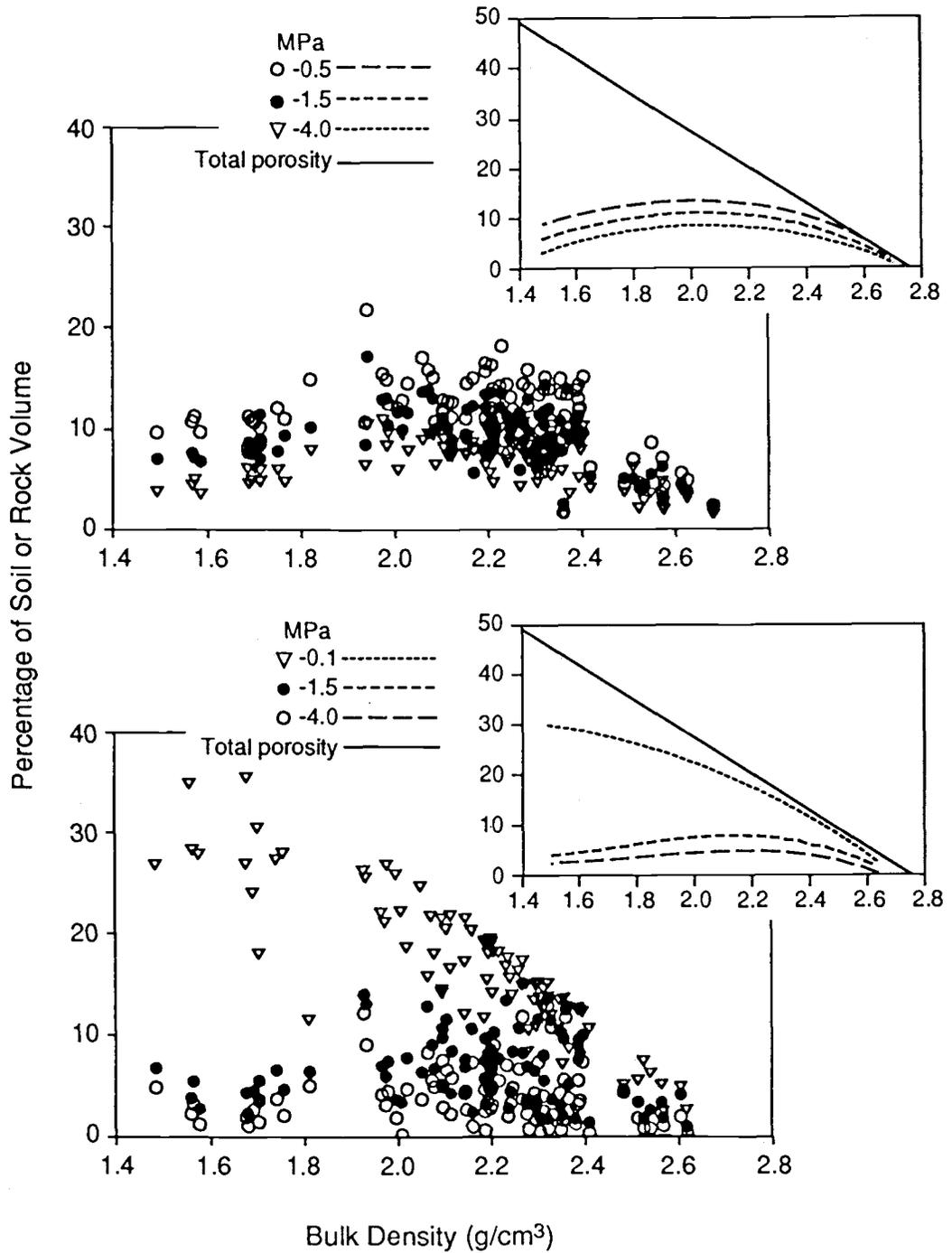


Figure 4.1. Water-holding capacity, expressed as a percentage of soil or rock volume, for different water matrix potentials. A) Results from oversolution equilibrium. B) Results from mercury-infusion porosity.

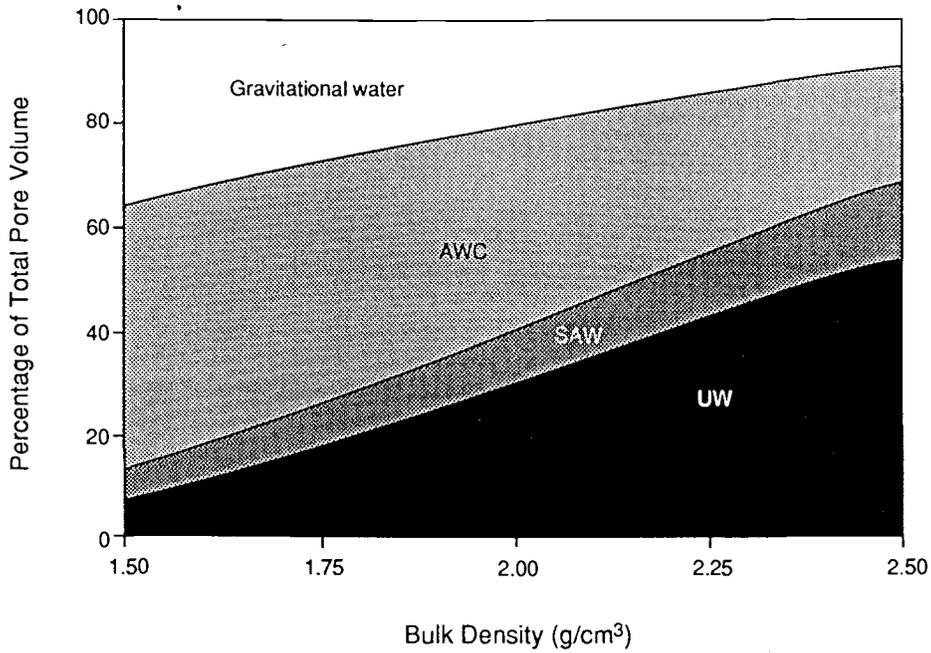


Figure 4.2. Space partitioning of water matrix potential, expressed as a percentage of total pore volume, in relation to bulk density. AWC = available water capacity, SAW = slowly available water, and UW = unavailable water.

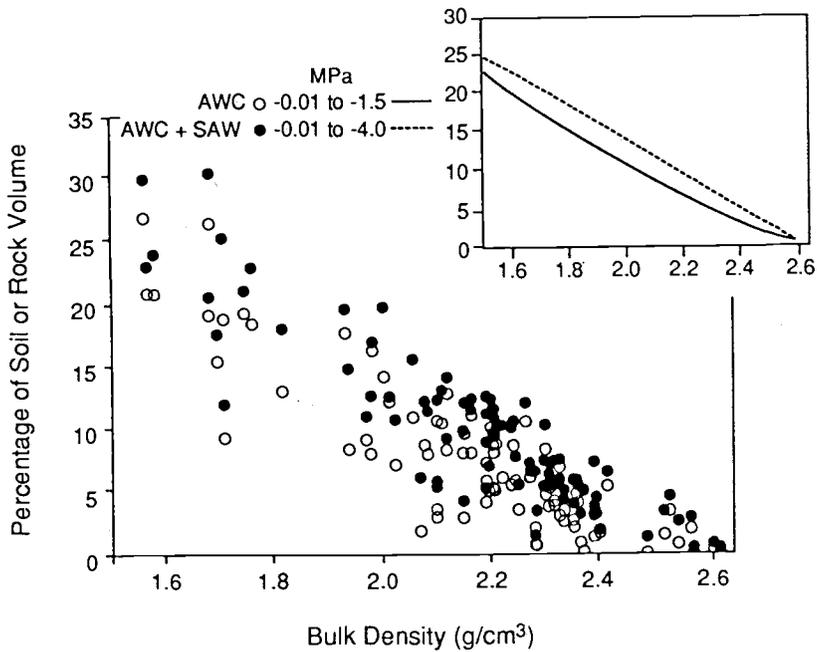


Figure 4.3. Available water capacity (AWC) alone and with slowly available water (SAW), expressed as the percentage of soil or rock volume, in relation to bulk density.

reflecting water uptake. Rock water content under living grass is close to the line of the AWC range (Fig. 4.4).

#### 4.5 Discussion

Pore volume of sedimentary rock in the AWC range can be as high as 15% at low rock bulk density (1.95-2.1 g/cm<sup>3</sup>). Similar values have been obtained for other rock types: for weathered granite 11%, (Jones and Graham, 1993), for sandstone 11% (Hansone and Blevins, 1979), and for siltstone 10% (Montagne, et al. 1992). The AWC volume in this study gradually decreased with increasing rock bulk density, but metasedimentary rock in this study still showed potentially available plant water, i.e. 8% of rock volume at 2.3 g/cm<sup>3</sup> density (SAW range included). For 3-m-deep rock, this percentage will account for 240 mm of unavailable water, which nearly triples the soil water-storage capacity, a tremendous amount of water potentially available to plants in semi-arid climates.

Most low-elevation forests in Mediterranean climates are subject to low summer precipitation and shallow soil (Bradbury, 1981; Nahal, 1981). Evapotranspiration potential typically exceeds soil water-holding capacity (Arkley, 1981), and only a fraction of the water that penetrates the soil and rock by deep percolation appears in the stream flow (Rowe and Coleman, 1951). In southwestern Oregon and northern California there are almost 4 million ha of such forests. In many cases, plant biomass production and soil infiltration rates exceed those being predicted from soil-only analyses. Both are likely attributable to underestimations of bedrock water storage, root penetration into the bedrock, summer water depletion, and the sink attenuating storm flow.

When evapotranspiration demand exceeds soil water-holding capacity, as it does on much of this mountainous terrain, rock is a crucial source of water, especially for some sclerophyll species, and perhaps other species, during prolonged

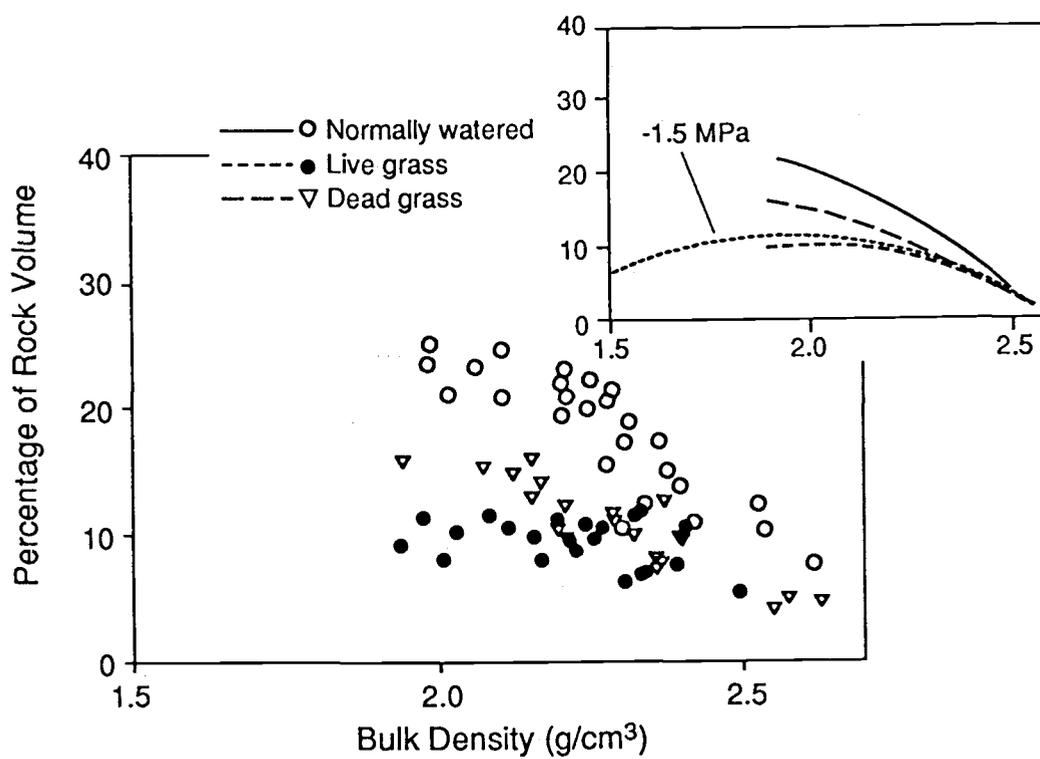


Figure 4.4. Water content in rock particles, as shown by a bioassay. Regression lines on the right are shown with the line for -1.5 MPa pore volume determined by oversolution equilibrium.

summer drought (Fisher and Stone, 1968). There is documented close association of roots with rock particles (Cannon, 1911), of roots growing in rock fissures (Hellmers et al., 1955; Lewis and Burgy, 1964; Zwieniecki and Newton, 1994) and even of roots growing into the intact rock matrix (Oppenheimer, 1957). Some species like *A. menziesii* and *A. viscida* adjust their root morphology to the fissure environment by flattening of the root cortex (Zwieniecki and Newton, 1995). End-of-summer water content indeed showed AWC was fully depleted from both soil and rock by madrone and ponderosa pine, and rock alone was depleted to -4.0 MPa by manzanita (Fig. 4.5). Even grass in this bioassay utilized AWC from rock particles in the bulk density range from 1.9 to 2.4 g/cm<sup>3</sup>. Grass roots concentrated around each rock particle and removed water through unsaturated flow resulting from suction at a low potential gradient.

Manzanita depletes water to -4.0 Mpa (SAW) from rock but only within the AWC range from soil. Removal capacity is presumably associated with hydraulic properties of unsaturated flow in soil and rock. Water from the AWC range and the gravitational water range in soil constitutes nearly all pore volume (80%), thus resistance to water flow will be high when this water is depleted. Most water pathways will break down and no water will flow toward roots, irrespective of the root length in those ranges (Carbon et al., 1980). In rock, a dense network of small pores can create pathways for unsaturated water flow that cannot be easily broken by water depletion from a few big pores; thus when plants can create adequate suction, water will flow toward roots even from a relatively long distance. Flat roots in small fissures (Zwieniecki and Newton, 1995) can operate like clods on a small pressure plate. Mats of roots (Jones and Graham, 1993; Zwieniecki and Newton, 1995) can further increase suction of a single root. Usually roots are tightly pressed between two rock surfaces; thus, they operate like water bridges (Pruess and Wang, 1987) and may intercept water flowing between neighboring rock boulders.

All of these processes suggest that roots may take up more water per unit length in rock fissures than in soil. Indeed, calculated water uptake efficiency by roots of madrone, manzanita, and ponderosa pine is two to three times higher for

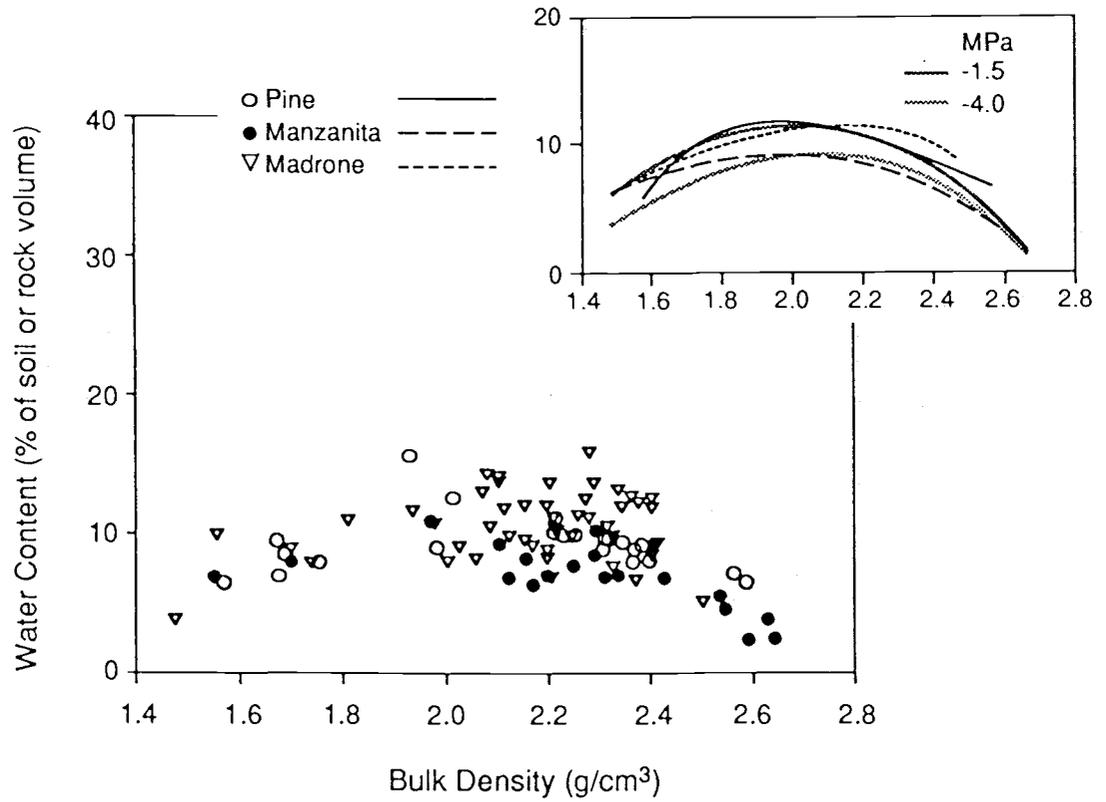


Figure 4.5. End-of-summer water content in soil and rock samples collected from a pine stand, a manzanita stand, and a madrone stand. Regression lines on the right are shown with the lines for pore volume for two matrix water potentials determined by oversolution equilibrium.

roots located in rock than in soil (M. Newton and M. Zwieniecki, 1995, unpublished data).

Large pores in low-density rock have hydrological significance as a surge reservoir. They can significantly contribute to instantaneous water capacity, thereby decreasing the likelihood of surface water runoff, hence erosion. Assuming that the top 3 m of the bedrock contributes 4% of its volume to instantaneous water storage (the average value found in this study), 120 mm of water may be stored for a short time following precipitation. Well-developed crack and fissure networks allow water to penetrate into the profile and to fill the gravitational pores in the rock beneath the soil. Permeability of bedrock likely decreased with depth. This bedrock reservoir may be a factor in attenuating storm flow and maintaining substantial flows between storms. However, 90% of pore diameters in rock are smaller than 14  $\mu\text{m}$ , and pores less than 50  $\mu\text{m}$  in diameter constitute more than 99% of the pore volume; thus penetration of the rock matrix is severely restricted because root tips are too big to penetrate such pores (Wiersum, 1957; Zwieniecki and Newton, 1994, 1995). Active rock-dissolving would be required for roots to penetrate the intact rock matrix, as was observed by Oppenheimer (1957). It is an open question whether penetration of the rock matrix by hyphae of mycorrhizal or saprophytic fungi is possible. It would require a network of pores with diameters greater than 1  $\mu\text{m}$  (K. Cromack, 1994, personal communication).

#### 4.6 Conclusions

Weathered and moderately weathered bedrock, with well-developed fissure networks penetrable by plant roots, can be a major source of water during prolonged summer drought for some plants in mediterranean-type ecosystems. This is especially true when soil is shallow and evapotranspiration demand exceeds water-storage capacity. Bedrock, having lower unit capacity but greater depth than soil, is a major storage reservoir. A high proportion of small pores can facilitate unsaturated water

flow toward roots through the rock matrix, with no significant changes in resistance to water flow resulting from discontinuity.

#### 4.7 Acknowledgements

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## 5. Seasonal pattern of water depletion from soil/rock profiles in a Mediterranean climate.

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### 5.1 Abstract

Sclerophyllous shrubs and conifers deplete water from soil/rock profiles in distinctly different patterns, based on neutron probe measurements from aluminum access tubes 3.2 m deep. Measurements were taken during two growing seasons (1993 and 1994) in southwestern Oregon (USA) under: Douglas-fir, Pacific madrone, ponderosa pine and whiteleaf manzanita covers of the same age. Both conifers show very limited ability to utilize water from bedrock, even during very dry periods. Ericaceous plants were very efficient in depletion of water from the deep rock layers, using nearly all available water and removing about twice as much water as conifers of the same age. Patterns of depletion suggest that water resources used by both types of plants overlaps considerably and competition will be very strong in mixed stands. Ability of ericaceous plants to utilize water from bedrock that is not available to conifers in late summer, will enhance their dominance potential.

### 5.2 Introduction.

Summer drought is a major limiting factor for vegetation development in a Mediterranean climate (di Castri 1981). Little of the total precipitation arrives during

summer. Poorly developed shallow soils (Zinke 1973; Bradbury 1981) offer very limited water storage for summer metabolism and transpiration. As a result, summer evapotranspiration demand often exceeds both precipitation and available water stored in soil (Arkley 1981; Joffre & Rambal 1993) leading to prolonged stomatal closure and mortality of plants vulnerable to water stress (Newton & Preest 1988).

When water available for plants is depleted, transpiration slows then stops, inducing a quasi dormant state (Newton & Preest 1988). Not all plants follow this pattern. Some species keep stomata open for a prolonged period under high summer water stress. Leaf water potential can be as low as -5 MPa as was observed for Pacific madrone (*Arbutus menziesii* Pursh. (Ericaceae)) (Morrow & Mooney 1974) and even lower for whiteleaf manzanita (*Arctostaphylos viscida* Parry (Ericaceae)) without changes in rate of transpiration. Many studies suggest that bedrock can be an additional resource of water for those plants (Cannon 1911; Helmers et. al. 1955; Lewis & Burgy 1964; Fisher & Stone 1968). Bedrock is capable of storing a considerable amount of water in a range of potential available to plants. Low density granite can store 12% of such water (Jones & Graham 1993) low density meta-sedimentary rock up to 20% (Wang et al. 1995; Zwieniecki, Newton unpublished manuscript) and siltstone 10% (Montagne et. al. 1992).

Plants have to grow roots into the rock medium to utilize such water. There are numerous reports on root presence in cracks (for review, see Stone & Kalisz 1991). Some species can reach the relatively high root length density of 0.3 cm/cm<sup>3</sup> in fractured rock (Zwieniecki & Newton 1994). Root length density is strongly affected by accessibility in rock via networks of fissures and fissure volume and less by bulk density of the rock (Zwieniecki & Newton 1994). Opening size of fissure is very strong limitation for penetration. Species are likely to vary in their ability to grow roots into very narrow space according to diameters of stele of fine roots, especially when fissures are filled with fine material (Wiersum 1957). Species, which can penetrate, are characterized by root morphological adaptation to the rock environment (Zwieniecki & Newton 1995).

The objective of this paper is to describe patterns of seasonal depletion of water from soil/rock profile by major components of Mediterranean forests in the Oregon and California (USA). We also evaluate amounts of water extracted from the bedrock and percent of potentially available water that is actually used by plants. Analyses are performed for two groups of woody plants: conifers and sclerophyll shrubs, with two examples of each.

### 5.3 Methods

Two sites in southwestern Oregon were chosen as representing an evergreen hardwood/ Douglas-fir type and a sclerophyll shrub type: the first site is characterized by average annual precipitation of 1200 mm and the second site precipitation of 600 mm respectively. Detailed descriptions of sites are given in Pabst et al. (1990). Both sites are covered with soil 40 to 70 cm deep described as gravelly loams or clay loams of the Vermisa and Beekman series (Bureau of land Management 1977). Underlying rock material is described as slightly to moderately weathered meta-sedimentary rock in both location.

During spring 1993 aluminum neutron probe access tubes were installed on both sites in several vegetation types. All tubes permitted measurements to a depth of 3.2 m deep. Tubes were installed on the first site in 14-year-old stands of pure Douglas-fir (*Pseudotsuga menziessi* (Mirb.) Franco) and mixtures of Pacific madrone (*Arbutus menziesii* Pursh)(90%) with Douglas-fir (10%) and on the second site in pure ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and mixtures of whiteleaf manzanita (*Arctostaphylos viscida* Parry)(95%) with ponderosa pine (5%) (percents are calculated on the bases of stemwood basal area). At both sites devegetated control plots were prepared (20 x 20 m). They were covered during the period of measurements with 6-mil black plastic to avoid recharge by summer rainfall or loss of water due to

evaporation from the surface. Number of tubes placed under different conditions is presented in Tab. 5.1.

Table 5.1. Number of aluminum neutron probe access tubes installed.

| vegetation type     | site 1 | site 2 |
|---------------------|--------|--------|
| control             | 4      | 1      |
| Douglas-fir         | 6      | -----  |
| Pacific madrone     | 4      | -----  |
| ponderosa pine      | -----  | 2      |
| whiteleaf manzanita | -----  | 2      |

Measurements were taken every month during two successive growing seasons, 1993 and 1994 (April through October). Measurements were taken from following depths: 0.3 m (soil), 0.6, 0.9, 1.2, 1.5, 2.0, 2.5, 3.0 m (rock) and it was assumed that they represent the following layers: 0-0.45 m (soil) 0.45-0.75, 0.75-1.05, 1.05-1.35, 1.35-1.75, 1.75-2.25, 2.25-2.75 and 2.75-3.25 m (rock). Depth of soil, 40-50 cm, was measured during the drilling procedure. Precipitation was measured concurrently with the neutron probe measurements. Depletion under vegetated plots was corrected with loss of water from devegetated plots by subtracting deep percolation measured under devegetated plots (Shachori et al. 1967). Control plots were left uncovered between seasons to allow water recharge of soil and rock during the winter period.

Depletion under each type of vegetation for a single layer was calculated on the bases of following formula

$$D_{(veg)ti} = a_i * [(R_{(veg)0i} - R_{(veg)ti}) - (R_{(con)0i} - R_{(con)ti})] \quad (1)$$

where  $D_{(veg)ti}$  is depletion under a particular vegetation cover at time  $t$  and layer  $i$ ,  $R_{(veg)ti}$  and  $R_{(con)ti}$  are average neutron probe readings for vegetated and control plot at time  $t$  and layer  $i$  and  $R_{(veg)0i}$  and  $R_{(con)0i}$  are the average neutron probe reading at time 0 and

layer  $i$ ,  $a_i$  is an  $i$ 'th layer of depth. Total water depletion is a sum of depletion of all layers, and with rainfall represents total evapotranspiration for particular period of time  $t_i$ .

The neutron probe was used to observed water depletion by subtracting present from previous measurement, a quantity that is independent of calibration or existence of large roots or other constant sources of bias. We thus measure only net change, i.e. depletion for any given interval.

#### 5.4 Results

Total cumulative evapotranspiration exceeded cumulative rainfall during both 1993 and 1994 vegetation seasons for all cover types (Fig. 5.1). During spring, rainfall was nearly sufficient to cover evapotranspiration demand to the end of June in 1993 and to the end of May in 1994. Later rainfall was very limited and both conifers and ericaceous plants depleted water from occupied soil and/or rock profile. There was more water available in 1993 than in 1994, and all species depleted more water in 1993 than in 1994. This is the combined effect of higher winter and summer precipitation in 1993 than in 1994 (Fig. 5.1). In both seasons conifers depleted approximately two thirds of the total depletion by madrone and manzanita, and about half that of the shrubs during July-October.

The average soil on both sites can store 19% of water by volume in the available water content (AWC) range (Zwieniecki & Newton 1995 unpublished manuscript). For a soil layer 45 cm deep this gives 85.5 mm of stored water. Douglas-fir in both seasons depleted slightly more than 50 mm of water, hence all water evapotranspired could have come from soil storage alone (Fig. 5.2). Total depletion by ponderosa pine was 120 mm and 95 mm in 1993 and 1994 seasons respectively. Thus depletion was slightly greater than soil AWC. Both madrone and manzanita depleted much more, close to 200 mm, and in the 1993 season manzanita depleted more than 250 mm from

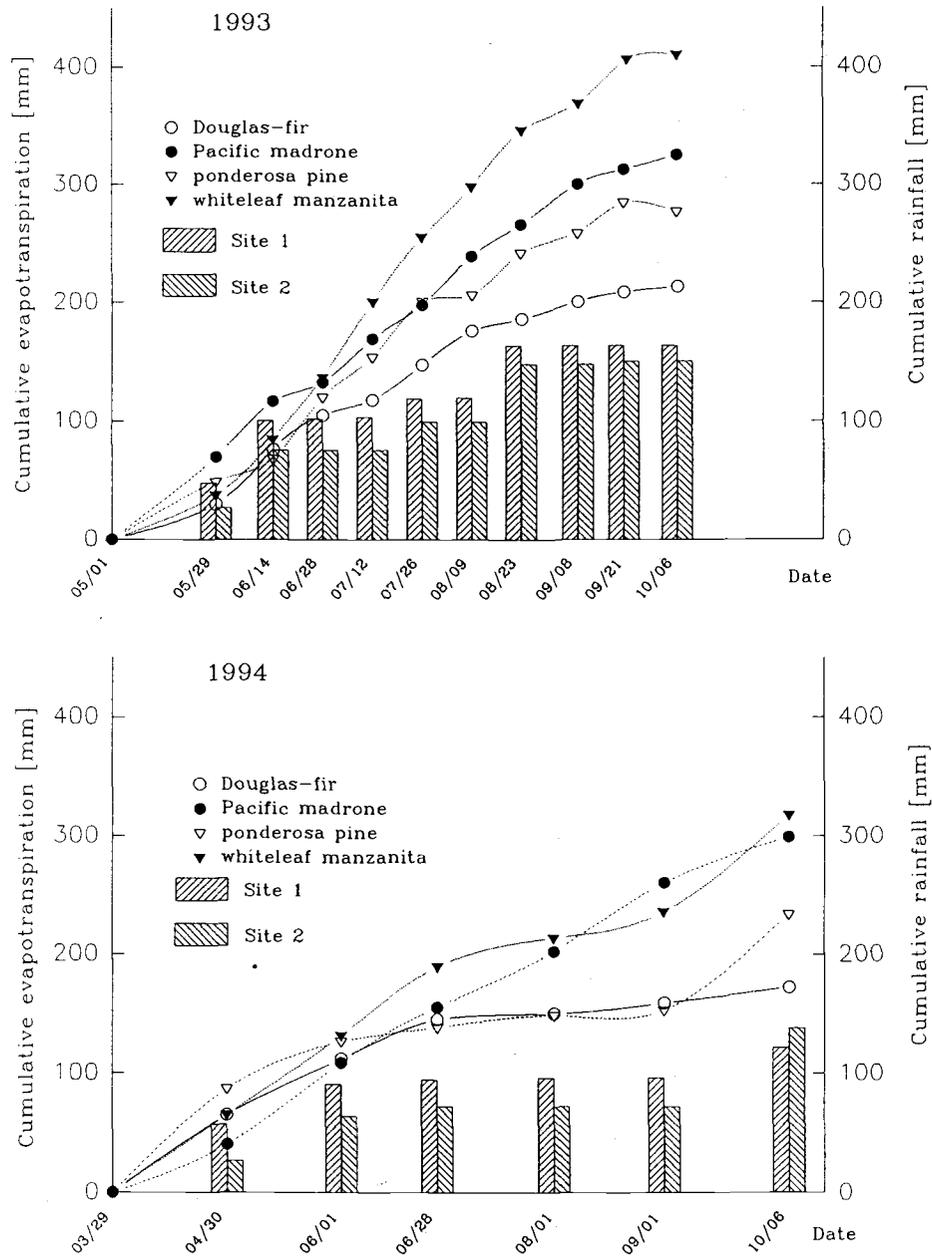


Figure 5.1. Cumulative evapotranspiration (estimated on the basis of water depletion from rock/soil profile 3.25 m deep and rainfall together) and cumulative rainfall for two following growing season in 1993 and 1994. Four different woody covers are presented at two locations.

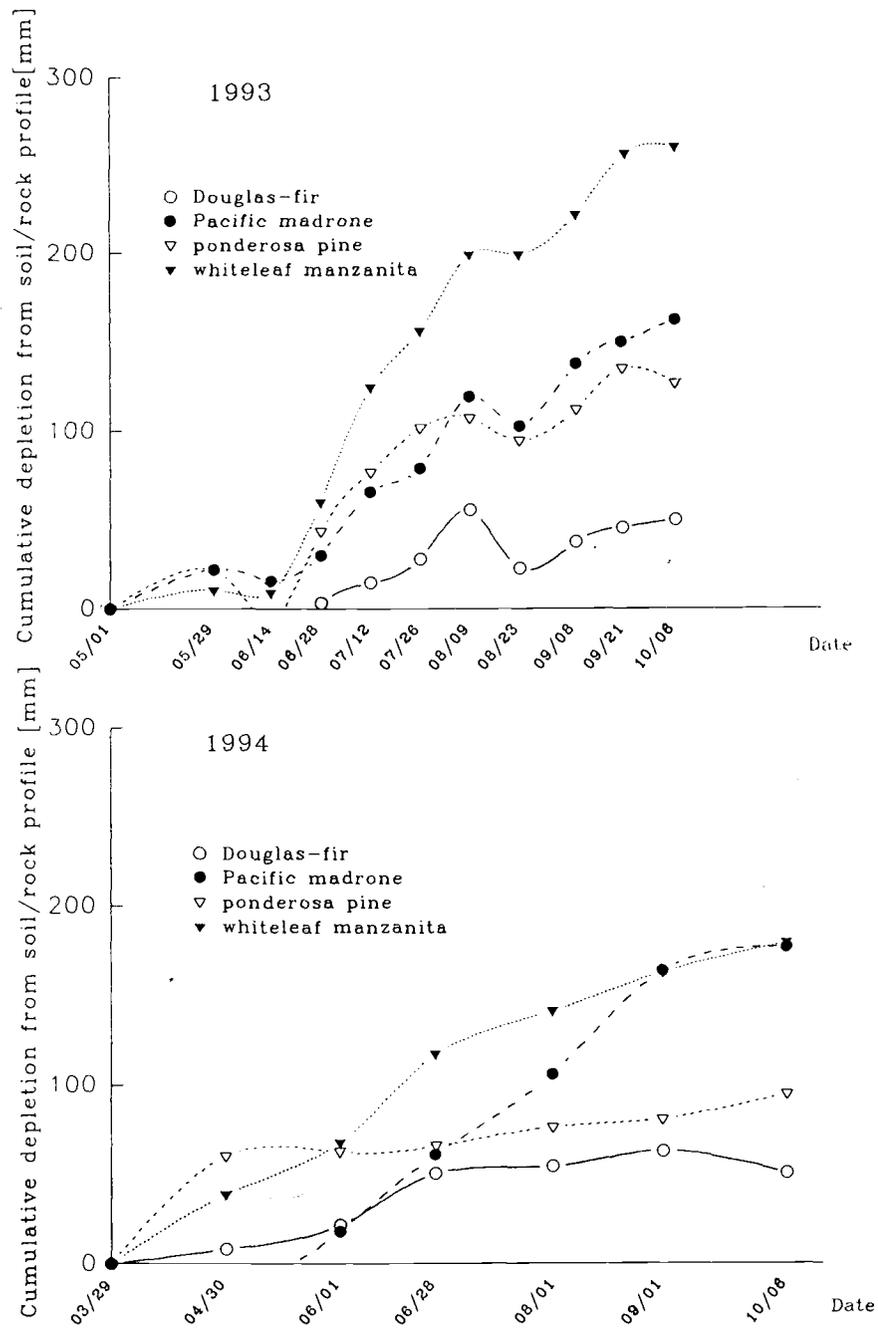


Figure 5.2. Cumulative depletion of water from soil/rock profile 3.25 m deep under four different woody covers.

the entire 3.2 m profile (Fig. 5.2) not counting contribution from deeper layers. These numbers significantly exceed soil storage capacity. The deficit was met each season by extracting 100-200 mm of water that was stored in rock.

Analysis of water depletion from the soil/rock profile generally follows the above pattern with certain species-specific exceptions. Douglas-fir did not deplete water from deeper parts of the profile. Only slight depletion was observed down to 1 m and very similar patterns of depletion occurred in consecutive seasons (Fig. 5.3). Ponderosa pine depleted up to 60 mm of water from the soil layer in both seasons and removed 20 mm of water from each rock layer down to 1.5 m depth in 1993 and 10 mm in 1994. Madrone expressed a different type of water depletion. Like Douglas-fir, madrone depleted 40 mm of water from the soil. It also depleted a measurable amount of water through all zones of the rock at the rate of  $>20$  mm per layer (Fig. 5.3). Manzanita was the most efficient in extracting water from soil, removing more than 70 mm in each season in addition to water extracted from the rock in 1993. Extraction from rock decreased in 1994, presumably due to inadequate recharge in deeper strata by below-average 1993/1994 winter precipitation. Manzanita depleted water to 2.25 m in 1994. Depletion below 2.25 m was less than 1993, but still around 10 mm per layer (Fig. 5.3).

In spring 1993, rain water through June was the most important source of transpired water for all species at  $>50\%$ . Later, lack of precipitation resulted in surface drying, hence depletion of the deeper water resource from soil/rock profile as gradual decrease of rainfall percentage was observed (Fig. 5.4). Soil water represented about 10% to 20% of water utilized through entire season in all cases. The rest of water came from the rock. In the 1994 growing season, Douglas-fir and madrone had patterns of water depletion very similar to those in 1993, but because of lower summer precipitation a larger contribution from rock was observed (Fig. 5.4) despite lower total water depletion from all layers. Ponderosa pine and manzanita had different patterns of resource uses in 1993 and in 1994. Lack of spring rainfall in 1994 caused reduced contribution of water stored in by soil nearly 50%. The rock contribution was also

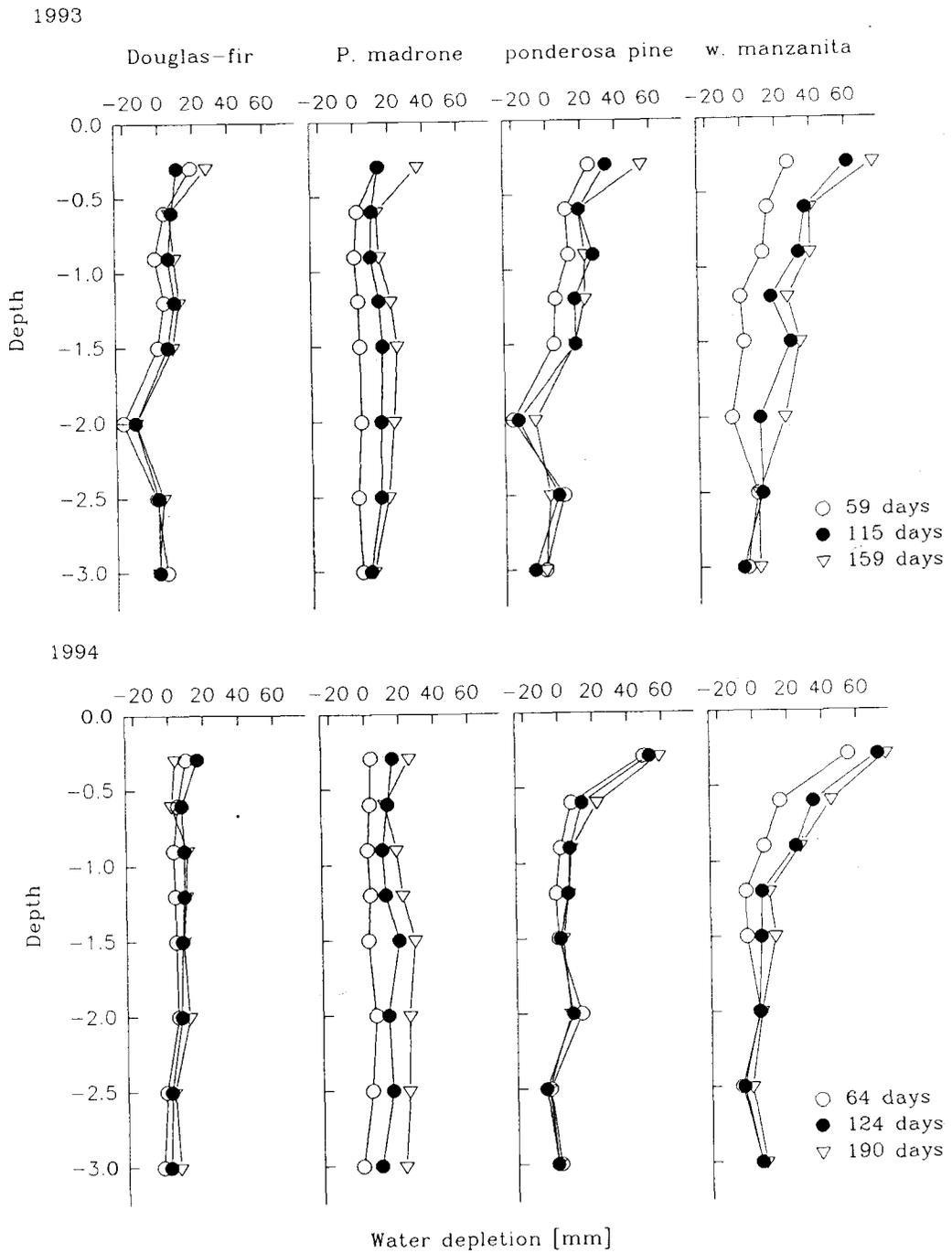


Figure 5.3. Depletion of water from different depths under different woody covers in two following seasons. Calculated errors for shown measurements are smaller than size of the points.

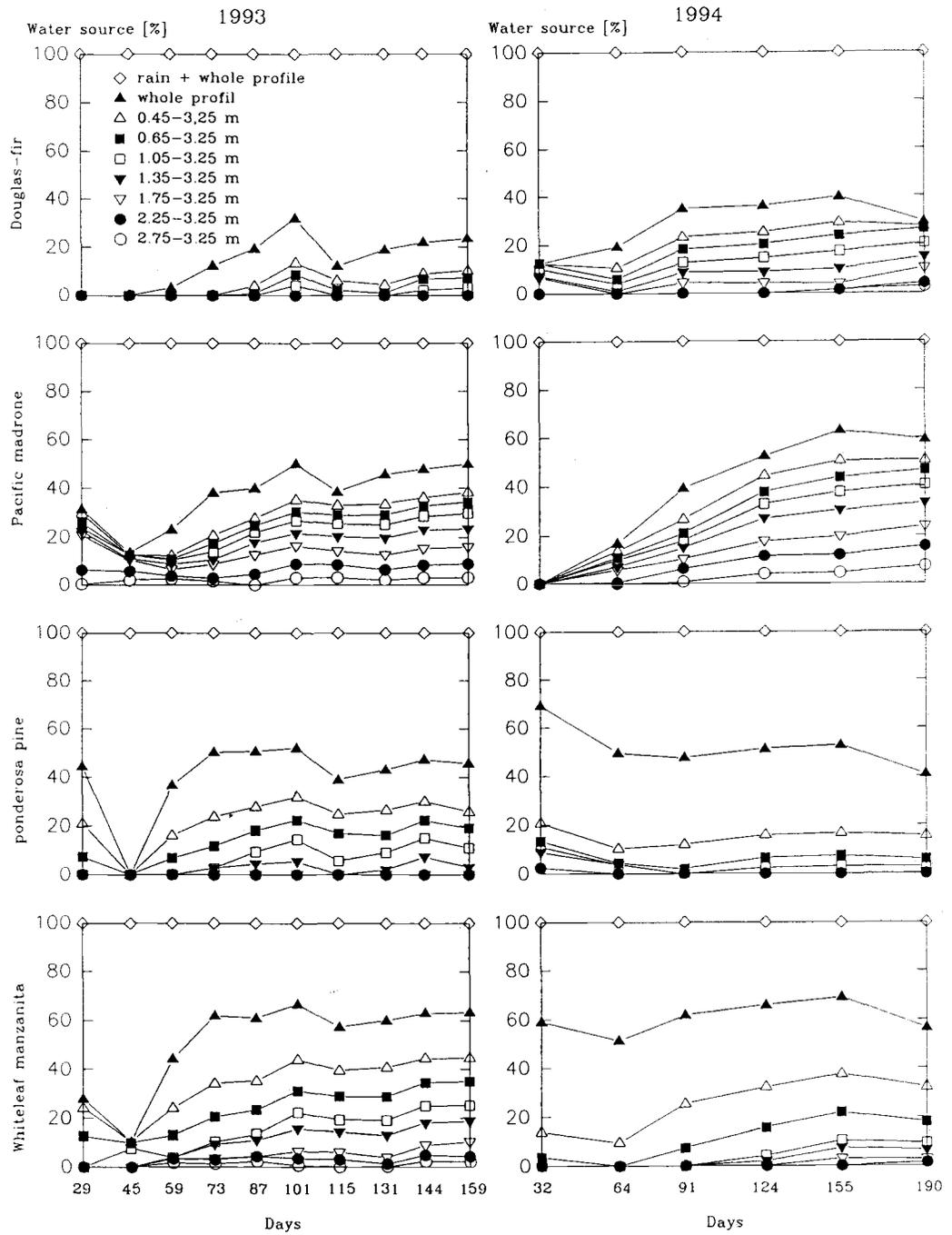


Figure 5.4. Seasonal changes in percentage of different water resource used by plants: rainfall, soil and rock layers.

smaller than that of the year before, specially from deep strata, presumably also due to lack of full recharge during dry 1993-1994 winter (Fig. 5.4).

In 1993 most of the summer rainfall occurred during April-May and June-July. Most of the water used by all species during this time was of rainfall origin. Deeper layers were used in spring only as a partial fulfillment of evapotranspiration, and mostly by madrone and manzanita. Later in the summer (August-September) all species decreased their rates of transpiration (measured as total depletion in two months period) below 50% of rates in prior periods (Fig. 5.5). Conifers depletion of water from rock was very limited. Most of their water came from soil despite some roots of ponderosa pine extending deep into fissures (Zwieniecki & Newton 1994). Madrone and manzanita used majority of water from rock layers. Nearly 60 % of total depletion occurred in this period from depth below 0.5. In 1994 rainfall distribution along summer was different from that in 1993. April-May and August-September were relatively rainy and majority of water used by plants was of rain origin during this periods. During dry period (June-July of 1994) water was depleted from deeper layer by all species. Total water depletion use was however distinctly smaller than that of more rainy periods. Depletion from layer below 1.75 m was negligible under pine and manzanita due to lack of full recharge of the this layer during winter of 1993-4 and contribution of shallower roots was most significant (Fig. 5.5). Rock water let manzanita maintain evapotranspiration at constant level and 3 to 4 times higher that of pine. Average rock density at the sites was  $2.25 \text{ g/cm}^3$  for all depths (Zwieniecki & Newton 1994). At the average density, available water holding capacity (AWC)(-0.1 to -1.5 MPa matrix water potential) is 6.15% by volume. AWC together with slowly available water (SAW), -0.1 to -4.0 MPa matrix water potential, is 7.85% (AWC and SAW are given on the basis of unpublished data Zwieniecki & Newton). Thus a typical meta-sedimentary, 2.8 m deep rock profile can hold 172.2 mm and 219.8 mm for AWC and AWC+SAW respectively. The 1992-3 winter was relatively wet and the soil/rock profile was fully recharged. The water depleted from the profile divided by water possibly stored in the profile in AWC and AWC+SAW times one hundred gives a percentage value of water resource used by vegetation. In 1994 the profile was not

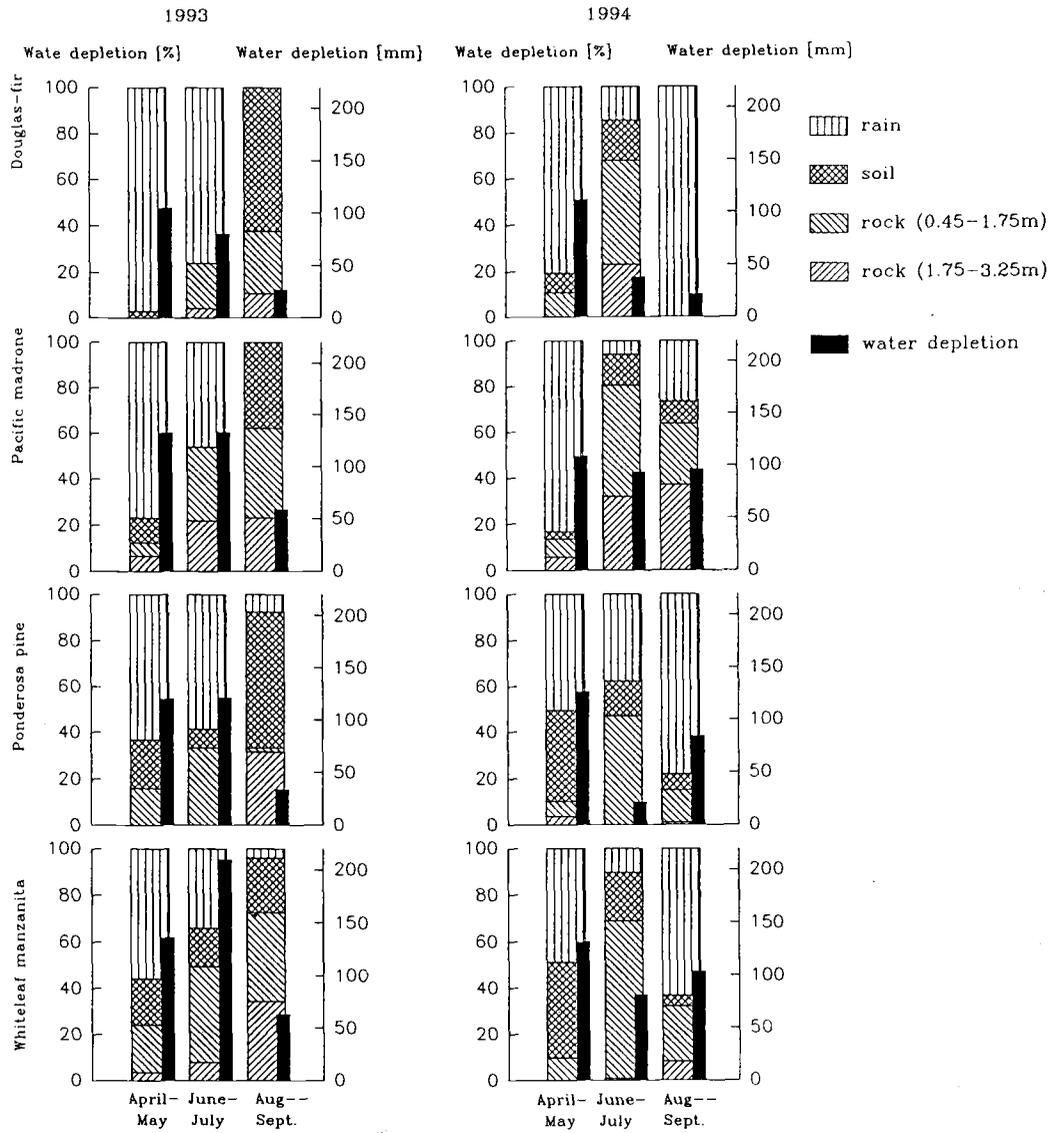


Figure 5.5. Percentage of different water resources utilized by plans in two month periods, and water depletion for this periods.

fully recharged especially on the second drier site. Thus the amount of available water at the start of the summer was decreased by the difference between neutron probe readings at the beginning of 1994 and 1993. Douglas-fir and Ponderosa pine used a maximum of 30% of all available water from the rock layer when fully recharged (Fig. 5.6). Madrone used more than 70% of all available water in 1993 and 96% in 1994, including all available water from AWC range. Manzanita had a pattern of water use very similar to that of madrone except that for manzanita we combined AWC and SAW water together because of ability of manzanita to deplete water from a much wider range of potentials than other species (Fig. 5.6).

## 5.5 Discussion

In non saline semi-arid climates such as mediterranean, water availability is the major limiting factor in plant ecosystem development. The ability of sites to store water and of plants to exploit it take on special significance (Rambal 1993). We have observed here that Pacific madrone and whiteleaf manzanita can gain access to twice as much water available for transpiration and production from summer rainfall and soil storage by utilizing water stored in bedrock. Some mediterranean species in Israel are also able to remove water from bedrock (Shachori et al. 1967) as are vines in southern France vineyards (Duteau 1987). In all evidence reviewed, the amount of water being depleted from the rock was approximately 200 mm. It appears that our observed phenomenon of water depletion from rock is widespread in semi-arid conditions around the world. Nevertheless, the data are very limited and exact evaluation to the degree to which this phenomenon influences semi-arid ecosystem development will require further refinement according to climate and soil zones.

Not all species are able to deplete water from the bedrock. Observed depletion under 14-year-old Douglas-fir was limited to the soil layer. Despite this, Douglas-fir was growing quite well while using less total water than less productive species

Potentially available water use [%]

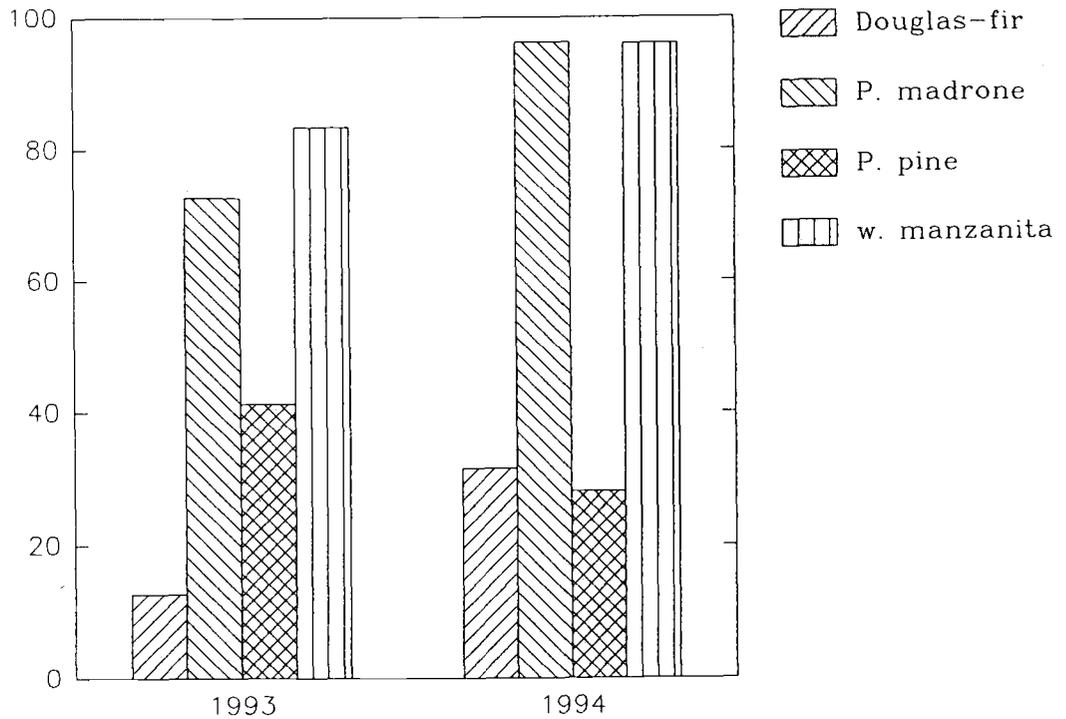


Figure 5.6. Percentage of uses of potentially available water form the bedrock by four different plants cover in two following years 1993 and 1994.

(Newton & Preest 1988). When summer drought was present and water from soil was nearly exhausted depletion dropped significantly. Although Douglas-fir did not deplete deeply, nearly 30% of water depleted was of bedrock origin from shallow layers in 1994. Former data on root distribution on these sites showed very limited ability of 14-year-old Douglas-fir to penetrate bed-rock (Zwieniecki & Newton 1994), thus it seems that lack of roots in bedrock was the major factor reducing the total amount of water taken from the rock. Slight depletion present during the dry period confirms that water is in the available range and that it can be depleted if roots reach it. Older Douglas-fir stands show considerably higher ability to penetrate the bedrock layer, perhaps expanding fissures down to 2 m (Wang et al 1995). Thus we can expect increasing contribution of bedrock water in total water used by older stands, and a gradual increase of site capacity to support higher tree biomass. We postulate that temporary periodic occupation of ericaceous shrubs/hardwoods may accelerate this process by providing root channels in fractured rock.

Ponderosa pine presents depletion patterns similar to those of Douglas-fir. During the dry period of the summer when soil water is depleted, the total depletion dropped significantly under pine but the water that was depleted came from the bedrock. However, low root density in the rock layer (Zwieniecki & Newton 1994) probably places an upper limit on depletion rate from the rock as in the Douglas-fir case but some what deeper.

Madrone and manzanita, both being ericaceous, have an ability to grow roots in the minute fissures of the bedrock (Zwieniecki & Newton 1995). Morphological adaptation of roots in very small cracks and at relatively high density allows depletion of a large amount of water during the dry period. Data presented in Newton & Zwieniecki (unpublished manuscript) shows also that roots from bedrock are highly efficient in terms of water uptake per unit of root length. In addition, low leaf water potential developed by manzanita can significantly contribute to water uptake from rock by allowing roots to develop a high suction gradient. This allows manzanita to deplete water from a wider range of matrix potential, extending to -4.0 MPa. This significantly increases available water content from 6.15% to 7.85% of the rock volume (on bases

of average rock bulk density) as was observed by Zwieniecki & Newton (1995 unpublished manuscript). Low leaf water potential was also observed for madrone and toyon sp. and it was suggested that this can contribute to total water uptake by those species (Morrow & Mooney 1974).

During spring, the rate of water depletion from soil was very similar under all measured plants, illustrating nearly equal ability to convert solar energy to latent heat of vaporization through transpiration. Differences show up exclusively during the dry period. Both conifers preserve water by stopping transpiration at times when ericaceous plants gradually shift to another water resource. This behavior is very important for management practices. Free development of ericaceous shrubs in mixture with conifers puts conifers in a disadvantageous competitive position. The high competitive power of ericaceous plants comes from their ability to use water that is unavailable to conifers, providing for continuous growth when coniferous plants have to stop growing. Soil is depleted by both groups of plants at the same time, thus deep-stored water promotes only growth of one group by extending the growing season selectively, and that group can occupy or capture resources already occupied by conifer roots, speeding the process of conifer exclusion from the site. We observed this directly as a function of density in the manzanita stands, when massive die-off of Douglas-fir 7-8-year-old plantations occurred during two consecutive dry years despite having clearly reached dominance (physically).

The percentage of rock water used by ericaceous plants shows that during summer they do reach and deplete most of the total available water, especially when summer and proceeding winter were relatively dry. Conifers of the same age showing evidence of water deficiency deplete only a very small percentage of available water from rock. We hypothesize that this difference of deep water resource uses can allow combination of groups of plants together for higher biomass production from a given area if one plant does not exclude the other. As is evident in the second site where most conifers were killed before age 14 even if they were three times taller than surrounding manzanita shrubs. The loss of most conifers before age 14 strongly suggests that below ground competition and exclusions is a major limitation in ecosystem development.

We did not observe a marked switch from soil to rock water use by ericaceous plants. Water was depleted gradually from the entire profile during summer. The rate of depletion was probably associated mostly with leaf water potential and water availability in the particular soil/rock water matrix potential. In the lower ranges of potential, more water is available in the rock than in soil (Zwieniecki & Newton unpublished manuscript) and it is possible that higher permeability of rock than soil at lower matrix potential can facilitate late summer rock water uptake as was observed for sandy and clay soils under dry sclerophyll forest in southern Australia (Carbon et. al. 1980) and woody plant cover in the Amazon basin (Nepstad et. al. 1994).

The above findings show how different strategies of woody plants are keyed to their ability to utilize water from bedrock, hence to form dominant communities somewhat independent of growth rate. For certain species bedrock has to be taken seriously as a major water resource and thus for site growth potential evaluation. Watershed analysis would be also seriously influenced by the type of plant cover and its ability to deplete bedrock water so to create sinks to serve as surge reservoirs. Water taken from bedrock has to be recharged during winter before winter storm flow can peak. Failure to take this water into account will significantly overestimate stream water outflow and recharge of ground water or resistance to water flow through the porous matrix calculated for the sites (Rowe & Coleman 1951).

## 5.6 Conclusions

1. Pacific madrone and whiteleaf manzanita are able to deplete water from bedrock during summer. This water significantly contributes to total water evapotranspired from sites where they or presumably other deeply rooted sclerophyll species grow..

2. Douglas-fir and ponderosa pine at age 14 lack ability to penetrate bedrock effectively and thus water uptake from the rock layer is very limited. They depend

largely on the soil reservoir and current rainfall. However, they also show evidence that water in rock could be utilized if a higher root density would be developed at older stands, provided sclerophyll cover is light enough to permit long-term survival.

3. Observed exclusion of conifers from dry sites by madrone and manzanita suggest that their ability to deplete deep water resources is advantageous in a semi-arid climate.

4. The amount of bedrock water depleted during summer is on the order of more than 200 mm and has to be taken into account for any projection of ecosystem development as well as for hydrologic modeling.

### 5.7 Acknowledgements

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## 6. Conclusions

On rocky sites with relatively shallow soils, tree roots present in the rock layer can tap water and nutrients held there and thus support the trees during a prolonged drought. Root morphology of the plants penetrating the rock fissures adjusts to the fissures environment, possibly facilitating its penetration, and increases root ability to utilize resources from the rock matrix. Currently used methods that restrict the investigation of vertical root distribution to the top 50–90 cm of soil should be modified to include any bedrock with measurable fissures.

Weathered and moderately weathered bedrock, with well-developed fissure networks penetrable by plant roots, can be a major source of water during prolonged summer drought for some plants in mediterranean-type ecosystems. This is especially true when soil is shallow and evapotranspiration demand exceeds water-storage capacity. Bedrock, having lower unit capacity but greater depth than soil, is a major storage reservoir. A high proportion of small pores can facilitate unsaturated water flow toward roots through the rock matrix, with no significant changes in resistance to water flow resulting from discontinuity.

Deeply rooted sclerophyll species like Pacific madrone and whiteleaf manzanita are able to deplete water from bedrock during summer. This water significantly contributes to total water evapotranspired from sites. Less adapted to harsh shallow soil environment conifers like Douglas-fir and ponderosa pine at age 14 lack ability to penetrate bedrock effectively and thus water uptake from the rock layer is very limited. They depend largely on the soil reservoir and current rainfall. However, they also show evidence that water in rock could be utilized if a higher root density would be developed at older stands, provided sclerophyll cover is light enough to permit long-term survival.

Observed exclusion of conifers from dry sites by madrone and manzanita suggest that their ability to deplete deep water resources is advantageous in a semi-arid climate and has to be taken seriously into account for projected ecosystem management tasks.

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