



## Effect of land use change on soil carbon in Hawaii

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**Abstract.** Organic carbon storage and turnover were altered in soils formed from volcanic ash (Andisols) as a result of conversion of tropical forest to pasture and sugarcane cropland. Changes in soil carbon storage after approximately a century of each land use were estimated using stable carbon isotope values and carbon contents. Total organic carbon stored in soils varied as a result of management, with pasture soils showing net carbon gain and sugarcane soils showing net carbon loss. In pasture soils, increases in carbon at depth (40 to 80 cm) are below the rooting zone of the introduced (C4) vegetation, and have stable carbon isotopic values indicative of forest (C3) plants. Within the pasture rooting zone (0–40 cm) the isotopic data reveals that additions of pasture (C4) organic matter have been offset by losses of C3 carbon. The concentration of Fe/Al oxides (soil minerals that bind with organic matter to form oxide-humus complexes) appear to control the quantity of carbon stored in soils, as well as the difference in the depth and magnitude of carbon storage changes that occur with each type of land use change. Sugarcane land use appears to induce dissociation of Fe/Al oxide-humus complexes and loss of oxide-associated organic matter from the profile. In pastures, Fe/Al oxide-humus complexes are translocated to deeper horizons in the soils, resulting in greater profile carbon storage and longer apparent turnover time of carbon stored below 50 cm depth. In this high precipitation region, carbon losses from the soil appear to occur via downward transport, either as colloids or in solution, in addition to the generally assumed pathway of flux to the atmosphere as CO<sub>2</sub>.

### Introduction

The majority of carbon in terrestrial ecosystems, both tropical and temperate, is stored as soil organic matter (Delaney et al. 1997; Eswaran et al. 1993; Schlesinger 1997). Land use changes such as forest clearing, cultivation and pasture introduction are known to result in changes in soil carbon content (Houghton et al. 1999; Paustian et al. 1997), yet the sign and magnitude of these changes varies with land cover and land management (Baskin and Binkley 1998; Hu et al. 1997; van Noordwijk et al. 1997). Agricultural cultivation is known to decrease carbon storage (Davidson and Ackerman 1993; Solomon et al. 2002; Yoneyama et al. 2001), and result in a net flux of carbon to the atmosphere (Schlesinger 1984). Changes in soil carbon after conversion of forests to pasture vary greatly from one site to another. Differences in carbon storage between pasture sites are attributed to variations in

vegetation type (Rhoades 1997; Skjemstad et al. 1990), pasture age (García-Oliva et al. 1994; Moraes et al. 1996), and physical properties of soils, specifically soil mineralogy (Parfitt et al. 1997; Veldkamp 1994). Although it is known that mineralogy greatly effects the turnover time of soil carbon (Sorenson 1981; Torn et al. 1997), most models use soil texture as an input parameter (for example: Century), but none utilize soil mineralogy.

The soil minerals most often associated with high carbon storage are found in abundance in soils formed from volcanic ash (Andisols). Andisols store more carbon than soils formed in more crystalline lithologies, and commonly contain 4% to 30% organic matter (Martin and Haider 1986). The high carbon content of volcanic ash soils is due primarily to complexation with aluminum and iron (Nanzzyo et al. 1993; Parfitt et al. 2002). Although they have more carbon to lose than other mineral soils, their high carbon holding capacity may also allow them to conserve it following land use changes.

Cultivation generally enhances microbial decomposition of organic carbon. In addition, it may also affect carbon storage by changing redox conditions, soil solution chemistry or the amount of water flowing through soils. Redox and solution chemistry changes have the potential to dissociate the bonds between the metals and the organic matter complexed to them (Schwertmann 1988) and thus to change soil carbon storage. For example, soil compaction may change soil microsite conditions from oxidizing to reducing, resulting in changes in mineralogy (Camacho et al. 1988) and the oxidation state of metals (Sposito 1989), and ultimately in the release of metals and organic matter into soil solution. Change in ionic strength of soil solution by fertilization and liming will also change the solubility of metal humus compounds (Ugolini and Dahlgren 1991). Such changes may result in release of metals complexed by organic functional groups (Takahashi et al. 1995). Changes in soil pH may also alter the ability of soils to retain carbon and nutrients (Krishnaswamy and Richter 2002).

We investigated the effect of land use changes from tropical forest to both cultivated sugarcane agriculture and pasture on volcanic ash soils. By studying the same land uses on soils experiencing different mean annual precipitation, we were also able to evaluate the relationships between differences in soil mineralogy (as a result of increased weathering) on carbon storage and loss.

## **Materials and methods**

### *Study area*

Study sites were located on the Hamakua Coast of Hawaii (Figure 1; Location of Hamakua Coast and Study Sites) on the northeast flank of Mauna Kea volcano. We chose sites with soils that had developed on similar volcanic ash deposits but that experienced two different climates. Sites included forest, pasture, and sugarcane on each end of a rainfall gradient. All sites have similar elevation (approximately 700

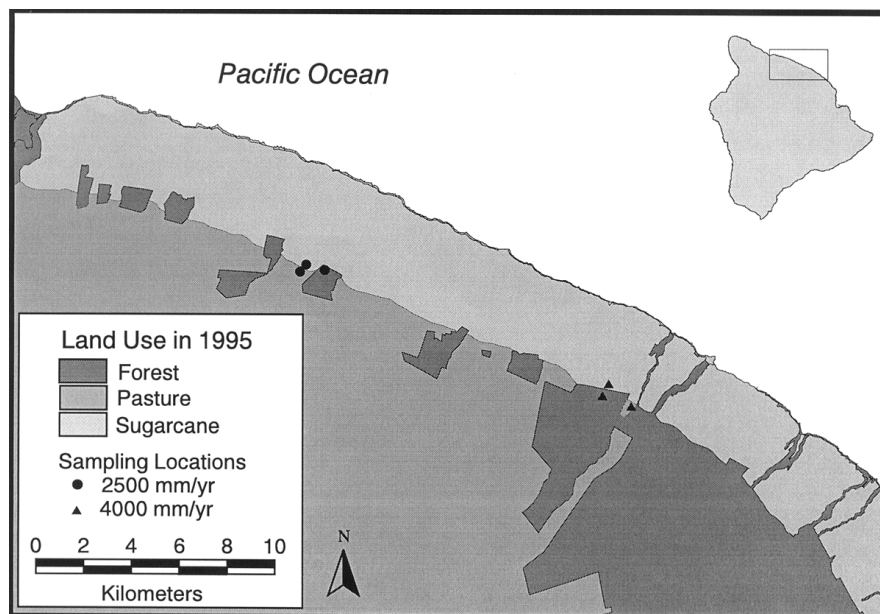


Figure 1. Location of Hamakua Coast and Study Sites.

m). In general, the climate is sub-humid tropical (Giambelluca and Sanderson 1993) with a mean annual temperature of 22 °C (Nullet and Sanderson 1993). Mean annual rainfall is approximately 4000 mm near the south end of the gradient at Hu-muula and 2500 mm near the north end at Paauhau (Giambelluca et al. 1986; Giambelluca and Sanderson 1993; NOAA 1976). Precipitation exceeds evapotranspiration in most months of the year (Juvik et al. 1978). All of the soils classify as Hapludands (NRCS 1996). The ash is estimated to be 15,000 to 20,000 years old (Clague and Hazlett 1989). Native rain forest vegetation, dominated by *Metrosideros polymorpha*, originally covered the entire area. Most of the forests at this elevation were cleared prior to 1910, although some remnant forests were cleared in the 1960s. Pasture has been the primary land use of cleared areas at elevations above 700 m. Conversion of forest to pastures was achieved by felling and removal of trees, spreading seed of African grasses, and introduction of livestock. Pastures contain C4 vegetation dominated by the African grasses *Pennisetum clandestinum* on the higher rainfall site and *Digitaria* sp. on the lower rainfall site. Pastures at both sites are at least 90 years old. Sugarcane agriculture has been the primary land use of cleared areas at elevations below 700 m. Conversion of forest to sugarcane was achieved by felling trees, removal of lumber, plowing with steam driven tractors and manual planting of cane. Sugarcane was grown on the higher rainfall site for at least 90 years and on the lower rainfall site for approximately 50 years. The sugarcane fields are not irrigated, and over the years, they have been cultivated to a depth of approximately 25 cm, fertilized and limed, and have had additions of calcium silicate to stimulate crop productivity.

*Sampling and sample preparation*

Soils were sampled on gently sloping, convex relief landscape positions. Forest soils were sampled in native forest stands. Pasture soils were sampled at least 20 m from trees located within the pasture to reduce the possibility of tree litter being added to the soil. Cane soils were sampled in undissected, gently sloping positions in the up-slope area of the cane/pasture boundary, greater than 30 m from field edges. Sites were chosen in locations with the least potential for surface soil losses as a result of erosion. Pasture and cane soils were collected no more than 1 km from forest soil profiles in the same precipitation zone. At each site, one soil pit was excavated to a depth of approximately 1.8 m beneath the soil surface. Soil profiles were described according to the procedures outlined by the Soil Conservation Service (SCS 1984). Horizons were sampled for chemical analyses by collecting a uniform cross sectional area of soil from the top to the bottom of the horizon, according to standard protocol (SCS 1984). Morphologic horizons greater than 30 cm were subdivided and sampled such that no sample represented more than a 30 cm horizon. In addition, two auger holes were excavated at least 300 m from each soil pit. The soil samples from the auger holes were collected at the same depth sequences determined for each horizon in the soil profile (i.e., for each soil horizon,  $n = 3$ ). An additional surface (0–5 cm) sample was collected for each site by bulk-ing four 0.3 L samples collected 25 m from the pit in four directions. Bulk density cores were sampled near the midpoint of each horizon in each profile and at each auger hole.

Vegetation was sampled in two ways: specimens were pressed in the field for later identification and plant and litter samples were collected in plastic bags and placed in coolers. Soil, plant and litter samples were kept on ice in coolers in the field and transported, chilled, to UC Berkeley. At UC Berkeley, samples were refrigerated at 5 °C for less than 2 months before being frozen and lyophilized. Roots (> 0.5 mm in diameter) were removed manually from dried samples. Lyophilized root-free-soil and lyophilized root samples were ground using a porcelain mortar and pestle. The soils contained no rock fragments and no  $\text{CaCO}_3$  as evidenced by a field test for effervescence. Plant and litter samples were dried at 100 °C for 48 hours and ground prior to mass spectrometric analysis.

*Physical and chemical analyses*

Soil bulk density was sampled for each horizon of each profile using  $0.5 \times 10^{-3} \text{ m}^3$  stainless steel rings (3 per horizon for each profile). The samples were oven dried at 100 °C to determine oven dry bulk density. Organo-iron and organo-aluminum compounds were extracted from soils using 1 M sodium pyrophosphate (Kononova and Bel'chikova 1970). Iron and aluminum concentrations in extracts were measured using a Perkin Elmer Plasma 40 inductively coupled plasma spectrometer. Content of pyrophosphate extractable iron and aluminum cations in each horizon were calculated as percent of total mineral material in that horizon.

Organic carbon and nitrogen content was determined using a Carlo Erba C/N analyzer. Stable carbon isotope values were determined using both sealed tube combustion and automated continuous flow mass spectrometers. For the sealed tube combustions, the ground samples were weighed into a Vycor tube, mixed with purified (carbon-free) CuO and Cu shot and Ag metal. The tubes were sealed under vacuum and combusted at 900 °C in a Thermolyne type 6000 muffle furnace (Boutton 1996). Carbon dioxide was isolated and purified by cryogenic distillation on a high vacuum manifold. The C isotope ratios were measured using three inter-calibrated mass spectrometers. The first was a VG Prism dual-inlet, triple-collector isotope ratio mass spectrometer at Lawrence Berkeley Laboratory's Center for Isotope Geochemistry. The measurements made by continuous flow were done using both a VG Optima mass spectrometer with a Carlo Erba C/N analyzer at the US Geological Survey's isotope laboratory in Menlo Park, CA and a Europa Scientific 20/20 mass spectrometer with a Europa ANCA-NT system C/N analyzer at UC Berkeley. All results are reported relative to the international PeeDee Belemnite (PDB) standard by calibration through National Biological Standard #19 (NBS-19). Analytical precision, determined as the standard deviation obtained on different combustions of the same homogenized sample, is 0.02‰  $\delta^{13}\text{C}$  for the VG Prism samples, 0.2‰  $\delta^{13}\text{C}$  for the VG Optima and 0.3‰  $\delta^{13}\text{C}$  for the Europa 20/20.

### Calculations

Carbon contents of soil samples were converted from percent by weight to total soil carbon in weight per volume using the method of Veldkamp (1994). Because pasture and cane soils were compacted, carbon accumulation in the top meter of soil depth was not directly comparable to forest. To address the compaction, pasture and cane horizon depths were expanded vertically by accounting for change in soil bulk density (García-Oliva et al. 1994; Lugo et al. 1986; Reiners et al. 1994; Trumbore et al. 1995; Veldkamp 1994).

In soils where the carbon isotope ratio results from a mixture between carbon from C3 and C4 plants, the percentage of soil organic carbon derived from each type of plant were calculated by solving for  $X_{(p,c)}$  in the following equation:

$$\delta^{13}\text{C}_n = (1 - X_{(p,c)})\delta^{13}\text{C}_F + (X_{(p,c)})\delta^{13}\text{C}_{C4} \quad (1)$$

Where  $\delta^{13}\text{C}_n$  is the  $\delta^{13}\text{C}$  value (‰) of soil carbon content in horizon "n",  $(1 - X_{p,c})$  is the proportion of carbon from forest plants in that horizon,  $X_{p,c}$  is the proportion of carbon from pasture or cane (C4) plants in that horizon,  $\delta^{13}\text{C}_F$  is the  $\delta^{13}\text{C}$  value (‰) of soil organic carbon at the equivalent depth in forest soil, and  $\delta^{13}\text{C}_{C4}$  is the  $\delta^{13}\text{C}$  value (‰) of soil organic matter derived from C4 plants at that site.  $\delta^{13}\text{C}_F$  for each individual depth (n) is derived by using the equation:

$$\delta^{13}\text{C}_F = \beta e^{-n\tau} + \delta^{13}\text{C}_D \quad (2)$$

Where  $n$  is the depth,  $\delta^{13}\text{C}_D$  is the  $\delta^{13}\text{C}$  value at depth where its value becomes constant in each soil, and the parameters  $\beta$  and  $\tau$  are determined for each site by fitting a curve to the data from the forest soil. Equation 2 describes the observed changes in isotope values as a function of depth. Using this equation, the percent of carbon from C4 plants at depths near the soil surface is less likely to be over-estimated than if one  $\delta^{13}\text{C}$  value is used for all depths.

Change in forest derived soil organic carbon content in pasture and cane sites as a function of time can be described using results from Equation 1 and a decay model (Amundson and Baisden 1998):

$$\frac{dC}{dt} = I - kC_{3(t=0)} \quad (3)$$

where  $t$  = time,  $C_3$  is the content of C3 carbon to a depth of one meter,  $I$  = the inputs of new C3 carbon to pasture and cane sites since conversion from forest, and  $k$  is the first order decay constant for the C3 carbon pool. Although C3 carbon may be added by translocation from higher in the soil profile or by decay of tree roots, the value of  $I$  for each of these additions can only be calculated if the factors effecting those additions (soil solution velocity, amount of carbon moved in solution, amount of carbon in woody roots, root decay rate) are known. For a first approximation, we assumed that  $I$  is zero, so that the equation becomes a simple, well-mixed one box model. The solution to this model is:

$$\ln(C_{3(t=x)}/C_{3(t=0)})t^{-1} = -k \quad (4)$$

The content of C3 carbon at time  $t = 0$  is approximated for each horizon by using the carbon content in horizons at equivalent depths in adjacent forest sites with similar precipitation levels. Time was estimated conservatively for each site as the difference between the sampling year and the year of the first documented converted land use. The content of C3 carbon at time  $t = x$  is the C3 soil carbon content in a given depth interval, adjusted for compaction. Apparent turnover time of C3 carbon in each depth interval is the inverse of the decay constant ( $k^{-1}$ ).

## Results

### *Bulk density*

Bulk densities ( $\rho$ ) of forest soils with the two different precipitation regimes were not significantly different from one another. In general, mean bulk densities in the top 0.3 m and top 1 m of pasture and cane soils were significantly greater than those of the adjacent forests ( $p < 0.01$ ). In the higher rainfall site, sugarcane soil  $\rho$  was significantly greater than in pasture soil at the same site, but this relationship was not observed in the lower rainfall site (Table 1).

Table 1. Mean soil bulk density ( $\rho$ ) to a depth of 0.3 m and 1 m, and mean soil organic carbon contents to 1 m depth before and after expansion of horizon depths by accounting for soil compaction. Values in parentheses represent the standard error of the means ( $n = 3$  profiles).

| Vegetation                           | $\rho$<br>mg m <sup>-2</sup> (se)* |                            | Organic C<br>kg m <sup>-2</sup> (se)** |                            |
|--------------------------------------|------------------------------------|----------------------------|--|----------------------------|
|                                      | to 0.3 m                           | to 1 m                     | to 1 m                                 | 1 m equivalent             |
| 2500 mm/yr mean annual precipitation |                                    |                            |  |                            |
| Forest                               | 0.38 (0.053) <sup>a</sup>          | 0.33 (0.028) <sup>a</sup>  | 31.07 (0.045) <sup>a</sup>             | 31.07 (0.220) <sup>b</sup> |
| Pasture                              | 0.44 (0.050) <sup>b</sup>          | 0.35 (0.037) <sup>ab</sup> | 36.76 (0.066) <sup>c</sup>             | 35.83 (0.302) <sup>d</sup> |
| Cane                                 | 0.44 (0.027) <sup>b</sup>          | 0.37 (0.031) <sup>a</sup>  | 25.84 (0.040) <sup>d</sup>             | 23.14 (0.668) <sup>c</sup> |
| 4000 mm/yr mean annual precipitation |                                    |                            |  |                            |
| Forest                               | 0.35 (0.057) <sup>a</sup>          | 0.32 (0.031) <sup>a</sup>  | 27.35 (0.087) <sup>a</sup>             | 27.36 (0.299) <sup>a</sup> |
| Pasture                              | 0.49 (0.047) <sup>b</sup>          | 0.39 (0.029) <sup>b</sup>  | 31.17 (0.081) <sup>b</sup>             | 30.61 (0.112) <sup>b</sup> |
| Cane                                 | 0.56 (0.012) <sup>c</sup>          | 0.42 (0.067) <sup>b</sup>  | 27.78 (0.039) <sup>c</sup>             | 25.40 (0.165) <sup>c</sup> |

\* se = standard error, letters indicate significance of differences between values:  $p < 0.01$  for bulk density to 0.3 m and  $p < 0.05$  for bulk density to 1.0 m.

\*\* se = standard error, letters indicate significance of differences between values:  $p < 0.01$  for organic carbon in top and  $p < 0.001$  for organic carbon in 1 m equivalent.

### Total carbon

Plotted on an individual horizon basis, carbon concentration (g C kg<sup>-1</sup> soil) was similar in surface horizons of forest soils at both sites. Below 20 cm, C concentrations were higher in 2500 mm/yr sites than in 4000 mm/yr sites (Figure 2). As a result, total carbon contents to 1 m depth in forest soils (g C kg<sup>-1</sup> soil) were greater in the lower rainfall site than in the higher rainfall site (Table 1). Distribution of root biomass, plotted at the horizon midpoints as weight of roots (kg/m<sup>3</sup>) in each horizon, is plotted in Figure 3. In the 4000 mm/yr rainfall site, root biomass in the top 20 cm of all land uses is twice that at the 2500 mm/yr rainfall site. In general, all soils have only small amounts of root biomass, and differences in root biomass between land uses are for the most part, not detectable. The only exception to this is in pasture soils, where at some depths between 50 and 100 cm, root biomass is greater than in adjacent forest and sugarcane soils.

Carbon content of soil (kg m<sup>-2</sup> to 1 m depth equivalent) under pasture and sugarcane management was significantly different from soils under forests in both higher rainfall ( $p < 0.05$ ) and lower rainfall sites ( $p < 0.001$ ) (Table 1). Pasture management resulted in a net carbon gain (12–15%) and sugarcane land use resulted in a net carbon loss (7–25%). The proportional carbon gains and losses were significantly greater, relative to forest soil carbon contents, in 2500 mm/yr sites than in 4000 mm/yr sites.

The vertical distribution of carbon also appeared to change with land use change. In the lower rainfall site, carbon content of the surface 0–10 cm (plotted at 5 cm depth in Figure 4a) in both pasture and cane soils was less than that of forest soil.



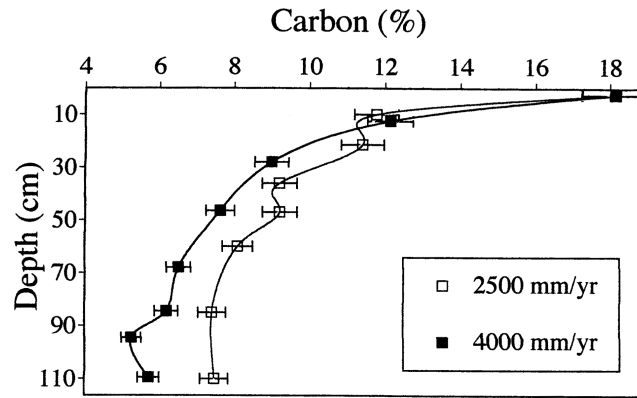


Figure 2. Mean soil carbon concentration and standard errors ( $n=3$ ) to 1 m depth beneath forest sites on Andisols with different mean annual precipitation: 2500 mm/yr and 4000 mm/yr. Carbon contents are plotted at the midpoint of each horizon. Splined lines connect the data points.

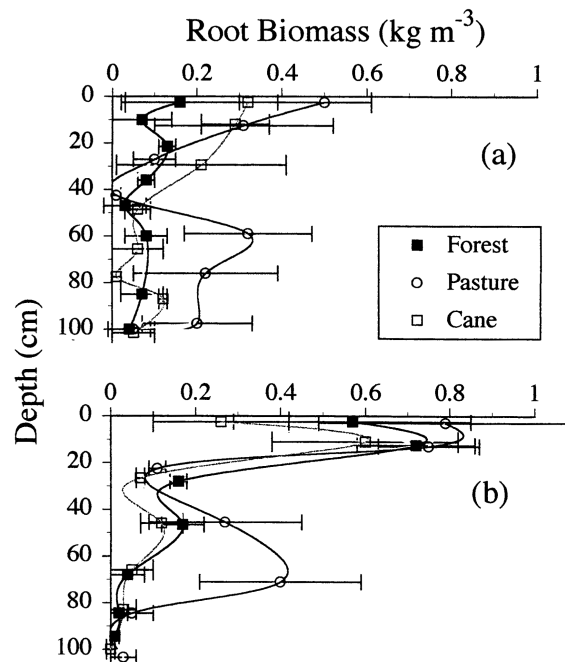


Figure 3. Mean root dry weight and standard errors ( $n=3$ ) to 1 m depth beneath three vegetation/land use types on Andisols with different mean annual precipitation: (a) 2500 mm/yr and (b) 4000 mm/yr. Root dry weights are plotted at the midpoint of each horizon.

In the pasture, soil carbon content was greater than the forest in most horizons between depths of 20 and 90 cm. In the cane, soil carbon content decreased relative to forest soil at all depths except between 50 and 70 cm. In the higher rainfall site



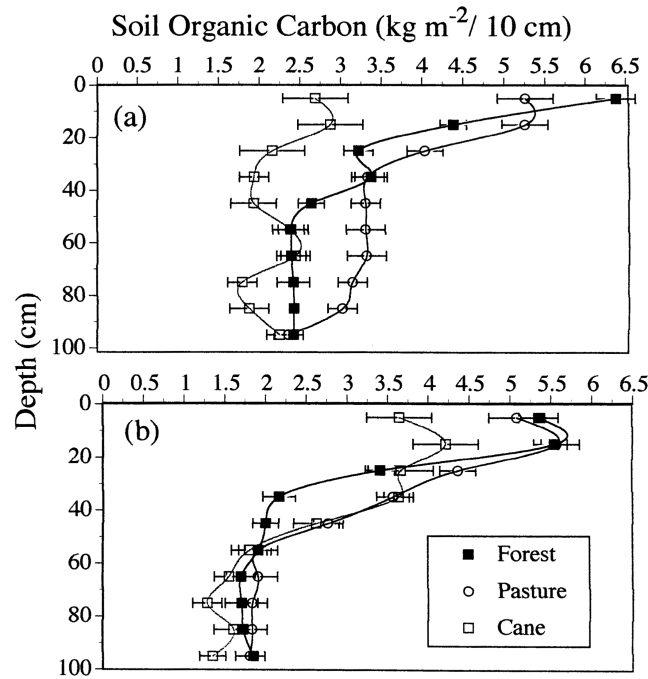


Figure 4. Mean soil carbon content in 10cm intervals ( $n=3$ ) to 1m depth beneath three vegetation/land use types on Andisols with different mean annual precipitation: (a) 2500 mm/yr and (b) 4000 mm/yr. Horizon depths in pasture and sugarcane soils are corrected for compaction, and carbon contents are plotted as total C in each uncompacted 10cm depth interval.

(Figure 4b), carbon in cane soil was significantly less than that of adjacent forest in the horizons nearest to the soil surface (0–20 cm depth).

#### Carbon-13 analyses

The isotopic values of the vegetation from forest reflected plants using the C3 photosynthetic pathway ( $\delta^{13}\text{C}$  values between  $-27.5$  and  $-33.7\text{‰}$ ) (Table 2). The  $\delta^{13}\text{C}$  values for soils beneath long standing C3 forests ranged from  $-27.7\text{‰}$  in the surface to  $-24.7\text{‰}$  at depths of 40 cm and below (Figure 5). The curves describing the changes in isotope ratios with depth in forest soils (Table 3) were calculated using Equation 2 and are plotted on Figures 5a and 5b.

The  $\delta^{13}\text{C}$  values of surface horizons from pasture and sugarcane sites reflect a mixture between C3 and C4 ( $\delta^{13}\text{C}$  values between  $-10.9$  and  $-12.6\text{‰}$ ) carbon sources (Figure 5). In soils presently under C4 vegetation (pasture grasses and sugarcane), the proportion of soil carbon from C4 sources is greatest near the soil surface. Stable carbon isotope values at lower depths are similar to those found under C3 vegetation (Figure 6). Losses of C3 carbon from the top meter of pasture soils were  $0.7 \text{ kg m}^{-2}$  (2% of forest soil carbon content) for the lower rainfall site and

Table 2. Field identification, scientific name, stable carbon isotopic composition and C/N ratio of vegetation from forest pasture and cane sites on Hawaii's Hamkua Coast.

| Site<br>MAP<br>(mm/yr) | Land<br>Use | Field ID                     | Sample ID                                  | $\delta^{13}\text{C}$<br>per<br>mil | SD*  | Plant<br>type | C/N<br>ratio | SD** |
|------------------------|-------------|------------------------------|--|-------------------------------------|------|---------------|--------------|------|
| 2,500                  | Forest      | fern "Hoio"                  | <i>Athyrium<br/>sandwichianum</i>          | -31.3                               | 0.02 | C3            | 12.78        | 0.17 |
| 2,500                  | Forest      | litter (stems and<br>leaves) | litter (stems and<br>leaves)               | -29.7                               | 0.01 | C3            | 28.91        | 0.23 |
| 2,500                  | Forest      | Common Guava<br>(leaves)     | <i>Psidium guajava</i>                     | -33.2                               | 0.09 | C3            | 16.98        | 0.31 |
| 2,500                  | Forest      | Common Guava<br>(leaves)     | <i>Psidium guajava</i>                     | -33.3                               | 0.01 | C3            | 31.21        | 0.41 |
| 2,500                  | Forest      | Ohi'a (branches)             | <i>Metrosideros<br/>polymorpha</i>         | -28.2                               | 0.01 | C3            | 79.30        | 2.96 |
| 2,500                  | Forest      | Ohi'a (leaves)               | <i>Metrosideros<br/>polymorpha</i>         | -28.0                               | 0.07 | C3            | 40.29        | 3.67 |
| 2,500                  | Pasture     | pasture grass (70%)          | <i>Digitaria sp.</i>                       | -10.8                               | 0.01 | C4            | 42.35        | 0.18 |
| 2,500                  | Pasture     | Broomsedge (30%<br>cover)    | <i>Andropogon<br/>virginicus</i>           | -10.9                               | 0.01 | C4            | 55.09        | 1.24 |
| 2,500                  | Cane        | Melinis (leaves)<br>(10%)    | <i>Melinis minutiflora</i>                 | -11.9                               | 0.07 | C4            | 41.99        | 0.14 |
| 2,500                  | Cane        | cane "Ko" (leaves)           | <i>Saccharum hybrid</i>                    | -11.9                               | 0.03 | C4            | 25.21        | 0.48 |
| 2,500                  | Cane        | cane "Ko" (stalk)            | <i>Saccharum hybrid</i>                    | -12.6                               | 0.01 | C4            | 173.03       | 0.86 |
| 4,000                  | Forest      | fern "Meu"                   | <i>Cibotium<br/>sanwicensis</i>            | -31.0                               | 0.02 | C3            | 13.72        | 0.19 |
| 4,000                  | Forest      | litter (mostly<br>leaves)    | litter (mostly<br>leaves)                  | -30.8                               | 0.04 | C3            | 35.00        | 0.46 |
| 4,000                  | Forest      | litter (mostly stems)        | litter (mostly stems)                      | -27.5                               | 0.05 | C3            | 62.33        | 0.80 |
| 4,000                  | Forest      | Strawberry Guava<br>(leaves) | <i>Psidium<br/>cattleianum</i>             | -33.0                               | 0.05 | C3            | 21.40        | 1.06 |
| 4,000                  | Forest      | Strawberry Guava<br>(stems)  | <i>Psidium<br/>cattleianum</i>             | -33.7                               | 0.01 | C3            | 79.85        | 0.62 |
| 4,000                  | Pasture     | Kikuyu (60%)                 | <i>Pennisetum clan-<br/>destinum Choiv</i> | -11.7                               | 0.05 | C4            | 39.30        | 0.24 |
| 4,000                  | Pasture     | Broomsedge (40%<br>cover)    | <i>Andropogon<br/>virginicus</i>           | -10.9                               | 0.01 | C4            | 55.09        | 1.24 |
| 4,000                  | Cane        | Melinis (leaves)<br>(10%)    | <i>Melinis minutiflora</i>                 | -12.1                               | 0.05 | C4            | 79.69        | 2.15 |
| 4,000                  | Cane        | cane "Ko" (leaves)           | <i>Saccharum hybrid</i>                    | -11.8                               | 0.01 | C4            | 65.77        | 1.95 |

\* SD is standard deviation, n = 3

\*\* SD is standard deviation, n = 6

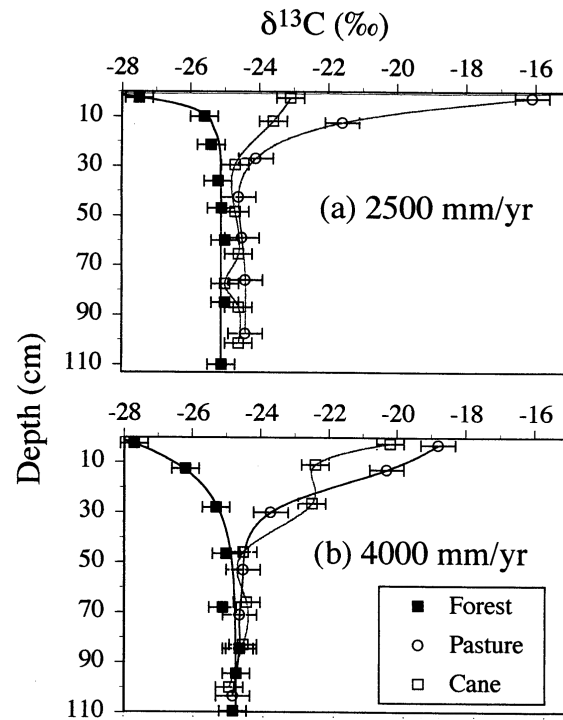


Figure 5. Isotopic values in soils beneath three vegetation types on Andisols with different mean annual precipitation: (a) 2500 mm/yr MAP and (b) 4000 mm/yr. Means and standard deviations of isotope values are plotted at midpoints of sampling intervals. The lines through the forest data represent the best fit parameters for equation (4). Parameters for each line are listed in Table 4.

Table 3. Constants and fitted parameters for models describing the change in stable carbon isotope value of forest soil carbon with depth.

| Site MAP (mm/yr) | $\delta^{13}\text{C}_{\text{pasture}}$ | $\delta^{13}\text{C}_{\text{cane}}$ | $\delta^{13}\text{C}_4$ |       | $B$    | $\tau$ |
|------------------|--|-------------------------------------|-------------------------|-------|--------|--------|
|                  |  |                                     | mean                    | se    |        |        |
| 2500             | -10.9                                  | -11.9                               | -25.11                  | 0.052 | -10.97 | -0.305 |
| 4000             | -10.9                                  | -11.9                               | -24.78                  | 0.064 | -3.43  | -0.067 |

2.9 kg m<sup>-2</sup> (11% forest soil carbon content) for the higher rainfall site. C<sub>4</sub> additions were 5.4 kg m<sup>-2</sup> (17%) and 6.2 kg m<sup>-2</sup> (23%), respectively. In pasture soils, carbon gained in surface horizons was C<sub>4</sub> carbon, while carbon apparently added at lower depths was primarily C<sub>3</sub> carbon (Figure 6). In cane soils, C<sub>3</sub> carbon losses in the top meter, relative to adjacent forest soils, were 6.6 kg m<sup>-2</sup> for both lower (21%) and higher (24%) rainfall sites. Additions of C<sub>4</sub> carbon were 1.8 kg m<sup>-2</sup> (6%) for lower rainfall and 4.6 kg m<sup>-2</sup> (17%) for higher rainfall sites.

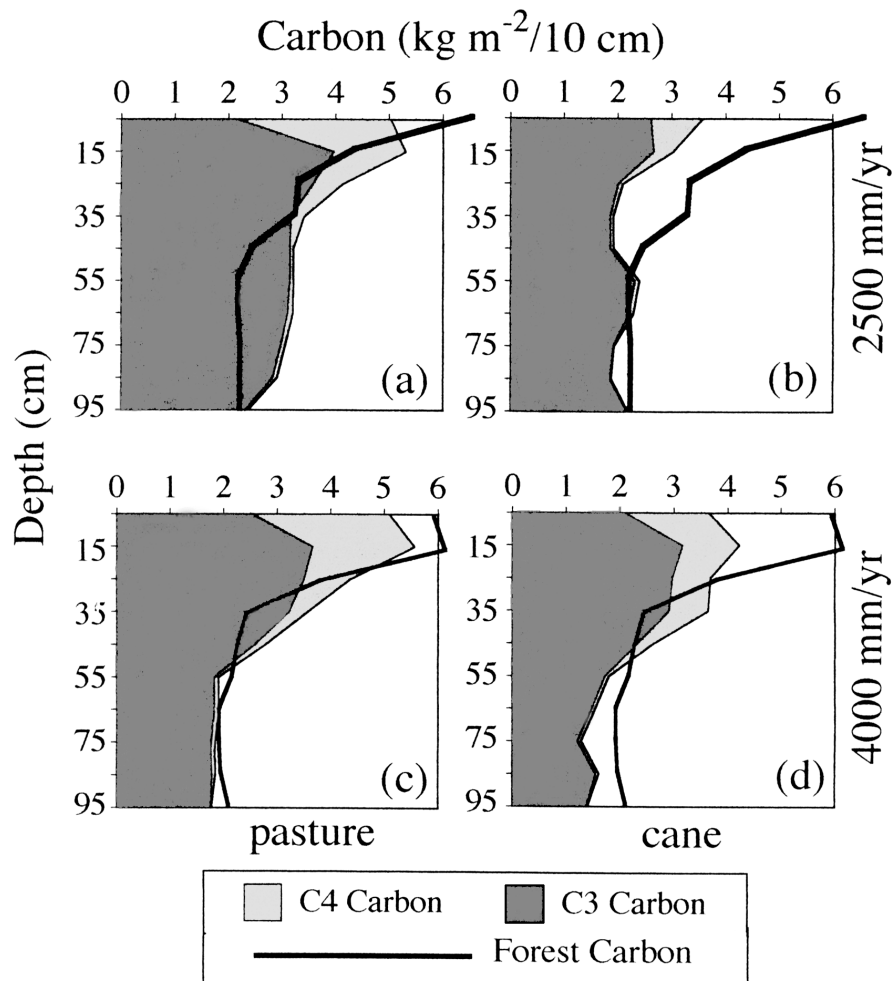


Figure 6. Soil organic carbon content derived from C3 and C4 plant in pasture and sugarcane soils on Andisols with different mean annual precipitation: (a) pasture with MAP of 2500 mm/year, (b) cane with MAP of 2500 mm/yr, (c) pasture with MAP of 4000 mm/yr, (d) cane with MAP of 4000 mm/yr. Pasture and cane are calculated after correction for compaction. Forest carbon contents are represented by the solid line.

#### *Pyrophosphate extractable Fe and Al*

Concentrations of pyrophosphate-extractable Fe (%) and pyrophosphate-extractable Al (%) in forest soils were significantly greater in most horizons in the top 60 cm of the 2500 mm/yr site than at similar depths at the 4000 mm/yr site (Figure 7) (Fe:  $p < 0.01$ , Al:  $p < 0.001$ ). Al and Fe contents in individual horizons were positively correlated with horizon soil carbon content (Figure 8). The best fit curves to describe the relationship between each cation and soil organic carbon content are sec-

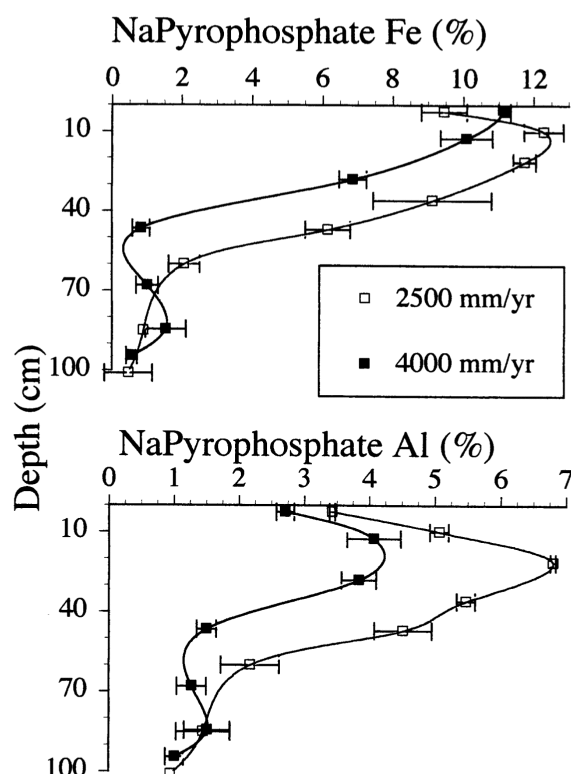


Figure 7. Sodium pyrophosphate-extractable iron and aluminum in soils Andisols with different mean annual precipitation: (a) Fe and (b) Al. Means and standard errors of values are plotted at midpoints of sampling intervals.

and order polynomials. Fe and Al are also positively correlated (linear regression with  $r^2 = 0.83$ ).

In the lower rainfall site, Fe and Al in the top 50 cm of sugarcane soil were less than in the forest soil (Figure 9). In the higher rainfall site, sugarcane soil had significantly less Fe in the top 30 cm than forest soil. Pasture soil at the lower rainfall site had Fe and Al contents that were significantly higher between depths of 50 and 80 cm than adjacent forest soil. At the 2500 mm/yr site, pyrophosphate extractable Al concentrations decreased significantly in the top 30 cm of the pasture soil relative to the forest soil. Pasture soil at the 4000 mm/yr site had higher Fe and Al, relative to forest soil, at 50 cm depth.

#### Carbon turnover

Apparent turnover of forest soil carbon (yr) for 10 cm depths in the top meter of pasture and sugarcane soils are listed in Table 4. In general, carbon turnover decreases with soil depth. Turnover is similar in the top 35 cm of all sites. However,

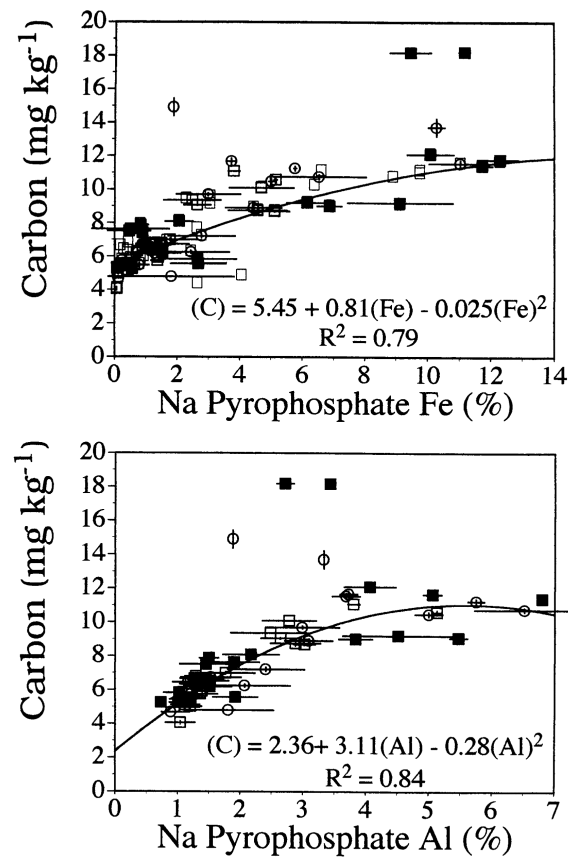


Figure 8. The relationship of pyrophosphate-extractable Fe and Al to organic C in Hamakua Coast Soils: (a) Fe vs. C and (b) Al vs. C. Plotted values represent means with standard errors for horizons from beneath forest, pasture, and cane land uses. The equations represent the best fit lines through all points except the 0–5 cm horizons of forest and pasture sites ( $n=57$ ).

in the pasture soil at the lower rainfall site, carbon turnover between 40 and 70 cm depth is much greater than in the adjacent sugarcane soil. The turnover is also faster than both cane and pasture soils of at higher rainfall site.

## Discussion

The limited number of pasture and sugarcane sites that are located directly adjacent to forested sites on similar landscape positions resulted in limited sampling ( $n = 3$ ) for each land use at each precipitation region. Despite this limited sampling, sites studied in this research provided a unique opportunity to examine the effects of both land use and soil mineralogy on the storage and turnover time of soil organic matter.

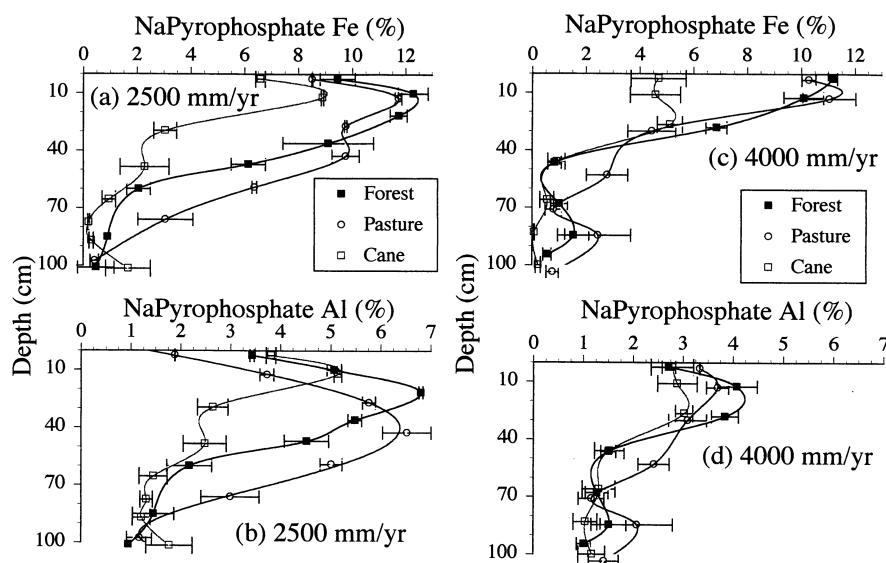


Figure 9. Sodium pyrophosphate-extractable Fe and Al beneath three vegetation types on Andisols with different mean annual precipitation (a) Fe on soils with MAP of 2500 mm/yr, (b) Al on soils with MAP of 2500 mm/yr, (c) Fe on soils with MAP of 4000 mm/yr, and (d) Al on soils with MAP of 4000 mm/yr. Means and standard errors of values are plotted at midpoints of sampling intervals.

#### Pasture

In agreement with previous studies (Feigl et al. 1995; García-Oliva et al. 1994; Lugo et al. 1986; Moraes et al. 1996), we found that conversion of tropical forest to pasture resulted in a gain of total soil carbon. The carbon gain in pasture soil was a result of increased carbon storage in subsurface horizons. Isotopic analyses revealed that accumulated carbon at depth is of C3 origin. Because root biomass in adjacent forest soils was low below 30 cm depth (Figure 3), we believe that the carbon was translocated from surface horizons. Changes in the patterns of pyrophosphate extractable Fe and Al distribution are correlated with changes in distribution of C3 soil carbon with depth in the profile. The C3 organic matter appears to have been physically transported down the soil profile as colloidal Fe/Al-humus complexes. The downward movement of these complexes is most likely facilitated by increased volume of water moving through the soil profile (per rainfall event) in pastures relative to unconverted forest (Sollins and Radulovich 1988; White 1985).

Carbon turnover times in the pasture soils are greater than turnover times determined for other tropical soils (Townsend et al. 1995; Trumbore et al. 1996). These differences are most likely a result of a difference in the methods used to calculate turnover time. The turnover times in Table 4 were determined using our stable carbon isotope values and the one pool model, while the other turnover times were measured using C-14 methods. C-14 methods measure a mean residence time for



Table 4. Total carbon content, C3 and C4 carbon content, time since last C3 input (t) and turnover time ( $\tau$ ) for 10 cm intervals.

| Vegetation   | Depth (cm) | Total C (Kg m <sup>-2</sup> ) | C3 (Kg m <sup>-2</sup> ) | C4 (Kg m <sup>-2</sup> ) | T (yr) | $\tau$ (yr) |
|--|------------|-------------------------------|--------------------------|--------------------------|--------|-------------|
| <b>Soils with 2500 mm/yr mean annual precipitation</b> |            |                               |                          |                          |        |             |
| Pasture  | 0–10       | 5.03                          | 2.17                     | 2.86                     | 90     | 107         |
|  | 10–20      | 5.30                          | 3.97                     | 1.33                     | 90     | 311         |
|  | 20–30      | 4.14                          | 3.58                     | 0.55                     | 90     | 627         |
|  | 30–40      | 3.41                          | 3.17                     | 0.24                     | 90     | 1232        |
|  | 40–50      | 3.21                          | 3.14                     | 0.07                     | 90     | 4359        |
|  | 50–60      | 3.21                          | 3.14                     | 0.07                     | 90     | 4356        |
|  | 60–70      | 3.20                          | 3.11                     | 0.09                     | 90     | 3229        |
|  | 70–80      | 3.07                          | 2.97                     | 0.09                     | 90     | 2871        |
|  | 80–90      | 2.91                          | 2.82                     | 0.09                     | 90     | 2969        |
|  | 90–100     | 2.37                          | 2.33                     | 0.04                     | 90     | 5264        |
| Cane   | 0–10       | 3.57                          | 2.61                     | 0.96                     | 50     | 160         |
|  | 10–20      | 3.03                          | 2.66                     | 0.37                     | 50     | 385         |
|  | 20–30      | 2.09                          | 2.00                     | 0.10                     | 50     | 1053        |
|  | 30–40      | 1.92                          | 1.86                     | 0.06                     | 50     | 1594        |
|  | 40–50      | 1.92                          | 1.86                     | 0.06                     | 50     | 1595        |
|  | 50–60      | 2.40                          | 2.31                     | 0.09                     | 50     | 1276        |
|  | 60–70      | 2.29                          | 2.20                     | 0.09                     | 50     | 1276        |
|  | 70–80      | 1.93                          | 1.90                     | 0.03                     | 50     | 3589        |
|  | 80–90      | 1.87                          | 1.85                     | 0.02                     | 50     | 6113        |
|  | 90–100     | 2.17                          | 2.16                     | 0.02                     | 50     | 6449        |
| <b>Soils with 4000 mm/yr mean annual precipitation</b> |            |                               |                          |                          |        |             |
| Pasture  | 0–10       | 5.08                          | 2.53                     | 2.56                     | 90     | 129         |
|  | 10–20      | 5.56                          | 3.66                     | 1.90                     | 90     | 216         |
|  | 20–30      | 4.36                          | 3.50                     | 0.86                     | 90     | 411         |
|  | 30–40      | 3.56                          | 3.21                     | 0.35                     | 90     | 869         |
|  | 40–50      | 2.77                          | 2.57                     | 0.20                     | 90     | 1232        |
|  | 50–60      | 1.91                          | 1.83                     | 0.08                     | 90     | 2074        |
|  | 60–70      | 1.91                          | 1.83                     | 0.08                     | 90     | 2074        |
|  | 70–80      | 1.84                          | 1.77                     | 0.07                     | 90     | 2492        |
|  | 80–90      | 1.84                          | 1.78                     | 0.07                     | 90     | 2492        |
|  | 90–100     | 1.77                          | 1.75                     | 0.02                     | 90     | 7343        |
| Cane   | 0–10       | 3.64                          | 2.09                     | 1.55                     | 90     | 163         |
|  | 10–20      | 4.21                          | 3.15                     | 1.06                     | 90     | 311         |
|  | 20–30      | 3.66                          | 2.97                     | 0.70                     | 90     | 427         |
|  | 30–40      | 3.63                          | 2.91                     | 0.72                     | 90     | 409         |
|  | 40–50      | 2.62                          | 2.32                     | 0.30                     | 90     | 743         |
|  | 50–60      | 1.80                          | 1.72                     | 0.08                     | 90     | 1911        |
|  | 60–70      | 1.55                          | 1.47                     | 0.08                     | 90     | 1634        |
|  | 70–80      | 1.28                          | 1.21                     | 0.07                     | 90     | 1634        |
|  | 80–90      | 1.61                          | 1.55                     | 0.06                     | 90     | 2297        |
|  | 90–100     | 1.40                          | 1.38                     | 0.02                     | 90     | 5894        |

all carbon, much of which is recently deposited and has a residence time of less than 30 years. The model we used calculates turnover time from the C3 carbon only, and assumes no inputs of C3 carbon after land use change. The apparent increases in C turnover time at depth in pasture soils are most likely a result of the movement of C3 carbon to those depths as a result of land use change.

An interesting aspect of these data is that by measuring soil carbon to a depth of 1 m, it appears that we observe some of the C3 carbon that has been lost from surface horizons. Without measuring and tabulating the C3 and C4 carbon contents to this depth, we would have overestimated the loss of C due to microbial degradation. These results point to the need to sample soils deeply in C budget studies.

### *Sugarcane*

The two sugarcane soils lost greater amounts of carbon ( $\text{kg m}^{-2}$ ) from the top meter of soil than the average of losses from agricultural sites converted from forest throughout the world. According to Davidson and Ackerman (1993), average soils (which typically have much lower organic matter contents prior to conversion than our soils did) lost 30% of carbon after forest clearing and two decades of cultivation. In the soils we studied, 12–26% of C is lost from the top meter after forest clearing and conversion to sugarcane. This reduction in soil C occurs in conjunction with some movement of soil C downward in the profile. Carbon turnover time in the cane soils is similar to turnover times determined for other agricultural soils (Anderson and Paul 1984; Balesdent et al. 1988).

### **Conclusions**

1. Initial forest soil carbon content and magnitude of loss or gain of soil carbon after land use change appears to be related to soil mineralogy, specifically the concentration of pyrophosphate extractable Fe/Al oxides in these volcanic ash soils. The Fe and Al oxides complex with organic matter, and help sequester it in soils. The soils with higher contents of these Fe and Al oxides have a greater ability to store carbon added by pasture land use. These soils also appear to have the ability to transport carbon sequestered in Fe/Al oxide-organic matter complexes, to deeper horizons outside the zone of the rhizosphere, and beyond zones that have rapid turnover rates.
2. Changes in soil solution chemistry following sugarcane land management, such as changes in soil solution ionic strength (Takahashi et al. 1995) result in the dissociation of Fe and Al humus complexes. Management practices facilitating changes in solution chemistry include liming, fertilization, and silica additions (Osher submitted). Once released from complexation with Fe and Al, organic matter is available for both leaching from the system as dissolved organic carbon, or for mineralization by soil micro-organisms and loss as  $\text{CO}_2$ . Thus, man-

agement practices that alter the solubility of Fe/Al humus complexes in these volcanic ash soils play a critical role in controlling C gains and losses.

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