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Decade-scale changes of soil carbon, nitrogen and exchangeable cations under chaparral and pine

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Abstract

Four large lysimeters on the San Dimas Experimental Forest, each filled with similar parent material and planted with monocultures of native species in 1946, provide a unique opportunity to quantify short-term effects of plant species on soil properties. The four species under which soils were investigated are scrub oak (Quercus ***dumosa*** Nutt.) , chamise ***(Adenostoma fasciculatum*** Hook. and Am.), ceanothus ***(Ceanothus crassifolia*** Torr.), and Coulter pine ***(Pinus coulteri*** B. Don). A mass-balance approach was used to measure changes in C, N, exchangeable base cations, and exchangeable acidity to a depth of 1 m in the mineral soils over a 41-year period. The C content increased in all of the soils, but the greatest change was in the soil under oak (3.7 kg m^{-3}), more than doubling the original amount. Since the source of C in these soils is the photosynthetic fixation of atmospheric CO_2, the mass of C accumulated reflects the magnitude of the CO_2 sink provided by chaparral soils in their initial stages-of formation. The calculated rate of soil C accumulation is as much as 0.09 kg m^{-3} yr^{-1}. The increase in N was highest in the soil under ceanothus (0.12 kg m^{-3}), the only N_2-fixing species in this study. Exchangeable Ca increased by 25.7 mol m^{-3} in the soil under oak, while the maximum increase in exchangeable Mg was 5.5 mol m^{-3} also under oak. Exchangeable Na was leached from all of the soils (a maximum of 2.4 mol m^{-3} lost from under chamise and ceanothus) and K was slightly depleted.

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1. Introduction

Soil chemical conditions of chaparral and conifer ecosystems in the Transverse and Peninsular Ranges of southern California have been reported (Vlamis et al., 1954; Hellmers

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et al., 1955; Hanawalt and Whittaker, 1977; Graham et al., 1988; Taylor et al., 1990), but the existing data document soil properties that developed in response to environmental conditions that are only partially known, over indeterminant, but generally long, time periods. To fully understand the more immediate implications of vegetation changes on soil chemical conditions, carefully controlled, relatively short-term experiments are required. These experiments must produce baseline data against which future changes can be measured. Such an experiment has been in progress on the San Dimas Experimental Forest in southern California.

The biotic soil forming factor (Jenny, 1941) is difficult to assess since vegetation commonly covaries with other factors such as climate, parent material, topography, and time. The soils of the large unconfined (earthen-walled) lysimeters at the San Dimas Experimental Forest provide a unique opportunity to quantify short-term effects of plant species on soil properties because the biotic factor is the only variable in a sequence of soils. The lysimeters (5.3 m by 5.3 m by 2.1 m deep) were filled in 1937 with homogenized sandy loam and, after a 9-yr stabilization period, were planted with monocultures of species native to the southern California mountains (Colman and Hamilton, 1947).

Previously, Graham and Wood (1991) demonstrated significant morphologic development and clay redistribution in the lysimeter soils and found that these changes were controlled, and varied, by plant species. In this study, we used a mass-balance approach to quantify subtle changes of C, N, exchangeable base cations, and mineral-derived nutrient pools within these mineral soils. Our goal is to develop data for prediction of relatively short-term (on the order of decades) soil property changes as influenced by native plant species.

2. Materials and methods

2.1. *Site description*

The site is located on the San Dimas Experimental Forest, 56 km northeast of Los Angeles, California, at an elevation of 830 m in the San Gabriel Mountains. The annual precipitation averages 678 mm and ranges from 292 to 1224 mm (Dunn et al., 1988). Most of the precipitation falls as rain between December and March. The mean annual air temperature is 14.4°C (Dunn et al., 1988) and the lysimeter soils probably satisfy the mesic temperature regime criteria (Graham and Wood, 199 1) The natural vegetation of the surrounding area is chaparral, dominantly chamise, hoaryleaf ceanothus, bigberry manzanita *(Arctostaphylos glauca* Lindl.), and scrub oak.

2.2. The lysimeters

The lysimeters were designed and arranged to minimize variation of all environmental influences except vegetation (Colman and Hamilton, 1947; Patric. 1961 a, b). A detailed description of the lysimeter installation and the soils is given by Patric (1961a) and Graham and Wood (1991). The lysimeters *were* excavated by hand and the soil material, derived from weathered diorite, was mixed thoroughly, passed through a 19 mm mesh screen. and stockpiled in a large, covered building. Analyses at the time showed no statistically significant difference in texture (fine sandy loam) in 100 random samples taken from the stockpile (Patric, 1961b).

The lysimeters were filled in 7.5 cm thick increments, each successive layer being chopped thoroughly with a flat-bladed spade after placement to insure uniform packing. Composite samples of each layer were collected during filling and archived in glass jars. A 5% slope was imposed on the lysimeter soil surfaces. In 1946, after a 9 yr settling period, monocultures of scrub oak, ceanothus, chamise, and Coulter pine were established on 17 m by 24 m areas, each including an unconfined lysimeter and surrounding buffer strips.

In 1960, a wildfire swept the lysimeter plots, introducing a typical chaparral ecosystem process. Photographic records show that the chamise and ceanothus stands were burned completely, leaving only charred stems. The oak and pine were less affected, with only spotty burning of litter under the oak and a light bum of loose needle litter (but not duff) under the pine (P.J. Zinke, 1994, pers. commun.) The chamise and ceanothus resprouted, and all stands were again vigorous and virtually pure by 1972 (J.H. Patric, 1974, unpubl. data) and persisted as such to the present.

2.3. *Field and laboratory methods*

In 1987, three pedons from each of the lysimeters were described and sampled by morphologic horizon using conventional procedures (Soil Conservation Service, 1984). In each case, one pedon was sampled to 1 m and two other pedons were sampled to 0.35 m. The soil morphological and physical properties are reported by Graham and Wood (199 1) . Bulk samples were air dried and sieved to remove coarse fragments (> 2 mm). Particle-size distribution was determined by the pipet method (Gee and Bauder, 1986). Carbon and exchangeable cations were measured in all three pedons, while N and exchangeable acidity were determined on only the 1 m deep pedon. All analyses were also performed on corresponding depths of the archived parent material from each lysimeter.

Bulk density of the soils sampled in 1987 was determined in triplicate for the 1 m deep pedon using Saran-coated clods, or cores in the case of thin, fragile A horizons (Soil Conservation Service, 1984). Bulk densities were not corrected for gravel contents, which ranged up to 12% (Graham and Wood, 1991). Bulk density of the original soil material was calculated from the known volume of the lysimeters and the mass of soil added (Patric, 1961b).

Effective cation exchange capacity (ECEC) was calculated from the sum of base cations and exchangeable acidity. Extractable base cations, determined using an automatic vacuum extractor and 1M NH_4OAc at pH ‘7.0 (Soil Conservation Service, 1984), are equivalent to exchangeable base cations because $CaCO_3$ and soluble salts were absent. Exchangeable acidity was determined by extracting with 1M KC1 at the pH of the soil and titration with O.lM NaOH (Thomas, 1982).

Soil pH was determined on 1: 1 soil:water mixtures with a glass electrode. Total N was measuredusing the Kjeldahl method (Bremnerand Mulvaney, 1982). Total C was measured by dry combustion (Nelson and Sommers, 1982).

2.4 Mass balance calculations

The derivation and application of mass-balance equations to hydrochemical and pedogenic processes are discussed in detail by Brewer (1964), Brimhall et al. (1992), and Chadwick et al. (1990). Volume, dry bulk density, and chemical composition of the parent material and 1987 soils are related to mass fluxes into or out of the profile. Analysis of the archived parent material, corresponding to the depths sampled in 1987, permitted the calculation of changes in chemical composition over a 41 yr period.

The first step in computing mass changes due to pedogenesis is the determination of strain, $\epsilon_{i,w}$, a measure of soil volumetric changes due to additions and losses of material. Strain is calculated using the equation from Brimhall and Dietrich, (1987):

$$\epsilon_{i,w} = \frac{(\rho_p)(C_{i,p})}{(\rho_w)(C_{i,w})} - 1$$

where p,, is the parent material bulk density, $C_{i,p}$ is the concentration (in weight percent) of an immobile component *i* in the parent material, ρ_w is the weathered soil bulk density, and $C_{i,w}$ is the concentration of *i* in the weathered soil.

The medium plus coarse sand fractions (0.25 to 1 .O mm) were used as the immobile component, *i*, to calculate strain in the 1987-sampled soils and are reported in Table 1. This combination of sands, selected because it constituted a large proportion of the profile, has undergone virtually no chemical or physical transformations during the past 41 years, and has not been added by eolian processes. Earthworms tend to avoid the larger sand fractions and gravels (Russell, 1973), supporting the concept that the coarser fractions are relatively immobile in the profile. We did not use the gravel and very coarse sand fraction because they represented a small portion of the total sample and, with their relatively large grain size, introduced a higher error and more variability into the depth-strain function.

The absolute gain or loss of an element, $\delta_{j,w}$, per unit volume of parent material is calculated as follows (Brimhall et al., 1992):

$$\delta_{j,w} = \rho_w C_{j,w}(\epsilon_{i,w} + 1) - \rho_p C_{j,p}$$

where $C_{j,w}$ and $C_{j,p}$ represent the concentration of an element or exchangeable cation, j, in the weathered soil and parent material, respectively. The $\delta_{j,w}$ takes into account changes in soil volume and mass flux of elements for each horizon. These values are summed to a depth of 1 m.

3. Results and discussion

3.1. Changes *in strain with soil depth*

Strain was positive and generally greatest in the surface horizons (Table 1). Below the A horizons, strain was fairly constant with depth and remained near zero or slightly negative. Positive ● ,.$_{w}$ reflects soil dilation resulting from increased porosity, incorporation of low density organic matter. and/or the dilution of the immobile components used to calculate

Table 1
Selected properties of the original fill material and pedons sampled to 100 cm depths

Horizon	Depth (cm)	Texture'			Bulk density (Mg m^{-3})	pH^{b}	$\epsilon_{i,.}$^{c}
		Sand	Clay	cs+ms			
Archived material[d]							
		57.8 (1.5)	11.0 (0.5)	17.2 (1.0)	1.57	5.9 (0.03)	
1987 Oak							
A	0-7	54.3	13.6	19.4	Cl.92	5.8	0.52 (0.10)
AC	7-20	58.4	11.2	18.7	1.71	5.6	-0.11 (0.01)
Cl	20-35	57.6	11.4	17.5	1.70	5.7	-0.04 (0.03)
c3	50-65	57.7	11.4	17.9	1.70	5.6	-0.12 (0.02)
C5	80-100	57.4	10.2	18.0	1.71	5.7	-0.16 (0.01)
1987 *Pine*							
A	0-1	60.8	8.8	18.3	1.08	4.9	0.35 (0.36)
BAt	I-10	58.1	11.0	18.0	1.75	5.8	-0.11 (0.01)
Bt	10-20	57.6	11.9	18.7	***1.76***	5.9	-0.16 (0.01)
BCt	20-35	56.6	11.9	18.2	1.72	5.8	-0.11 (0.01)
c2	50-65	57.5	11.4	17.6	1 54	6.0	-0.13 (0.01)
c4	80-100	57.7	10.5	17.7	1 80	6.1	-0.19 (0.02)
1987 *Chamise*							
Al	0-1	57.4	11.4	19.7	1.38	5.7	0.01 (0.06)
A2	1-7	57.7	10.9	17.7	1.65	6.2	– 0.06 (0.02)
AC	7-20	58.6	11.6	17.4	1.79	6.3	– 0.08 (0.01)
Cl	20-35	51.5	11.5	17.5	1.69	5.6	-0.13 (0.01)
c3	50-65	56.5	11.8	16.3	1.73	5.9	-0.10 (0.01)
C5	80-100	56.9	10.1	16.6	.75	5.9	– 0.07 (0.01)
1987 *Ceanothus*							
Al	0-2	56.1	14.8	19.2	0.92	5.4	0.57 (0.20)
A2	2-10	57.8	11.5	17.8	1.67	5.4	– 0.05 (0.03)
AC	IO-20	58.4	11.7	19.2	1.67	6.0	– 0.22 (0.01)
Cl	20-35	57.8	11.9	17.9	1.72	5.8	-0.07 (0.01)
C3	50-65	57.5	11.5	16.8	1.61	5.8	0.04 (0.05)
C5	SO-100	57.5	10.8	17.4	1.74	5.8	-0.14 (0.01)

'Sand = 0.05 to 2 mm: Clay < 0.002 mm; cs + ms = 0.25 to 1 .0 mm. Values in %(w/w) of < 2 mm fraction.

[b] pH determined on 1:l soil:water mixture. Values reported here are considered more accurate than those reported by Graham and Wood (1991).

'Strain calculated using cs + ms as the immobile component (C_i)J Means and standard deviations (in parentheses) were calculated using replicate bulk densities for the 1987 soils. The $C_{i,p}$ values used were cs + ms for archived samples corresponding to the appropnate 1987 horizons. not the mean i 17.2%) reported in this table.

[d] n = 24 samples of the original fill material collected at similar depths as the 1987 pedon honzons from all four unconfined lysimeters. Standard deviations are in parentheses.

$\epsilon_{i,w}$. Earthworm activity, observed in all but the soil under pine, mixes organic matter into the soil and increases porosity, resulting in decreased bulk density (Graham and Wood, 199 1) . Negative $\epsilon_{i,w}$ values result from increased bulk density of the 1987-sampled soils and indicate soil collapse or settling. Settling cracks in the soil under chamise were observed in 1987 (Graham and Wood, 1991). The pattern of strain in these lysimeter soils results from their overall compaction and settling over time, as well as faunal activity and incorporation of organic matter at the surface.

Calculated strain values could also be affected by the different methods used to measure bulk density for the original fill material and the pedons sampled in 1987. The clod method usually gives higher values than other methods because it does not account for interclod spaces (Blake and Hartge, 1986). In the 1987-sampled soils, however, structural development was either insufficient to produce interclod spaces or was fine enough to be included within the sampled clod volume.

3.2. *Carbon and nitrogen*

From 1946 to 1987, the C content in the A horizons increased 17-fold to 3.5% under oak, 8-fold to 1.3% under pine, 27-fold to 4.4% under chamise, and 13-fold to 5.5% under ceanothus. Over the same time, the A horizon N content increased 9-fold to 0.17% under oak, 6-fold to 0.11% under pine, 9-fold to 0.17% under chamise, and 20-fold to 0.40% under ceanothus (Table 2). Carbon and N concentrations in the soil show a strong linear relationship ($N = 0.007 + 0.057C$; $r^2 = 0.907$) and their changes were prominent in the upper 20 cm of the soils (Fig. 1) .

Integrating the absolute elemental changes to the 1-m depth accounts for total mass input or loss from that thickness of the soil profile (Table 3). Absolute increases in C and N were noted in all of the 1987-sampled soils. The largest increase in C was found in the soil under scrub oak, which also had the thickest A horizon due to the incorporation of plant litter by earthworms (Graham and Wood, 1991) . The source of C in these soils is the photosynthetic fixation of atmospheric CO_2. The rate of CO_2-C sequestration, calculated by dividing the total accumulation (Table 3) by 41 years, was 0.02 to 0.09 kg $m^{-3} yr^{-1}$ during this initial stage of soil formation. These values are five to ten times greater than those reported for older soils (4 to 240 ka) in a moist temperate grassland ecosystem in northern California (Chadwick et al., 1994).

The effect of fire on total soil C depends on the burn intensity. Severe burning (> 500°C) results in combustion of organic matter and nearly complete loss of organic C within the upper 1 to 8 cm of mineral soil (Ulery and Graham, 1993). These temperatures are usually only reached under concentrated fuel, such as fallen logs. Moderate burning, such as that experienced by the chaparral lysimeter plots in 1960, has little direct effect on the mineral soil, but burns standing vegetation and the litter layer, producing ash on the soil surface. Wood-ash, containing C in the form of calcite (Ulery et al., 1993) or charred woody material, can be readily incorporated into surface soils by leaching or other natural mixing processes. Thus, fire may increase the rate of C accumulation in stable soils of chaparral ecosystems. Many natural chaparral sites, however, are on unstable slopes that experience considerable erosion after fire, resulting in loss of wood-ash, litter, and mineral soil (DeBano and Conrad, 1978).

Table 2
Carbon, N, and exchangeable cation contents of the parent material, p; and the “weathered” or 1987 soil, **w**

Horizon		C_w	N_p	N_w	Cation content (cmol kg-‘)								(cmol kg^{-1})	
	(%)	(%)	(%)	(%)	Ca_p	Ca_w	Mg_p	Mg_w	Na_p	Na_w	K_p	K_w	acid, ^{b}	acid,
Oak														
A	0.20	3.48 (0.34)	0.02	0.17	8.17	14.46 (0.53)	5.84	6.76 (0.21)	0.18	0.05 (0.02)	0.12	0.33 (0.02)	0.26	0.13
AC	0.24	0.39 (0.01)	0.02	0.03	8.01	10.56 (0.29)	5.99	6.70 (0.09)	0.20	0.05 (0.01)	0.14	0.12 (0.00)	0.27	0.45
Cl	0.20	0.27 (0.02)	0.02	0.02	7.93	9.70 (0.81)	5.62	6.53 (0.17)	0.18	0.08 (0.03)	0.13	0.11 (0.01)	0.25	0.46
c3	0.20	0.21	0.02	0.02	8.11	10.05	5.31	5.78	0.17	0.06	0.12	0.10	0.23	0.44
C5	0.16	0.19	0.02	0.01	8.31	9.23	6.49	6.73	0.22	0.18	0.12	0.11	0.28	0.44
Pine														
A	0.16	1.29 (0.20)	0.02	0.11	8.34	7.80(1.14)	5.97	4.22 (0.09)	0.15	0.05 (0.04)	0.11	0.28 (0.06)	0.15	0.45
BAt	0.23	0.51 (0.08)	0.02	0.04	8.62	9.64 (0.14)	6.13	5.89 (0.08)	0.15	0.04 (0.03)	0.12	0.19 (0.01)	0.21	0.51
Bt	0.18	0.40 (0.06)	0.02	0.03	7.75	10.63 (0.08)	5.70	6.11 (0.41)	0.17	0.05 (0.04)	0.13	0.14 (0.02)	0.22	0.42
BCt	0.20	0.34 (0.05)	0.02	0.02	7.89	9.81 (0.34)	5.67	5.97 (0.36)	0.20	0.04 (0.02)	0.13	0.13 (0.01)	0.24	0.42
c2	0.23	0.32	0.02	0.02	7.79	9.79	5.30	5.90	0.17	0.06	0.13	0.11	0.24	0.31
c4	0.16	0.26	0.02	0.02	7.95	9.31	6.08	6.50	0.23	0.21	0.12	0.11	0.24	0.33
Chamise														
Al	0.16	4.31 (0.46)	0.02	0.17	8.41	13.23 (1.31)	4.68	5.16 (0.45)	0.18	0.01 (0.01)	0.13	0.33 (0.03)	0.26	0.17
A2	0.24	0.88 (0.29)	0.02	0.06	8.61	9.99 (0.65)	4.87	5.39 (0.43)	0.18	0.01 (0.01)	0.14	0.16 (0.02)	0.25	0.11
AC	0.27	0.35 (0.15)	0.02	0.02	8.34	9.50 (0.30)	4.39	5.68 (0.27)	0.18	0.00 (0.00)	0.14	0.11 (0.02)	0.26	0.23
Cl	0.32	0.25 (0.09)	0.02	0.02	8.91	8.79 (0.40)	5.36	5.70 (0.48)	0.17	0.02 (0.01)	0.14	0.11 (0.02)	0.25	0.41
c3	0.18	0.20	0.02	0.02	9.39	8.79	5.56	5.45	0.20	0.04	0.13	0.08	0.27	0.40
c5	0.25	0.18	0.02	0.02	9.80	9.25	6.12	6.20	0.25	0.11	0.12	0.11	0.29	0.42
Ceanothus														
Al	0.41	5.47 (1.89)	0.02	0.40	8.36	15.82 (2.29)	5.76	5.66 (1.45)	0.19	0.02 (0.01)	0.12	0.45 (0.08)	0.25	0.26
A2	0.26	0.54 (0.13)	0.02	0.06	8.59	10.77 (0.94)	5.66	6.05 (1.46)	0.19	0.02 (0.02)	0.14	0.14 (0.02)	0.28	0.09
AC	0.19	0.29 (0.03)	0.02	0.03	8.46	9.65 (0.48)	5.67	6.40 (1.06)	0.19	0.02 (0.04)	0.14	0.10 (0.01)	0.29	0.27
Cl	0.28	0.27 (0.01)	0.02	0.02	8.33	8.99 (0.19)	5.88	6.24 (1.15)	0.19	0.04 (0.04)	0.14	0.10 (0.01)	0.25	0.42
c3	0.28	0.22	0.02	0.01	9.48	10.72	6.34	5.72	0.19	0.05	0.14	0.11	0.24	0.45.
c5	0.23	0.18	0.02	0.02	8.76	9.72	5.96	6.71	0.25	0.12	0.13	0.09	0.29	0.59

“Standard deviation is reported in parentheses for mean values from triplicate pedon sampling. All other values for the 1987 soil; are from a single pedon.

[b] KCl-extractable acidity.

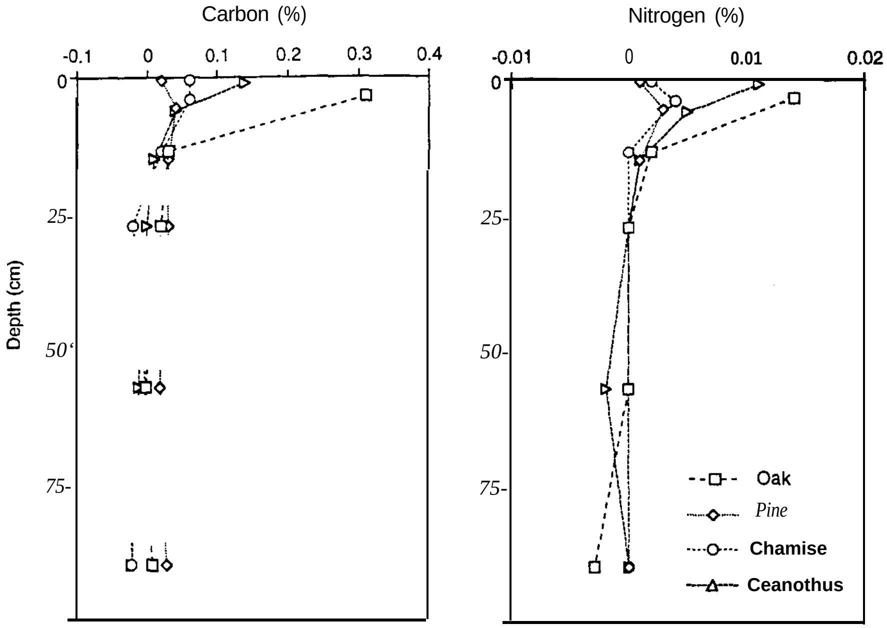

Fig. 1. Change ($\delta_{j,w}$) in C and N with depth in each of the lysimeters, corrected for soil volume and density changes.

The soils under ceanothus and oak had the highest overall increases in N, with rates of 0.003 kg $m^{-3} yr^{-1}$ over the 1 m depth. The N additions are probably due to inputs from microbial fixation (under ceanothus), incorporation of organic matter, and atmospheric fallout. Atmospheric deposition of nitrogen oxides (NO,) and ammonium (NH_4^+), common in southern California smog (Bytnerowicz et al., 1987), may be a significant contributor to the N content of these soils. Riggan et al. (198.5) measured inorganic N input of 0.0023 kg $m^{-2} yr^{-1}$ from canopy throughfall in native chaparral at the San Dimas Experimental Forest. The major source of this N was dry deposition, but 0.0008 kg $m^{-2} yr^{-1}$ came from rain. This total rate is two orders of magnitude higher than that for a California chaparral site with near natural atmospheric conditions (Schlesinger et al., 1982), and nearly matches

Table 3
Total accumulations after 41 yr of C, N, exchangeable cations, and effective cation exchange capacity (ECEC) integrated over the soil profile depth of 1 meter[a]

	C	N	Exchangeable (mol m^{-3})					
	(kg m^{-3})	(kg m^{-3})	Ca	Mg	Na	K	Acidity[b]	ECEC
Oak	3.1	0.11	25.7	5.5	−1.6	-0.1	2.5	32.0
Pine	2.0	0.04	21.2	1.4	−1.6	-0.1	1.9	22.8
Chamise	0.9	0.06	-0.7	4.6	−2.4	-0.4	1.5	2.6
Ceanothus	1.4	0.12	17.0	1.6	−2.4	-0.5	2.5	18.2

[a] For these summations, values were interpolated for the 35-50 and 65-80 cm depths.
[b] KCl-extractable acidity.

the maximum annual accumulation rate (0.003 kg m^{-2}) for the upper 1 m of the lysimete soils.

In his study of N in chaparral soils, Zinke (1969) investigated the concentrations of N in both the vegetation and soils of the San Dimas unconfined lysimeters. His results showed that total N (including soil and surface litter N) increased more, relative to the parent material, in the soil under ceanothus than under other vegetation types. Zinke (1969) suggested that this gain was in response to N_2-fixation by the ceanothus and showed that most of the N added to the ceanothus lysimeter was associated with the above-ground vegetation and surface litter. The scrub oak stand had slightly less total N than the ceanothus soil-vegetation system, but had the largest N gain in the soil alone (Zinke, 1969), perhaps because of greater incorporation of organic matter into the soil by earthworm activity under oak.

Chaparral fires result in net loss of N from the ecosystem. DeBano and Conrad (1978) reported a soil N loss of 0.0036 kg m^{-2} out of a total 0.0146 kg m^{-2} for plants, litter, and soil combined. Most soil N was lost from the upper 2 cm because soil temperatures during burning were relatively cool below this depth. As with C, N can be added to the mineral soil by wood-ash deposits (Christensen and Muller, 1975), so a net increase in N within the mineral soil after fire is possible.

3.3. *Exchangeable cations, acidity, and CEC*

Exchangeable Ca increased by ≥ 5 cmol kg^{-1} in three of the 1987 A horizons relative to the parent material (Table 2). The amount of Ca and Mg on the exchange in the A horizon under pine was lower than in the parent material (Fig. 2). For all soils, the amounts of K and Na on the exchange were much less than either Ca or Mg (Fig. 2).

Integrated over the 1 m depth, exchangeable and exchangeble Ca increased under all but chamise Mg increased under each vegetation type, (Table 3). Addition of Ca on the exchange was most pronounced for the soil under oak (Fig. 2). Atmospheric deposition of Ca and Mg, decomposition of organic matter, and weathering of primary minerals are possible sources of exchangeable cations. Fauna1 activity, including the previously mentioned earthworm activity, contributes to higher organic matter decomposition rates, releasing Ca and Mg to exchange sites (Binkley and Richter, 1987).

Another potential source of exchangeable cations is wood-ash, which is high in Ca and other nutrient elements (Ulery et al., 1993). The wildfire in 1960 mineralized the above-ground biomass of the chamise and ceanothus stands. In contrast, wood-ash production was spotty under the oak and virtually nonexistent under the pine (P.J. Zinke, 1994, pers. commun.) . Thus, less Ca and Mg was released by burning to exchange sites in the A horizon under oak and pine. In general, the organic matter of all four species contains considerably less Mg than Ca (unpubl. data; Zinke, 1977), resulting in overall lower total additions of Mg to exchange sites (Table 3). The soil under chamise is a notable exception in that the exchangeable Mg increased over a 1 m depth while the Ca decreased (Table 3). Hanawalt and Whittaker (1977) also reported higher exchangeable Mg values for soils under chamise than for those under other southern California vegetation types they studied.

Exchangeable Na was lower throughout the 1987 soil profiles than in the corresponding parent material samples for all of the vegetation types (Fig. 2). The negative values for

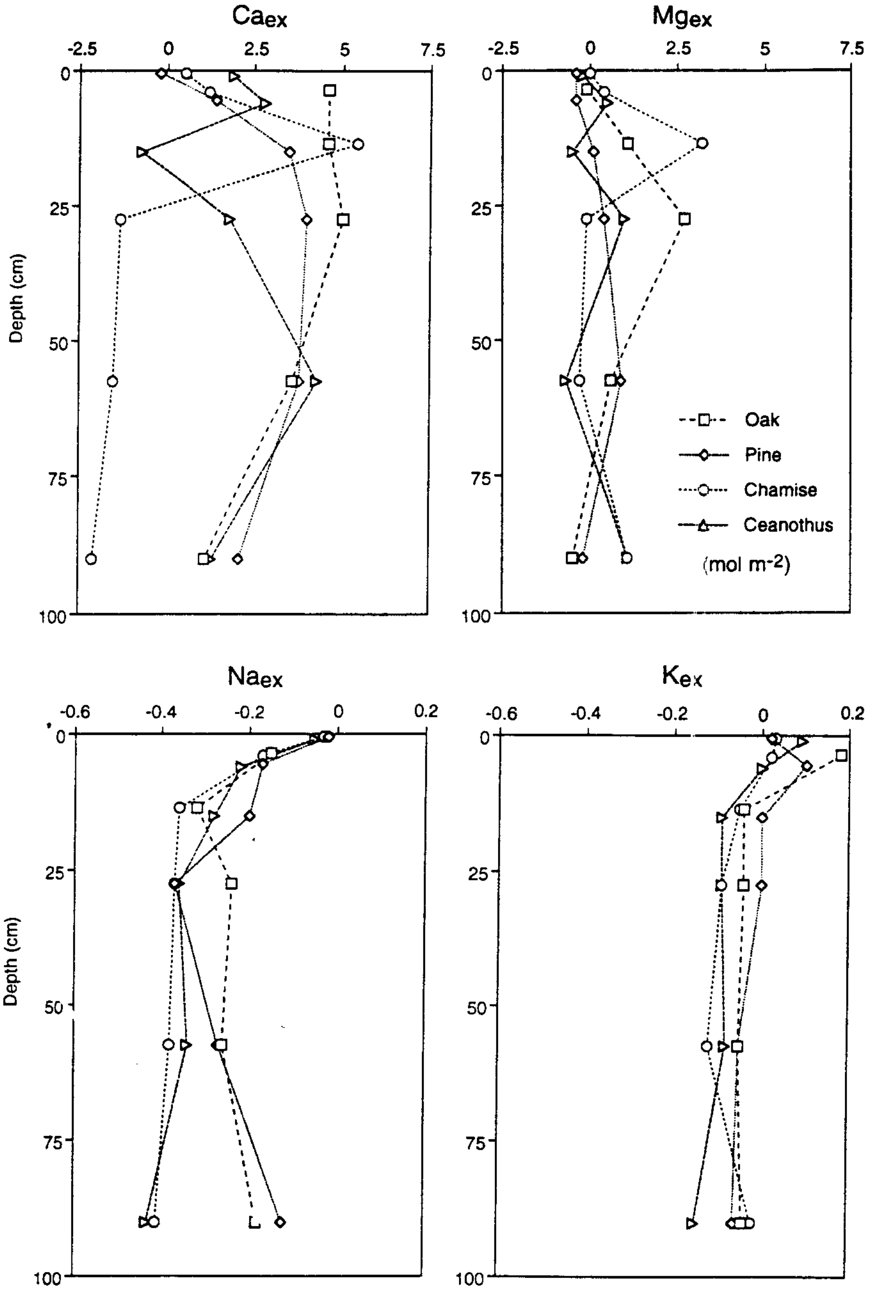

Fig. 2. Change ($\delta_{j,w}$) in exchangeable base cations with depth in each of the lysimeters, corrected for soil volume and density changes.

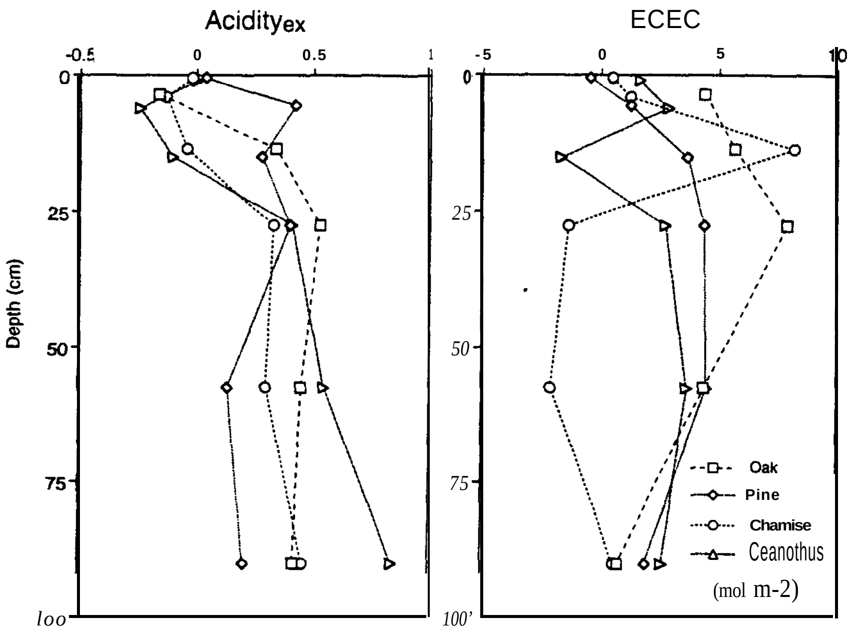

Fig. 3. Change ($\delta_{j,w}$) in exchangeable acidity and effective cation exchange capacity (ECEC) with depth in each of the Iysimeters. corrected for soil volume and density changes.

exchangeable Na in Table 3 indicate that Na was leached from the soils for the full 1 m depth considered in this study.

Exchangeable K increased in the A horizons of each of the soils relative to the parent material, but decreased with depth (Table 2). Below 20 cm, K was depleted from the soils (Fig. 2). These redistribution trends suggest biocycling; that is, uptake of K by plant roots deeper in the profile and subsequent deposition of K in organic litter on the soil surface. Potassium is also a component of wood-ash and may have been deposited at the surface during the fire in 1960. Exchangeable K was nearly unchanged in the oak and pine soils within the 1 m profile and decreased slightly in the chamise and ceanothus soils (Table 3 j . Preferential uptake and retention of K by the standing phytomass may account for observed K depletions. Furthermore. these soils contain vermiculite which may fix K and render it non-extractable by NH_4OAc solutions (Douglas, 1989), a mechanism that may help account for low values of exchangeable K.

Total exchangeable acidity is composed of H and hydrolyzable Al on exchange sites. Aluminum is tightly bound to organic compounds and, unless the pH of the soil is below 5.5, very little H exists on the exchange (Thomas, 1982). With the exception of the A horizons under pine and ceanothus, the soil pH values were > 5.5 (Table l), indicating minimal exchangeable acidity (<0.6 cmol kg-‘, Table 2), and virtually no exchangeable H, for all of the soils. Exchangeable acidity generally increased in the soils, relative to the parent material, below 20 cm (Fig. 3). In the surface horizons, only the soil developed under pine had noticeably higher exchangeable acidity than the parent material. The A horizon under pine had a substantially lower pH than the surface horizons of the other three soils, which had pH values that were closer to those of the original fill material (Table 1).

Binkley and Richter (1987) reported lower soil pH values under pine species compared to other plants and also noted that burning tends to raise soil pH. Lower soil pH and higher exchangeable acidity under pine may be the result of the acidifying pine needle litter and/ or the absence of wood-ash under the pine after the 1960 fire.

Exchangeable acidity increased slightly within the upper 1 m of all soils (Table 3). A marked increase in exchangeable acidity in the deepest horizon was observed in the soil under the N_2-fixing ceanothus (Fig. 3). Nitrification of surplus N results in a net production of H (Van Miegrot and Cole, 1985), and may help increase exchangeable acidity, as has been noted in soils under N,-fixing red alder (Alnus rubra) (Johnson et al., 1991) .

The effective cation exchange capacity (ECEC) is the CEC of the soil at the soil's pH and is calculated as the sum of the extractable cations and the exchangeable acidity. Reflecting the increases in exchangeable Ca, Mg, and acidity, the ECEC increased in all of the soils. Total increases in ECEC were highest for the soil under oak and lowest in the chamise soil (Fig. 3)) but there was no apparent relationship between plant species and ECEC with depth. New exchange sites result from incorporated organic matter and clay minerals produced by weathering. In some horizons increased soil pH may contribute to higher ECEC by creating more negatively charged sites on materials with pH-dependent charge. Overall, these mechanisms contributed to an increase in ECEC by 3 to 32 mol m^{-3} over 41 years (Table 3), or at annual rates of between 7 and 78 cmol $m^{-3} yr^{-1}$.

4. Conclusions

After 41 years, increases in soil C, corrected for soil volume and density changes, ranged from 1.0 to 3.6 kg m^{-2} over 1 m depth. These data provide a baseline range for the C-fixation abilities of fire-affected southern California chaparral soils. The soil developed under scrub oak had the highest total additions of C and exchangeable Ca. The A horizon in this lysimeter was 7 cm thick compared to 1 or 2 cm for A horizons developed under other types of vegetation. Earthworm activity was highest under oak and the resulting incorporation of organic matter is probably responsible for the higher soil C and exchangeable Ca values.

Soil N increased slightly in the soils of each vegetation type, but was highest under ceanothus (0.14 kg m^{-3}), apparently because of N_2-fixation by that species. The increase in exchangeable acidity was also highest in this soil and may be contributed to by acidity produced during nitrification of microbially fixed N.

Exchangeable Na was lost from the soils under all of the vegetation types and replaced by other exchangeable cations. This rapid decrease demonstrates how readily Na is leached during the initial stages of pedogenesis. Exchangeable K did not change much in these soils, but has accumulated slightly at the soil surface as a result of biocycling. The ECEC increased in all of the soils in response to the addition of exchange sites associated with organic matter, clay minerals, and, in some cases, a slightly higher pH, which produces more negative sites on pH-dependent-charged materials.

In this decade-scale study. amounts and distributions of elements and chemical properties. particularly C, N, Ca, and Mg. varied substantially within the mineral soils in response to the type of vegetation established during the initial stages of pedogenesis. The results suggest that shifts in vegetation, for example those induced by climate change, can quickly change soil chemical properties and the role of soils as sinks or sources in biogeochemical cycles.

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References

Binkley, D. and Richter, D., 1987. Nutrient Cycles and H' Budgets of Forest Ecosystems. Advances in Ecological Research, 16. Academic Press, London.

Blake, G.R. and Hartge, K.H., 1986. Bulk density. In: A. Klute (Editor), Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA. Madison, WI, pp. 363-375.

Bremner, J.M. and Mulvaney, C.S., 1982. Nitrogen — Total. In: A.L. Page (Editor), Methods of Soil Analysis, Part 2.2nd ed. Agron. Monog. 9. ASA and SSSA, Madison, WI, pp. 595-624.

Brewer, R., 1964. Fabric and Mineral Analysis of Soils. Wiley, New York.

Brimhall, G.H. and Dietrich, W.E., 1987. Constitutive mass balance relations between chemical composition. volume, density, porosity and strain in metosomatic hydrochemical systems: Results on weathering and pedogenesis. Geochim. Cosmochim. Acta, 5 1: 567-587.

Brimhall, G.H., Chadwick, O.A., Lewis, C.J., Compston, W., Williams, I.S., Danti, K.J., Dietrich, W.E., Power, M.E., Hendricks, D., Bratt, J.. 1992. Deformational mass transport and invasive processes in soil evolution. Science, 255: 695-702.

Bytnerowicz, A.. Miller. P.R., Olszyk, D.M.. Dawson, P.J. and Fox, C.A., 1987. Gaseous and particulate air pollution in the San Gabriel Mountains of southern California. Atmos. Environ., 21: 1805-1814.

Chadwick, O.A., Brimhall, G.H. and Hendricks, D.M., 1990. From a black to a gray box — a mass balance interpretation of pedogenesis. Geomorphology, 3: 369-390.

Chadwick, O.A., Kelly. E.F.. Menitts, D.M. and Amundson, R.G., 1994. Carbon dioxide consumption during soil development. Biogeochemistry, 24: 115-127.

Christensen. N.L. and Muller. C.H.. 1975. Effects of fire on factors controlling plant growth in *Adenostoma* chaparral. Ecol. Monogr., 45: 29-55.

Colman, E.A. and Hamilton, E.L., 1947. The San Dimas lysimeters. USDA For. Serv., California Forest and Range Exp. Stn. Res. Note 47. Berkeley , CA.

DeBano, L.F. and Conrad, C.E.. 1978. The effect of fire on nutrients in a chaparral ecosystem. Ecology, 59: 489-497.

Douglas, L.A., 1989. Vermiculites. In: J.B. Dixon and S.B. Weed (Editors), Minerals in Soil Environments. 2nd ed. SSSA, Madison, WI, pp. 635-674.

Dunn, P.H., Barro, SC., Wells, W.G.. Poth, M.A., Wohlgemuth, P.M. and Colver, C.G., 1988. The San Dimas Experimental Forest: 50 years of **research.** U.S. For. Serv. Gen. Tech. Rep. PSW-104. Pac. Southwest For. Range Exp. Stn., Berkeley, CA.

Gee. G.W. and Bauder, J.W., 1986. Particle-size analysis. In: A. Klute (Editor), Methods of Soil Analysis. Part 1.2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, Wl, pp. 377-382.

Graham. R.C. and Wood. H.B., 1991. Morphologic development and clay redistribution in lysimeter soils under chaparral and pine. Soil Sci. Soc. Am. J.. 55: 1638-1646.

Graham. R.C.. Herbert. B.E. and Ervin. J.O.. 1988. Mineralogy and incipient pedogenesis of Entisols in anorthosite terrane of the San **Gabriel** Mountains California Soil Sci. Soc. Am. J., 53: 738-746.

Hanawalt. R.B. and Whittaker. R.H.. 1977. Altitudinal patterns of Na, K. Ca and Mg in soils and plants in the San Jacinto Mountains, California. Soil Sci., 123: 25-36.

Hellmers. H.. Bonner. J.F. and Kelleher. J.M., 1955. Soil femlity: A watershed management problem in the San Gabriel Mountains of southern California. Soil Sci.. 80: 189-197.

Jenny. H.. 1941. Factors of Soil Formation. ,McGraw-Hill. New York.

Johnson, D.W., Cresser. MS., Nilsson. S.I., Turner. J.. Ulrich, B.. Binkley. D. and Cole. D.W.. 199 l. Soil changes in forest ecosystems: evidence for and probable causes. Proc. R. Soc. Edinburgh. 978: 81-l 16.

Nelson. D.W. and Sommers. LE., 1982. Total carbon. organic carbon and organic matter. In: A. Klute (Editor). ‘Methods of Soils Analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA. .Madison. WI. pp. 539-580.

Panic, J.H.. 196la. 4 forester looks at lysimeters. J. For.. 59: 889-893.

Panic. J.H.. 1961b. The San Dimas large lysimeters. J. Soil Water Conserv.. 16: 13-17.

Riggan. P.J.. Lockwood. R.N. and Lopez, E.N.. 1985. Atmospheric deposnion processes and their importance as sources of nutrients in a chaparral ecosystem of southern California. Environ. Sci. Technol.. 19: 781-789.

Russell. E.W.. 1973. Soil Conditions and Plant Growth. Longman, New York.

Schlesinger. W.H.. Gray, J.T. and Gilliam, F.S., 1982. Atmospheric deposition processes **and** their importance as sources of **nutrients** in a chaparral ecosystem of southern California. Water Resour. Res., 18: 623-629.

Soil Conservation Service. 1984. Procedures for collecting soil samples and methods of analysis for soil survey USDA-SCS Soil Sw. Invest. Rep. no. 1. U.S. Gov. Print. Office, Washington. DC.

Taylor. K.. Graham, R.C. and Ervin, J.O., 1990. Laumontite in soils of the San Gabriel Mountains. California Soil Sci. Soc. Am. J., 54: 1483-1489.

Thomas. G.W.. 1982. Exchangeable cations. In: A.L. Page (Editor), Methods of Soil Analysis Part 2. 2nd ed Agron. Monogr. 9. ASA and SSSA. Madison. WI. pp. 159-165.

Ulery. A.L. and Graham. R.C., 1993. Forest fire effects on soil color and texture. Soil Sci. Soc. Am. J.. 57: 13.5 140.

Ulery. A.L.. Graham. R.C. and Amrhein. C., 1993. Wood-ash composition and soil pH following intense burning Soil Sci.. 156: 358-364.

Van Miegrot. H. and Cole. D.W., 1985. Acidification sources in red alder and Douglas fir soils — importance of nitrification. Soil Sci. Soc. Am. J., 49: 1274-1279.

Vlamis. J.. Stone, E.C. and Young, C.L., 1954. Nutrient status of brushland soils *in* southern California. Soil Sci 78: 5 l-55.

Zinke, P.J.. 1969. Nitrogen storage of several California forest soil-vegetation systems. In: Biology and Ecolog of Nitrogen. Proc U.S. Natl. Comm. Int. Biol. Prog. Cont. Davis, CA. 28 Nov.-l Dec. 1967. Natl. Acad. Sci Washington, DC, pp. 40-53.

Zinke. PJ.. 1977. Mineral cycling in fire-type ecosystems. Proc. Symp. Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems. Aug. 1-5, 1977. USDA For. Serv. Geo. Tech. Rep. wo- pp. 85-94.