Modification of soil structural and hydraulic properties after 50 years of imposed chaparral and pine vegetation

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Abstract

Although biotic communities have long been recognized as important factors in soil development, especially of A horizons, few studies have addressed their influence on soil physical properties in nonagricultural settings. A biosequence of 50-year-old soils supporting near monocultures of Coulter pine (*Pinus coulteri*), scrub oak (*Quercus dumosa*), and chamise (*Adenostoma fasciculatum*) was used to determine the relative influence of vegetation type and associated soil organisms on the development of soil structural characteristics and water flow. Total porosity ranged from a high of 51% in the heavily worm-worked A horizon under oak to a low of 39% within the 35- to 50-cm depth under pine, where earthworms were absent. Macroporosity (pores with diameters >300 μm) was highest in the A horizon under oak (15.6%) and lowest under pine (9.5%). Saturated hydraulic conductivity of surface soils ranged from 10.8 cm h^{-1} under oak to 3.2 cm h^{-1} under pine. Soil under chamise, which had fewer earthworms than that under oak, had K_{sat} and bulk density values intermediate between oak and pine. Root and macrofauna distributions suggest that roots are the dominant factor in the development of macroporosity under pine, while earthworms have had the greatest effect under oak. Porosity has increased at an average rate of 0.22% per year in the 0- to 7-cm depth under oak (from 41% to 56%), but has not been significantly altered within the same depth under pine. Below the 7-cm depth, porosity values are similar for each vegetation type and the original parent material. Available water capacity (AWC) within the first 0- to 7-cm depth has increased from the original values (about 0.11 m^3 m^{-3}) to 0.17 m^3 m^{-3} under oak, 0.16 m^3 m^{-3} under chamise, and 0.13 m^3 m^{-3} under pine. The data show that the presence of

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burrowing macrofauna, which is determined by litter palatability and therefore indirectly controlled by vegetation, can significantly influence porosity, increasing the water-holding capacity of a soil.

1. Introduction

Biotic communities supported by a soil can exert a strong control on its structural attributes, thereby modifying its hydraulic processes (Oades, 1993). Roots contribute to the formation of aggregates directly by enmeshing particles, and indirectly through the production of exudates, which act as glue in soils (Oades, 1989, 1993). Plants alter wetting and drying cycles that are important to the stabilization of aggregates and formation of soil structure (Oades, 1989; Chadwick and Graham, 2000). Root channels with live or decaying roots can increase saturated hydraulic conductivity by serving as conduits for preferential flow. Root systems can also contribute to unsaturated flow in soils (Beven and Germann, 1982). The litter layer indirectly promotes formation of macropores by serving as a food source for burrowing soil fauna (Angers and Caron, 1998). Due to dietary requirements and preferences, this effect is plant species-dependent.

Soil-dwelling organisms have long been considered important in the development of soil macropore systems (Ehlers, 1975; Beven and Germann, 1982; Knight et al., 1992; van Vilet et al., 1998). Much research has concentrated on the importance of earthworms on soil hydraulic properties. Within 10 years of their introduction, earthworms have increased infiltration rates by 12–13 mm/h compared to soils with no earthworms (Stockdill, 1966). Macroporosity increased from 5.7% to 7.1% within 105 days following inoculation of lysimeter soils with earthworms (primarily *Aporrectodea caliginosa* and *Lumbricus rubellus*) (Knight et al., 1992). Total burrow length was correlated to K_{sat} ($r = 0.94$) in a column experiment with *A. caliginosa* (Joschko et al., 1992). Inoculated columns had percolation rates approaching 20 times those of control columns with no earthworms. Earthworm burrows have such a strong influence on soil physical properties, primarily water infiltration and aeration, because they are continuous, interconnected channels that are among the largest of soil pores (Lee, 1985). When earthworms are present, their casts, which are commonly more stable than other soil aggregates, often make up the majority of structural aggregates in the upper 10–20 cm of soil (Lee and Foster, 1991).

In this study, a biosequence within the San Dimas Experimental Forest (SDEF) in southern California was used to determine the relative influence of chaparral species (scrub oak and chamise) and pine, and their associated macrofaunal populations, on the development of soil physical and hydraulic properties. Previous studies of physical properties of the San Dimas biosequence soils have shown differences in soil morphology and clay distribution (Graham and Wood, 1991), and aggregate stability (Graham et al., 1995) between soils forming under oak and pine after only 50 years of pedogenesis. Research conducted at the SDEF biosequence has provided some of the most valuable

experimental evidence of the effect of tree species on soil structure (Binkley, 1995), warranting further studies of the physical and hydraulic properties of these soils. The overall goal of this study was to determine if changes in bulk density, pore size distribution, aggregate stability, and soil structure have been great enough to alter water flow and retention within each soil.

2. Materials and methods

2.1. Environmental setting

The SDEF is a US Forest Service watershed research facility in the San Gabriel Mountains, about 56 km northeast of Los Angeles, CA. The climate is of Mediterranean type with warm, dry summers and mild, wet winters. The annual precipitation averages 678 mm, most of which falls between December and March, and the mean annual air temperature is 14.4 °C (Dunn et al., 1988). Chaparral, the dominant vegetation type within the SDEF, is a sclerophyllous, fire-adapted community that occurs in zones of the southwestern US characterized by a Mediterranean climate (Steward and Webber, 1981). Two of the species used in this study, scrub oak and chamise, are dominant chaparral species in southern California (Steward and Webber, 1981; Hanes 1981). Unconfined (earthen-walled) pits measuring 5.3 × 5.3 × 2.1 m deep were constructed in 1937, at an elevation of 839 m, as part of a comprehensive lysimeter program to monitor changes in water availability under different plant communities. The pits, referred to as "lysimeters," were filled with soil material that had been excavated on site, homogenized, and sieved to remove rock fragments and aggregates greater than 19 mm in diameter. The fill material was fine, sandy loam derived from the weathering of diorite. During the filling of the lysimeters, samples were taken from every 7.5 cm fill increment and archived, providing knowledge of the system at time zero. After allowing for a settling period of 3 years (1937–1940), during which each lysimeter was covered with a mulch, excess fill material was removed from the surface and the lysimeters were planted with an annual grass (*Bromus mollis* L.). Six years later (1946), the grass was burned and replaced with monocultures of native species, including chamise (*Adenostoma fasciculatum* Hook. and Arn.), scrub oak (*Quercus dumosa* Nutt), and Coulter pine (*Pinus coulteri* B. Don.). The design of the lysimeters, with slopes of 5% and south aspects, minimized variation of all environmental conditions except vegetation (Colman and Hamilton, 1947; Patric, 1961), creating a true biosequence.

2.2. Field methods

In order to minimize disturbance to this unique experiment, pedons that were originally studied in 1987 (Graham and Wood, 1991) were reexcavated and slightly expanded to obtain samples from freshly exposed material. Three replicate pedons each under Coulter pine, scrub oak, and chamise stands were described and sampled by morphological horizons, except for the C horizons, which were arbitrarily separated by depth. Selected morphological, chemical, and physical properties from each pedon are shown in Table 1.

Table 1
Selected morphological, chemical, and physical data from pedons under pine, oak, and chamise

Horizon	Depth (cm)	Color		Roots[a]	Structure[b]	pH[c]	OC (g kg^{-1})	Sand[d]	Silt[d] (g kg^{-1})	Clay[d]	Total porosity[e] (%)
		Dry	Moist								
Pine											
Oi1	10–6	Fresh pine needles, twigs, some grass									
Oi2	6–4	Partially decomposed pine needles									
Oe	4–0	Mostly decomposed pine needles									
A	0–1	10YR4/4	10YR4/3	3vf, 2f	2msbk	5.22	31.5	610	300	90	n.d.
BAt	1–10	10YR5/4	7.5YR4/4	2vf and f, 1m and co	2msbk	5.73	6.3	580	310	110	41
Bt	10–20	7.5YR5/4	7.5YR4/4	1vf-co	1msbk	5.86	4.9	580	300	120	41
BCt	20–35	7.5YR5/4	7.5YR4/4	1vf-m	M	6.07	4.9	570	320	120	41
C1	35–50	7.5YR5/4	7.5YR4/4	1vf-co	M	6.10	2.9	570	310	120	39
C2	50–65	7.5YR5/4	7.5YR4/4	1vf-co	M	6.14	2.4	580	310	110	40
Oak											
Oi	7–0	Fresh oak leaves, twigs, worm casts, and some pine needles									
A	0–7.5	10YR5/3	10YR3/3	2vf and f	3fsbk → 3fgr	5.69	24.9	540	320	140	52
AC	7.5–20	10YR5/4	7.5YR4/4	2vf-m	1msbk → m	5.39	5.4	580	300	110	43
C1	20–35	7.5YR5/4	7.5YR4/4	1vf and co	M	5.44	2.6	580	310	110	42
C2	35–50	7.5YR5/4	7.5YR4/4	1vf and co, 2f and m	M	5.63	2.3	570	310	120	40
C3	50–65	7.5YR5/4	7.5YR4/4	1vf and co, 2f and m	M	5.57	2.0	580	310	110	40
Chamise											
Oi	3–0	Fresh chamise leaves, twigs, and worm casts									
A1	0–1	10YR4/4	10YR3/3	1vf	3msbk → 3fgr	5.63	43.8	580	310	110	n.d.
A2	1–7	10YR5/4	10YR4/4	2vf and f	2msbk	5.86	9.9	580	320	110	46
AC	7–20	7.5YR5/4	10YR4/4	2vf and f	1msbk	5.90	4.2	590	300	110	41
C1	20–35	7.5YR5/4	7.5YR4/4	2vf-m	M	5.65	2.7	580	310	110	40
C2	35–50	7.5YR5/4	7.5YR4/4	2vf-m	M	5.57	2.1	560	320	120	40
C3	50–65	7.5YR5/4	7.5YR4/4	2vf-m	M	5.53	2.5	570	320	110	40

During the 1996 excavations, volumetric soil samples averaging 0.01 m^3 were hand-sorted to remove all soil macrofauna (body length >10 mm) and coarse (>5 mm in diameter) and medium-sized (2–5 mm in diameter) roots. The depth intervals for volumetric samples corresponded to the soil horizons and sampling was continued to 100 cm in one pit, and 65 cm in the other two. Macrofauna, which were rarely found below the 50-cm depth, were counted and identified. Root diameter and length were measured in the laboratory. Between four and seven replicate clods ranging from about 40 to 200 cm^3 were extracted from each horizon for determination of bulk density in the laboratory using the saran-coated clod method (Natural Resources Conservation Service, 1996). Four soil cores (5 cm diameter × 6 cm long) were collected from each horizon.

2.3. Laboratory methods

Soil cores were placed in Tempe cells and saturated hydraulic conductivity (K_{sat}) was determined using the falling head method (Klute and Dirksen, 1986). The same cores were subsequently prepared for water retention measurements. After covering the bottom of each core with cheesecloth, they were placed in water and allowed to saturate. Saturated cores were placed on a tension table and allowed to drain at a certain potential (-0.001 to -0.006 MPa); once equilibrium was reached, the core was weighed and volumetric water content calculated for that tension. A pressure plate apparatus was used to collect moisture content data at lower soil water potentials (-0.01 to -1.5 MPa).

Pore size distribution data were obtained from water retention data (Danielson and Sutherland, 1986) using the relationship between soil water potential and pore radius:

$$r = -2\gamma\cos\theta/h\rho g \tag{1}$$

where h is the soil water potential (cm), γ is the surface tension, θ is the contact angle water makes with the surface of mineral particles (assumed to be zero), r is the radius of a cylindrical pore, ρ is the density of water, and g is the acceleration due to gravity. Although there may be errors associated with the water desorption method for calculating pore size distribution, it is the most commonly used technique and, when done carefully, gives relatively accurate and useful results (Danielson and Sutherland, 1986). Macropores have been defined in the literature as having diameters from 30 to 10,000 μm (Beven and Germann, 1982). In this study, macropores will be considered to have a diameter >300 μm because the smallest diameter of earthworm channels found in the biosequence soils was approximately 300 μm.

Notes to Table 1:

[a] 1 = few (<1 gm^{-2}), 2 = common (1–5 dm^{-2}), 3 = many (>5 dm^{-2}); vf = very fine, f = fine, m = medium, co = coarse.

[b] 1 = weak, 2 = moderate, 3 = strong; f = fine, m = medium, sbk = subangular blocky, gr = granular, M = massive, → = parting to.

[c] pH determined on 1:1 soil:water mixture.

[d] Reported by Graham and Wood (1991) for samples from 1987 sampling of the same pedons.

[e] Calculated from 1996 bulk density (determined using saran coated clods) assuming particle density of 2.65 Mg m^{-3}.
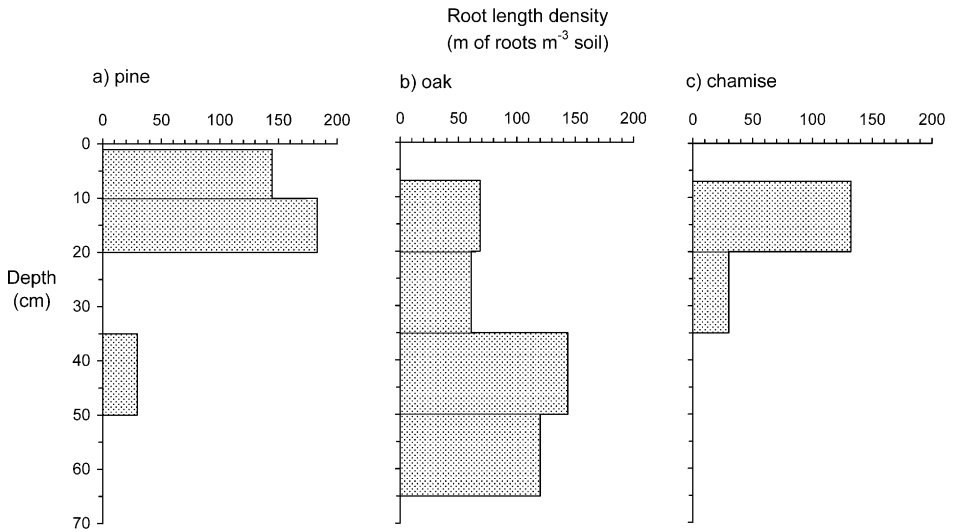
Fig. 1. Distribution of roots (>2 mm) with depth under (a) pine, (b) oak, and (c) chamise. Sampling was done in March 1997. Roots were sampled to a depth of 65 cm. Lack of horizontal bar indicates that no roots >2 mm roots were present for that depth.
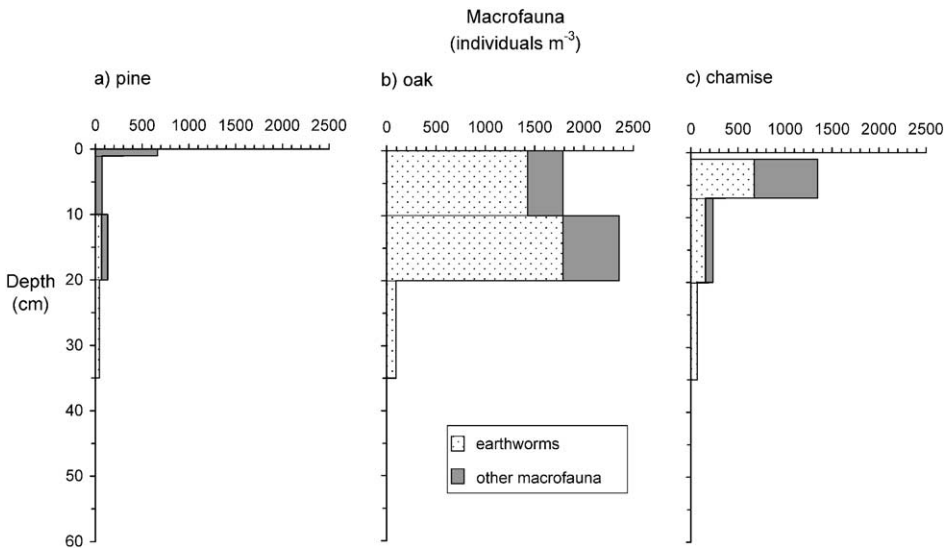

Fig. 2. Distribution of macrofauna with depth under (a) pine, (b) oak, and (c) chamise. Sampling was done in March 1997 to a depth of 50 cm. Lack of a horizontal bar indicates that macrofauna were absent from that depth. The presence of earthworms under pine in a single pedon is probably due to its proximity to an invading shrub (*Ribes* sp.). No earthworms were found in the other pedons sampled under pine (data not shown).

3. Results

3.1. Root and macrofauna distributions

Pine had more roots >2 mm in diameter in the top 20 cm of soil than did oak or chamise (Fig. 1). The greatest density of roots >2 mm in diameter under oak was found at the 35- to 50-cm depth while pine and chamise had more roots of this size above 20 cm.

Oak supported larger populations of macrofauna than did pine and chamise (Fig. 2). Macrofaunal communities under oak consisted predominately of earthworms, while
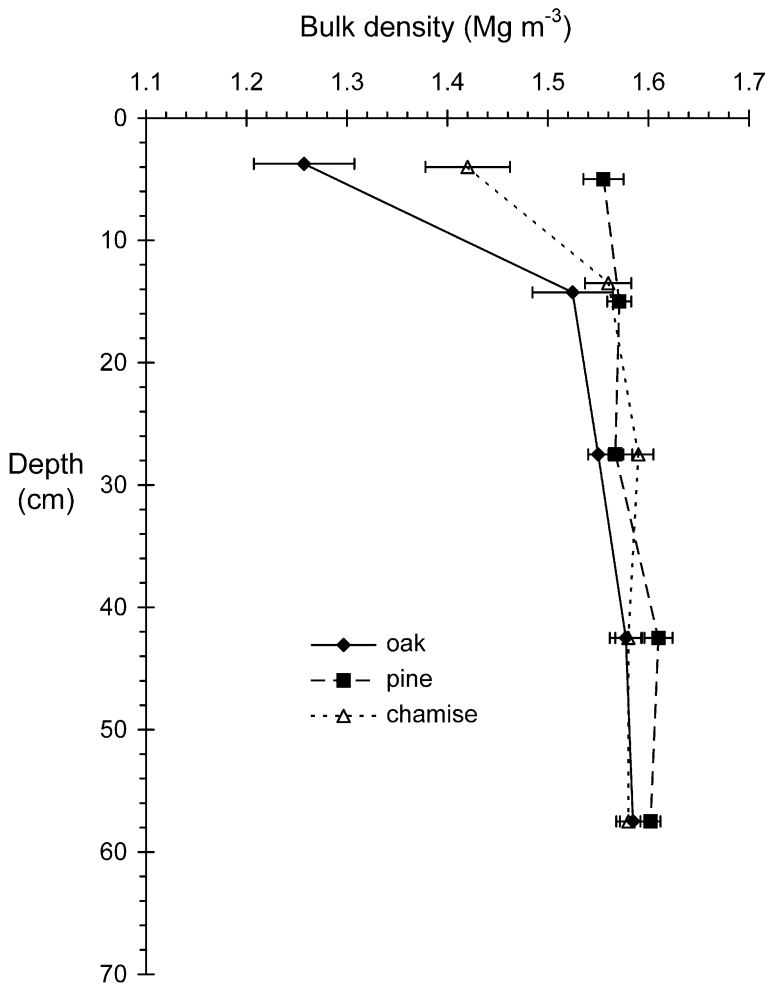

Fig. 3. Bulk density with depth in soils supporting oak, pine, and chamise. Horizontal bars represent standard error.

populations under chamise were more evenly distributed between earthworms and other macrofauna. Under pine, earthworms were found in only one of the three pedons and most of the macrofauna were found within the thin (0–1 cm) A horizon. All earthworms were identified as *A. caliginosa* or *Aporrectodea trapezoides* (A. Peterson and P.F. Hendrix, personal communication, 1998). The origin of the nonnative earthworms sampled under oak and chamise is unknown. It is reasonable to assume, however, that they were introduced during planting of the lysimeters or nearby areas (Graham et al., 1995). *A. caliginosa* and *A. trapezoides* are classified as endogenic earthworms, which are medium-
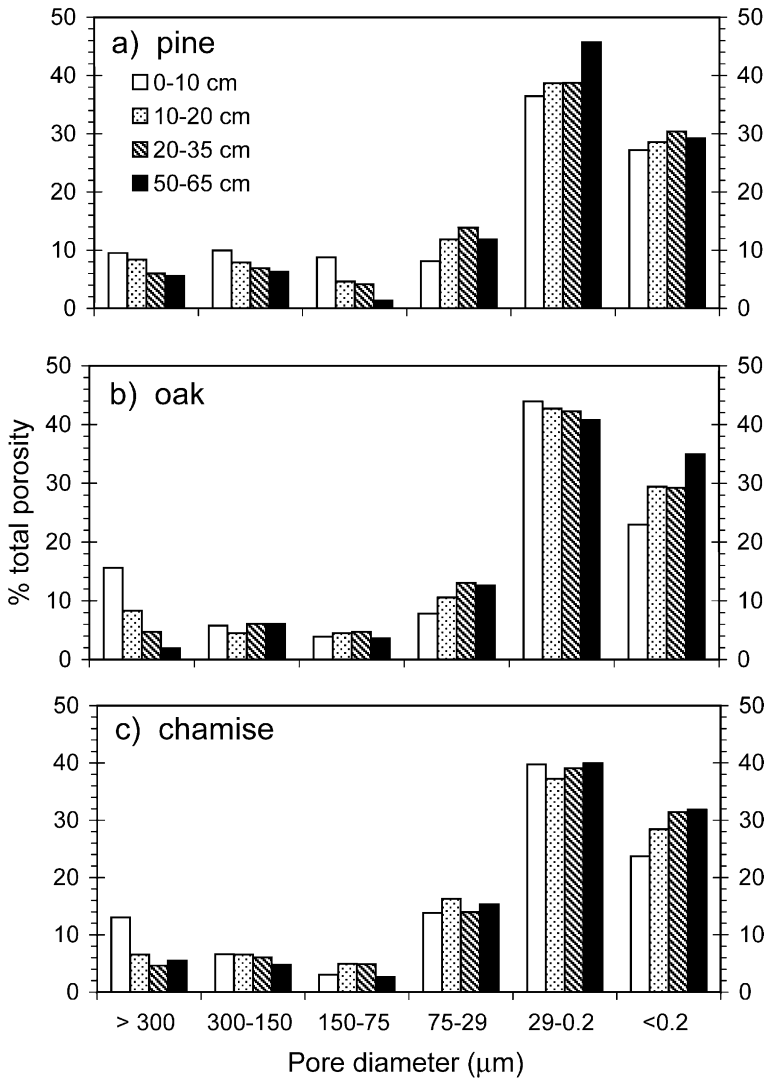

Fig. 4. Effective pore size distribution with depth for soils supporting (a) pine, (b) oak, and (c) chamise.

sized, live in organo-mineral horizons, and feed on soil enriched in organic matter (Bouché, 1977). Other soil macrofauna collected included spiders, ground beetles, centipedes, millipedes, and ants.

3.2. Soil structure

In these biosequence soils, obvious structural units have developed in the top 20 cm of each soil during the 50-year period of soil formation. Below 20 cm, each soil lacks
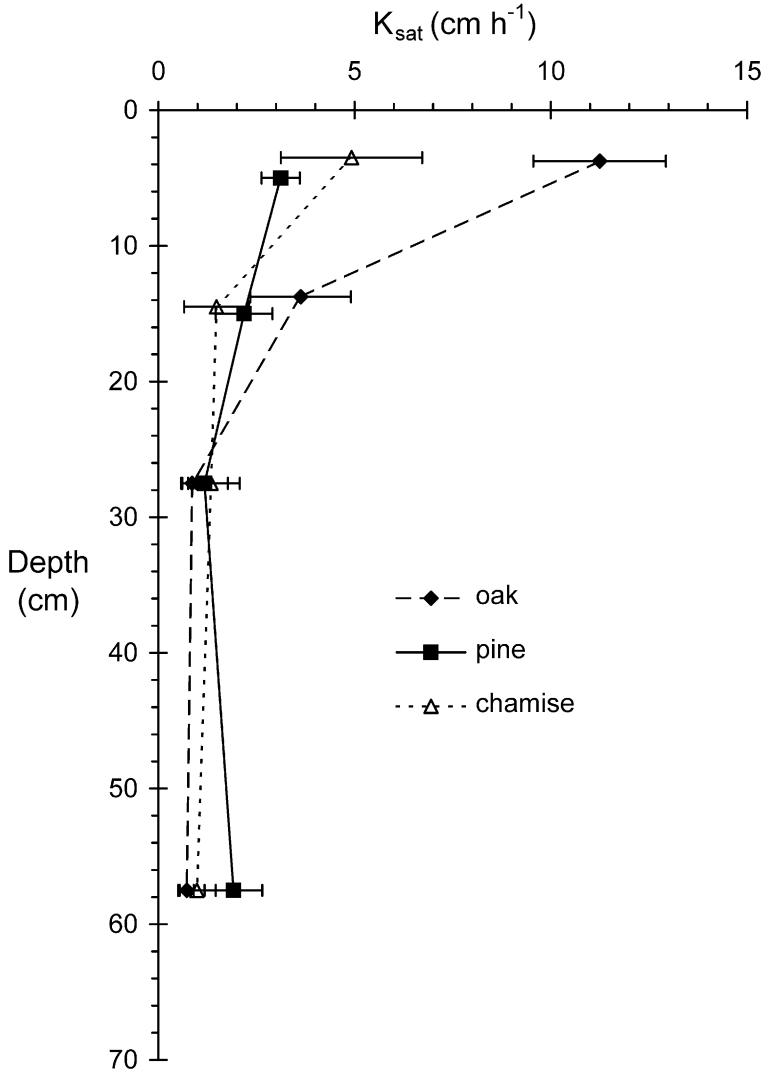

Fig. 5. Saturated hydraulic conductivity with depth in soils supporting oak, pine, and chamise. Horizontal bars represent standard error.

structure and is massive. Under oak and chamise, the A horizons are characterized by fine and medium subangular blocky structure that parts into fine granules (Table 1). Soil structure in the pine A horizon is somewhat coarser, subangular blocky, and does not display any granular properties.

3.3. Bulk density and pore size distribution

Bulk density was lowest in the surface horizons and increased with depth under each vegetation type. Bulk density values ranged from 1.26 Mg m^{-3} in the heavily worm-worked A horizon under oak to 1.61 Mg m^{-3} for the 35- to 50-cm depth under pine (Fig. 3).

Effective pore size distributions, calculated from water retention data from the 0- to 7-cm depth of each soil, show that pores >300 μm in diameter make up 9.5% of total porosity under pine (Fig. 4a), 15.6% under oak (Fig. 4b), and 13.0% under chamise (Fig. 4c). The percentage of pores with diameters >300 μm generally decreases with depth in all three soils. This trend was most pronounced under oak, where pores >300 μm diameter decreased from 16% in the A horizon to 2% in the C horizon (50–65 cm).

3.4. Alteration of K_{sat} and AWC

Saturated hydraulic conductivity values ranged from 11.2 to 0.72 cm h^{-1} (Fig. 5). In the upper 7 cm of soil, K_{sat} values were highest under oak (11.2 cm h^{-1}), followed by
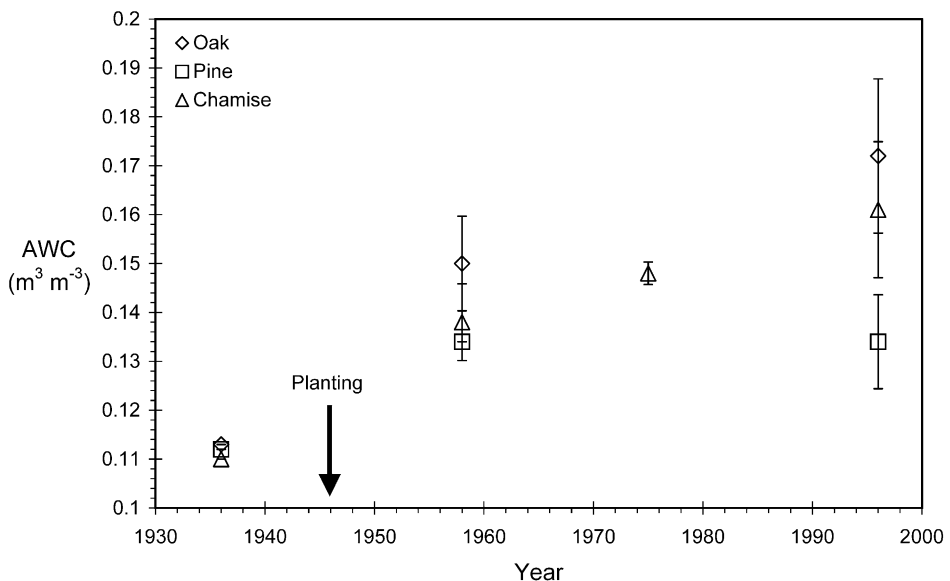

Fig. 6. Available water capacity (AWC) calculated from 0.03 and 1.5 MPa volumetric water contents for the 0- to 7-cm depth under pine, oak, and chamise. Data for 1936, 1958, and 1975 are from Zinke (unpublished data, 1977).

chamise (4.9 cm h^{-1}), and were lowest under pine (3.1 cm h^{-1}). Below the 25-cm depth, K_{sat} values were similar under all three vegetation types.

From 1936 to 1958 (the first 12 years of the experiment), available water capacity (AWC) of the 0- to 7.6-cm depth under oak increased from 0.11 to 0.15 m^3 m^{-3} (Fig. 6). During the same 12 years, the AWC increased from 0.11 to 0.14 m^3 m^{-3} under chamise, and from 0.11 to 0.13 m^3 m^{-3} under pine. Since 1958, AWC has not increased under pine. By 1996, the AWC showed a clear difference between the chaparral (AWC$_{oak}$ = 0.17 m^3 m^{-3} and AWC$_{chamise}$ = 0.16 m^3 m^{-3}) species and pine (AWC$_{pine}$ = 0.13 m^3 m^{-3}).

4. Discussion

4.1. Soil structure

The strong expression of granular soil structure under oak and chamise is due to the presence of earthworm fecal casts. Earthworm casts made up 95% of the A horizon under oak and 50% of the A horizon under chamise. Worm casts are an intimate mixture of fine mineral grains and decomposing, mucilage-coated organic fragments as well as polysaccharide-producing fungi (Shipitalo and Protz, 1988; Satchell, 1983; Graham et al., 1995). Upon drying, earthworm casts can exhibit much higher degrees of aggregate stability than "noncast" aggregates. Aggregate stability, within A horizons, was found to be 15% greater under oak than pine (Graham et al., 1995) after 41 years of pedogenesis in these same biosequence soils. Under oak and chamise, granules made of individual casts are aggregated, forming small subangular blocks that can easily be broken into individual granules.

Under pine, the subangular blocky structure is not expressed as strongly, and does not break down into smaller granules. Granular structure, which is generally associated with the extensive fine root system found in grasslands, is present under the chaparral species and absent under pine where there are more roots of this size (Table 1). This demonstrates the importance of earthworms in promoting good soil structure in chaparral soils. Granular structure is less common than subangular blocky structure within these soil–plant systems, and is noted to be a major diagnostic property of chaparral soils that support earthworms (Wood and James, 1993).

Wetting and drying cycles have been shown to influence the expression and size of peds (Chadwick and Graham, 2000). Although oak and pine A horizons wet and dry at similar rates (Johnson-Maynard, 1999) they have very different soil structures. Taken together, the data show that the order of importance in determining soil structure and hydraulic properties in these soils is macrofauna>roots>microclimate.

4.2. Bulk density and pore size distribution

Although pine has more medium and coarse roots in the top 10 cm of soil (Fig. 1), the lowest bulk density (highest porosity) values were under oak and chamise (Fig. 3), suggesting that medium and coarse roots, alone, are not a major contributor to total porosity in these soils. Although total porosity has not significantly changed under pine, a positive

correlation was found between roots and macroporosity ($r = 0.91$), suggesting that roots have altered the size distribution of pore space under pine. As roots decompose, they leave behind channels, thereby increasing the pore space (decreasing the bulk density) of the soil.

Under oak and chamise, the horizons with the highest earthworm densities (Fig. 2) correspond to those with the lowest bulk densities (highest porosities) (Fig. 3). Earthworms can create porosity over relatively short time spans (Joschko et al., 1992; Knight et al., 1992) through their burrowing and subsurface casting activities (Satchell, 1967; Edwards and Lofty, 1977). Macrofauna and roots are considered the major biological agents determining bulk density of a soil (Glinski and Lipiec, 1990; Coleman and Crossley, 1996). In the pine biosequence soils, where earthworms are absent, total porosity has not significantly changed over the 50 years of soil formation.

Earthworm burrowing has likely increased macroporosity in the 0- to 7-cm depth under oak and chamise, as compared to macroporosity in the same depth under pine (Fig. 4). Earthworms have created macropores that reach the soil surface under oak. These pores are probably more important to infiltration during heavy rains than to saturated flow within the profile because saturation of the soil rarely occurs. During a 2-year monitoring period (1997–1998), the 0- to 7-cm depth under chamise reached saturation on only 1 day, while the pine (0–10 cm) and oak (0–7.5 cm) soils did not reach saturation at any time (Johnson-Maynard et al., 1999).

4.3. Alteration of K_{sat} and AWC

Higher K_{sat} values in the top 7 cm under oak and chamise, as compared to under pine, correspond to increases in porosity relative to the original fill material. The creation of water-conducting macropores by earthworms is likely responsible for increases in K_{sat}. Under oak, K_{sat} is an order of magnitude faster in the A horizon, where earthworms are abundant, than in the C horizon (Fig. 5), demonstrating the effectiveness of burrowing earthworms at altering hydraulic properties. At depths where earthworm density is low or nil, the K_{sat} under oak is only slightly lower than that of the 0- to 10-cm depth under pine, where earthworms are absent. Comparison of K_{sat} values of the A horizon under oak to those of the relatively unaltered C3 horizon (50–65 cm), and between oak and pine soils, indicates that earthworms have increased K_{sat} by an order of magnitude over a 50-year period.

Although the changes in K_{sat} shown in this study are lower than the reported increase in K_{sat} from 4 to 93 cm h^{-1} in the top 10 cm of a grassland soil 8 years after the introduction of earthworms (Hoogerkamp et al., 1983), both examples demonstrate that earthworms can substantially increase K_{sat} within relatively short time spans. Furthermore, no prior information on the importance of earthworms relative to hydraulic behavior in chaparral ecosystems is available in the literature. The effect of earthworms on K_{sat} in these soils is limited in depth due to the feeding habits of the worms. The relatively shallow burrowing A. caliginosa and A. trapezoides could be beneficial in managed systems with deep soils because they increase porosity and water movement within the root zone, but may not encourage deeper leaching that would move nitrate or pesticides to the water table.

The available water capacity under pine has not appreciably changed since 1958, despite the above and below ground additions of organic carbon from the well-established

stand and the redistribution of pore space caused by roots in the 0- to 7-cm depth. Higher AWC values found within this depth under oak and chamise are ultimately due to an increase in the percentage of pores that drain between -0.03 and -1.5 MPa (equivalent diameter of approximately $0.2–10$ µm). Increased pore space in the range of $0.2–10$ µm is due to a combination of pores created by very fine roots (<1 mm in diameter), casting activity of earthworms (Syers and Springett, 1983), and direct incorporation of organic matter by earthworms (Stockdill and Cossens, 1966; Syers and Springett, 1983). In the top 10 cm of soil, pine had more or similar amounts of very fine roots than did oak (Table 1). Despite the greater or equal density of roots under pine, AWC values were lower than in the chaparral soils. Apparently, earthworms have been the major force in the development of AWC in the chaparral soils.

5. Conclusions

Depending on the palatability of each vegetation type, macrofauna populations that differ in size and composition have developed under each vegetation type. Indirectly, through their ability to support earthworms, the chaparral species have significantly increased both the rate and expression of soil structure, total porosity, and pore size distribution. Over the 50-year period of soil formation, the alteration of these physical properties resulted in measurable differences in hydraulic properties as demonstrated by higher K_{sat} and AWC.

Acknowledgements

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