Rates of Soil Carbon Accumulation and Transformation in a Ponderosa Pine Forest Using High Resolution Chronosequence Analysis

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Summary

A series of deposits from debris flow events over the past 400 years provide a soil chronosequence in the San Bernardino Mountains that is used to study soil carbon accumulation and organic matter transformations with a decade-scale resolution. Carbon dynamics in the mineral soil can be divided into three stages within this 400-year period. In the first 40 years of soil development, carbon that was incorporated into the debris flow material during transport and deposition is lost at a rate of -0.030 $kg*m^{-2}*y^{-1}$. Rapid carbon accumulation, at a rate of 0.033 $kg*m^{-2}*y^{-1}$, begins at 40 years and continues to 97 years, but is mostly limited to the upper 5 cm of the soil profile. After 97 years, the rate of carbon accumulation is slowed to 0.0056 $kg*m^{-2}*y^{1}$ and carbon begins to accumulate in the subsoil. Subsoil accumulation of carbon during the third stage is likely to originate from roots, rather than processes of bioturbation or leaching. The C/N ratio of the soil organic matter in the A-horizon is around 20 to 30 throughout most of the chronosequence, except at 40 and 60 years, when C/N ratio was elevated.

Objectives

1. Assess the rate of carbon accumulation on a scale of decades over the span of four centuries.
2. Interpret the processes by which carbon is incorporated into soils of different ages.
3. Determine the forms of soil organic matter as a function of soil age.

Approach and Procedures

The study area is near the town of Forest Falls at the 1,675-m elevation in the San Bernardino Mountains of Southern California. The mean annual temperature is 11^{o}C and the mean annual precipitation is 650 mm, occurring as rain and snow, mostly from November through March. Debris flows, initiated by high-intensity monsoonal rainfall events, arise from an adjacent ridge which reaches an elevation of 2,500 m (Morton and Hauser 2001). The geologic material of the ridge is highly fractured gneiss, which produces sandy loam-textured debris flow material with a rock fragment (mostly gravel- to stone-sized) content of 35 to 70%. The debris flows comprise an alluvial fan deposit covering about 30 ha at the foot of the ridge. Segments of the variously aged deposits are preserved and support forest stands dominated by ponderosa pine (*Pinus ponderosa*) and incense cedar (*Calocedrus decurrens*). The ages of these stands closely reflect the ages of the deposits on which they occur, since tree seedlings sprout within a year or two after the debris flow deposition. The deposits are a good approximation of a chronosequence (Jenny 1941; Birkeland 1999) because they experience the same climate, they have access to the

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same biotic disseminules, the flow surfaces have consistent topographic expression, and they are all composed of the same geologic material. The major variable is age.

Soil pits on eight debris flow deposits were excavated to 1-m depth for morphologic description and sampling. The ages of the flows were determined based on the age of trees from even-age stands, except for the youngest flow (<0.5 y), the timing of which was well documented. Soil samples were taken by morphologic horizon or in 3 to 20 cm increments (finer sampling near the surface) to a depth of 1 meter. Bulk soil samples were returned to the lab and sieved to remove and weigh the coarse fragments (>2 mm). Stones and boulders were weighed in the field and used to calculate rock content on a volume basis using rock density. Bulk densities were determined using clod samples (Hirmas and Furquim 2006). Total carbon was measured using a C/N analyzer (Nelson and Sommers 1996) and recalculated to a volume basis using soil bulk density values and rock fragment content corrections. When encountered, carbonate-C was determined manometrically (Loeppert and Suarez 1996) and factored out, so that total C is taken as a measure of organic C.

Results

The soils described at Forest Falls were most often classified as sandy-skeletal, mixed, mesic Typic Xerorthents. Deposit depth was highly variable. In some places along the channel levee deposits were as thick as 2 meters, while nearby deposits could be as thin as a few cm and probably resulted from sediment redistribution after the debris flow event. When the shallow deposits (<1 m) were described we encountered buried O and A horizons, and soils were classified as sandy-skeletal, mixed, mesic Typic Xerofluvents. The deposits were rich in gravels (7-47% by volume) and courser rock fragments (19-51% by volume). The pH of most soils ranged from 5.0 to 7.5, but did not follow a consistent trend with depth or age. One exception was the <0.5-year old soil, which had a pH range from 7.7 to 8.0, due to trace amounts of calcite that were inherited from the parent material. Calcite was not present in older profiles, suggesting that it is rapidly leached from the debris flow deposits.

The 40- to 97-year-old soils each had a thin A horizon (2-3 cm), while the older profiles (300 and 460 years old) had a 4 to 8 cm thick A horizon. Bw horizons with weak to moderate structure were described in soils as young as 40 years. The <0.5 year-old soil expressed no horizonation. There was no evidence of bioturbation (i.e., krotovinas, earthworm casts) in any of the soil profiles.

The concentrations of organic carbon within the <2-mm fraction of the mineral soils are plotted in figure 1. The youngest deposit contained some organic carbon in the form of plant detritus (branches, leaves, litter) incorporated during the debris flow event. From 40 to 70 years carbon accumulation is mostly limited to the upper 5 cm of soil (*fig. 1, B-D*), while from 97 to 460 years carbon increases in the subsoil as well (*fig. 1, F-H*). Buried O and A horizons that were encountered in some profiles account for the high levels of carbon in the lower parts of these profiles (fig. 1 E and G).

Trends in total organic carbon in the mineral soil over time are shown in figure 2. Total organic carbon in the 300-year-old soil does not include carbon in the buried soil, which predates the deposit age. Total carbon in this profile was calculated to 1-m depth by assuming that the carbon content of the lowest part of the surface deposit continued to 1 m. That assumption is reasonable considering the uniformity with depth of carbon content below 60 cm in other soils at the site (*fig. 1*). The other profile containing a buried soil (*fig. 1, E*) was not included in the study of total carbon accumulation because an age estimate could not be attained for the surface deposit.

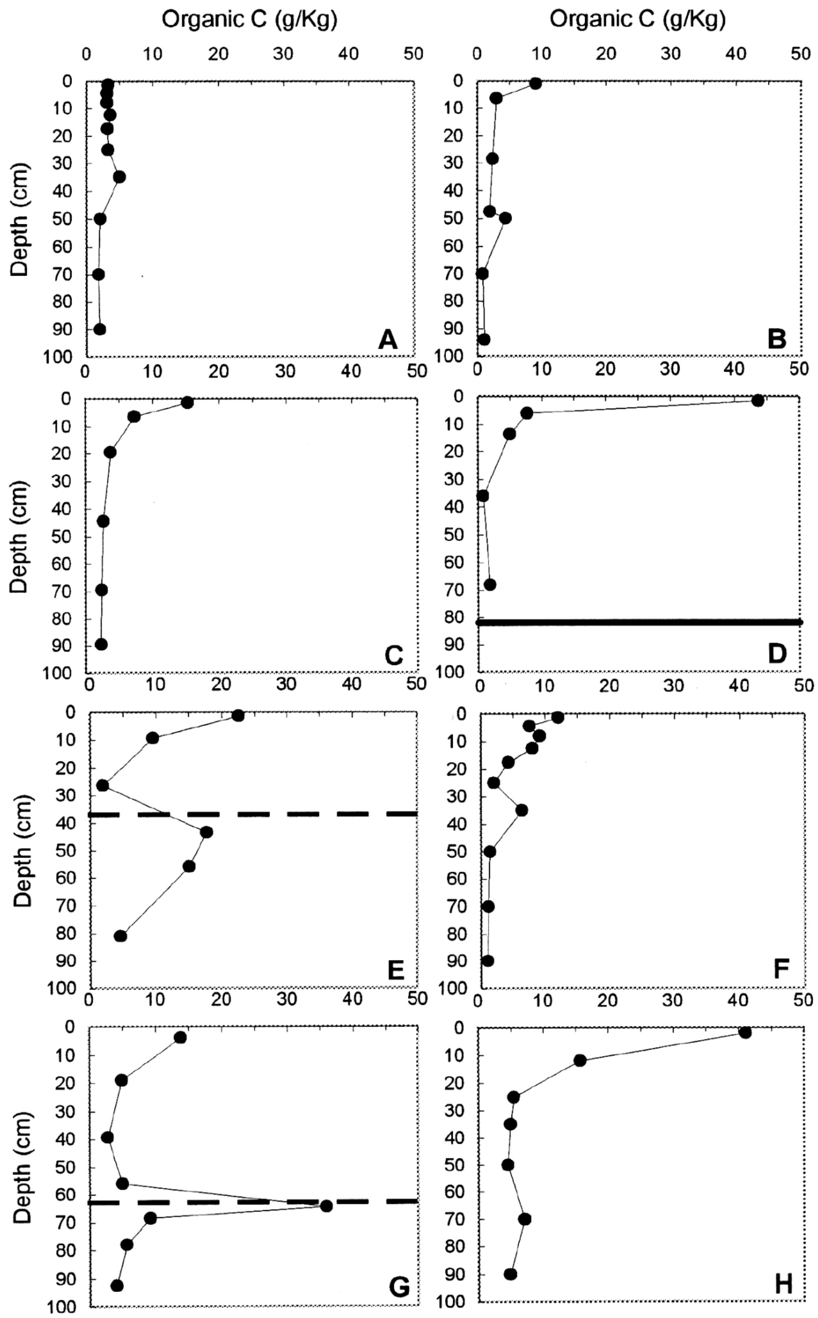

Figure 1. Depth distributions of organic carbon concentrations in the <2-mm fraction of the: (A) <0.5-year-old, (B) 40-year-old, (C) 60-year-old, (D) 70-year-old, (F) 97-year-old, (G) 300-year-old, and (H) 460-year-old soils. Profile (E) depicts the carbon distribution of a soil of unknown

age overlying an 80-year-old buried soil. The solid line, in (D), represents a root-restricting boulder and the dashed lines, in (E) and (G), represent the surface of a buried soil.

The trends in total organic carbon dynamics can be divided in to three stages with differing rates of carbon accumulation or depletion (*fig. 2, I-III*). During stage I (0-40 years) there is a net loss of organic carbon from the soil at a rate of -0.030 $kg*m^{-2}*y^{-1}$. The most rapid carbon accumulation occurs during stage II (40-97 years) at 0.033 $kg*m^{-2}*y^{-1}$. During stage III (97-460 years) carbon accumulation slows to 0.0056 $kg*m^{-2}*y^{-1}$.

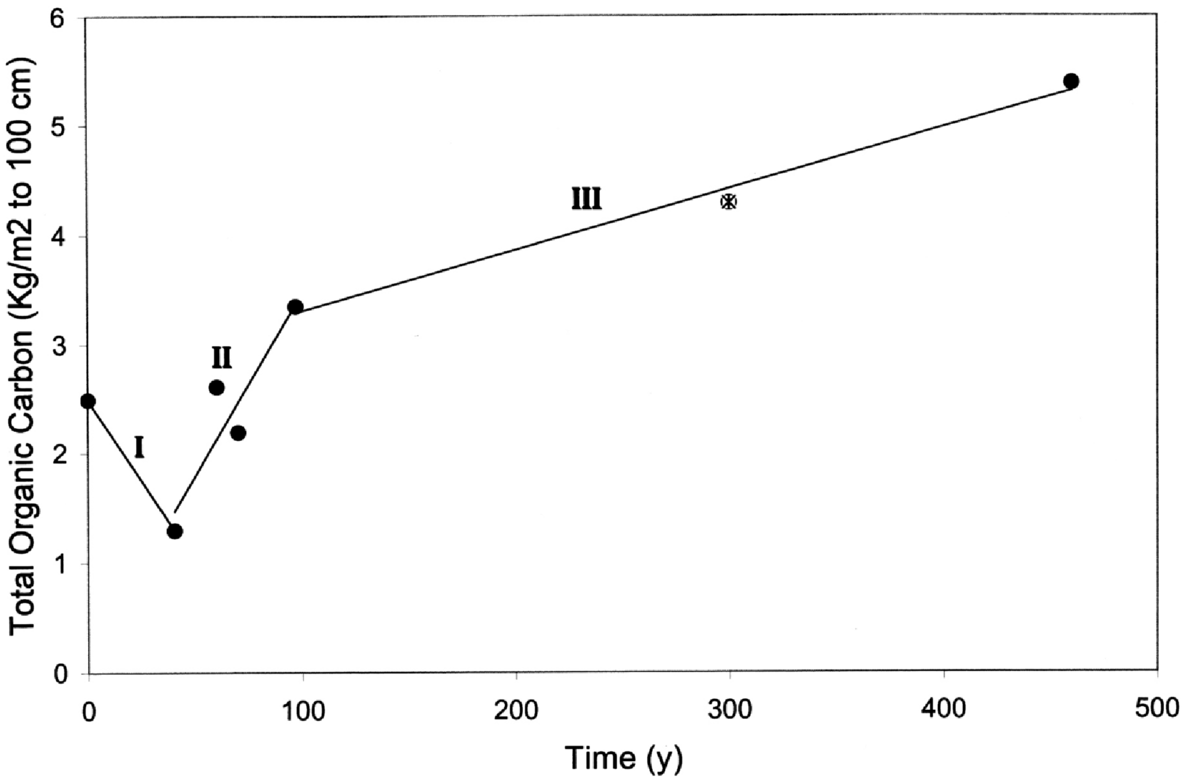

Figure 2. Total organic carbon of soil profiles to 100-cm depth as a function of time. The symbol ⊗ represents the 300-year-old soil for which carbon content of the lower profile was estimated, as described in the text. Roman numerals indicate stages of C-accumulation, referred to in the text.

The C/N ratio of the soil organic matter in the A-horizons was relatively stable (around 20-30) throughout most of the chronosequence (*fig. 3*). However, there was a brief elevation of C/N ratio observed in the 40 and 60-year-old soils (45 and 69, respectively).

Discussion

Rates of Carbon Accumulation. Relatively few chronosequence studies have addressed soil carbon accumulation in coniferous forest settings on a short time scale similar to the one of this chronosequence at Forest Falls. One such chronosequence is in Northern California on the southeast slopes of Mt. Shasta where soils have formed under ponderosa pine on volcanic mudflow deposits with ages (when first studied) of 27, 60, 205, 566, and 1,200+ years (Dickson and Crocker 1953; Sollins et al. 1983; Lilienfein et al. 2003).

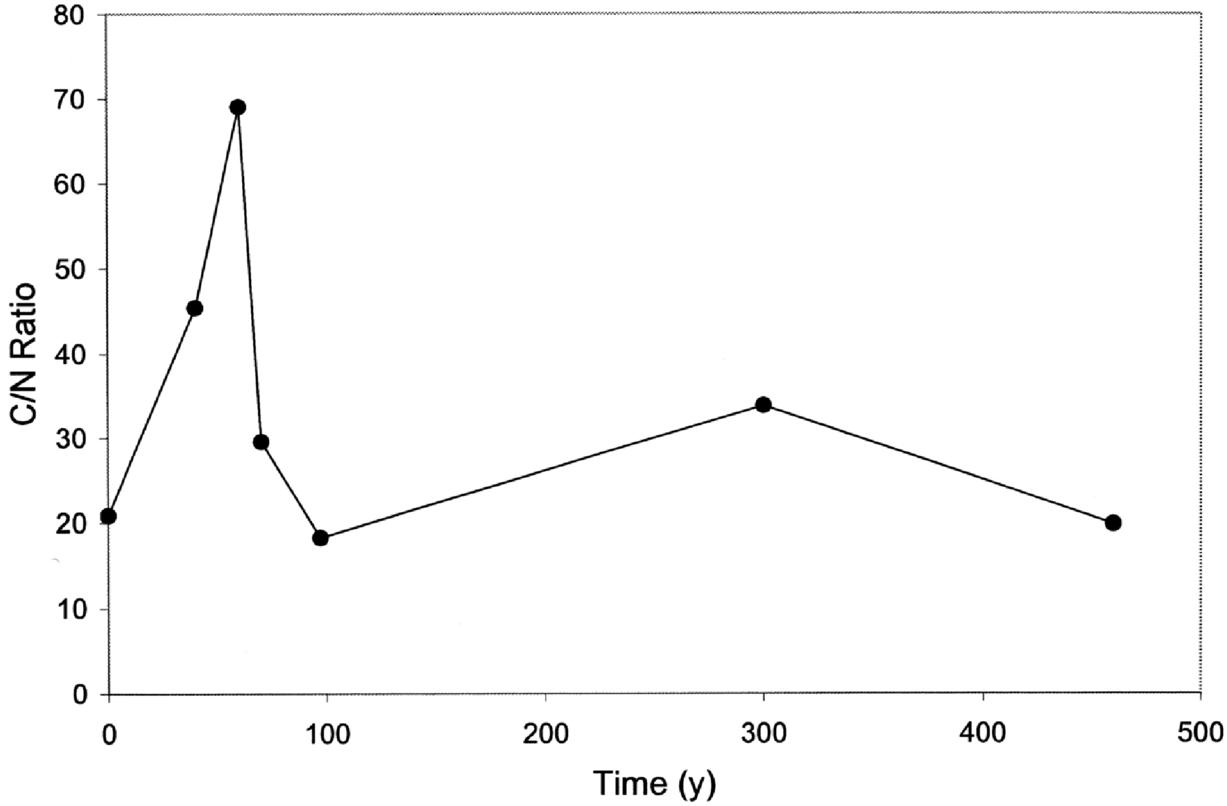

Figure 3. C/N ratio of the A-horizon as a function of time.

Trends in carbon accumulation in the Mt. Shasta soils, described by Dickson and Crocker (1953), bear similarity to the three-stage trend described at Forest Falls. As we observed at Forest Falls (*fig. 2, II*), the Mt. Shasta soils experienced an early rapid accumulation stage, though it is of shorter duration (33 years vs. 57 years at Forest Falls) and the carbon accumulation rate is nearly four times that observed at Forest Falls (0.127 $Kg*m^{-2}*y^{-1}$ and 0.033 $Kg*m^{-2}*y^{-1}$, respectively). This may be a factor of climatic differences between the sites, since Forest Falls receives only half as much rainfall as the Mt. Shasta site. The drier climate at Forest Falls may reduce the net primary productivity of the forest ecosystem, as well as the activity of decomposer populations, which could limit the amount of carbon fixed and the rate at which it is incorporated into the soil. Following the rapid accumulation phase, there is a phase of slower carbon accumulation at both Mt. Shasta and Forest Falls (*fig. 2, III*). The rates of carbon accumulation are similar during this phase, however, C-accumulation in stage III is still somewhat faster at Mt. Shasta (0.0087 $kg*m^{-2}*y^{-1}$) than at Forest Falls (0.0056 $kg*m^{-2}*y^{-1}$). Though the initial decline in carbon content (*fig. 2, I*) was not observed at Mt. Shasta, this may be because no very young (<1 y) deposit was studied for the Mt. Shasta chronosequence.

Based on observations of the forest litter, Dickson and Crocker (1953) attributed the rapid accumulation phase to a period of excessive leaf abscission in response to tree stress by overcrowding. They attributed the slowed accumulation phase to the slower-decomposing woody-debris that is added to the forest floor as the overcrowded trees die. A similar mechanism may control carbon accumulation at Forest Falls, though further observations of the forest litter are required to test this hypothesis.

Processes of carbon incorporation. Mechanisms by which carbon could be incorporated into the subsoil are bioturbation, input from root growth in the subsoil, or leaching of colloidal organic matter. Bioturbation does not seem to be an important mechanism for mixing organic matter into the subsoil at this site. We have not observed any evidence of mixing by burrowing rodents, earthworms, or other macrofauna. This is consistent with previous observations that earthworms are not active under pine, resulting in a concentration of organic matter inputs in a shallow A-horizon (Quideau et al. 1998). A relevant observation, made at both Mt. Shasta and Forest Falls, is that the inflection point between the rapid and slowed carbon accumulation (*fig. 2*) corresponds in age with the transition between profiles where carbon accumulates primarily at the surface (*fig. 1 B-D*) and profiles in which carbon accumulates in the subsoil (*fig. 1 F-H*) (Dickson and Crocker 1953). Considering Dickson and Crocker's (1953) mechanism for the latter two stages of carbon accumulation, presented in the previous section, the increase in subsoil carbon correlates with the death of overcrowded trees and could result from the decay of roots from those trees. However, further study of root dynamics is necessary to test this hypothesis. Leaching of colloidal organic matter has not been addressed in this study. However, a study of dissolved organic matter was made at the Mt. Shasta chronosequence (Lilienfein et al. 2004). That study suggests that the ability to adsorb dissolved organic matter in the subsoil develops over a longer time scale than relevant at the Forest Falls chronosequence and that the adsorption is dependent on the volcanic parent material of the Mt. Shasta mudflows.

An additional process that promotes carbon storage in the soils at Forest Falls and Mt. Shasta is the burial of C-rich O and A horizons by overlying debris flow deposits. Buried soils are frequently encountered at both the Forest Falls and Mt. Shasta sites (Dickson and Crocker 1953 and Sollins et al. 1983). The buried O and A horizons are a complicating issue in our understanding of C-accumulation in the overlying soil. In the buried soils, we cannot sort out what carbon came from the roots of the current forest ecosystem and what carbon was present before the overlying material was deposited. Furthermore, these buried horizons may provide nutrients to the developing ecosystem, without which productivity might be limited. However, the buried soils do contain high levels of carbon (fig. 1 E and G). Thus, buried soils may serve as a significant sink for carbon in geomorphic settings subject to rapid depositional events, such as debris flow and mudflow fans.

Forms of soil organic matter. Our observation that C/N ratio is dynamic over the first 70 years and fairly stable thereafter is consistent with other chronosequence studies of early soil development (fig. 3) (Kaye et al. 2003). The highest C/N ratio at Forest Falls (69) is exceptionally high when compared with those observed in other chronosequence studies. This may be because such short-lived properties are most readily detected using high-resolution chronosequence analyses. The peak in C/N ratio may reflect an influx of fresh organic matter that decomposes to form a residual pool with a more stable C/N ratio. With that residual pool in place, subsequent inputs of fresh organic matter, with high C/N ratio, are overshadowed in the analysis of the bulk soil.

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