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COMPARISON OF LABORATORY AND MODELING SIMULATION METHODS FOR ESTIMATING SOIL CARBON POOLS IN TROPICAL FOREST SOILS

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Summary—Availability of methods to determine kinetically-defined soil carbon pools may assist in better understanding soil organic matter turnover in tropical soils and its relationship with soil mineral fractions and nutrient cycling. Our objective was to compare three methods of estimating soil C pools for the top mineral soil horizon of 13 tropical forest soils with a wide range of clay content and differing soil mineralogies. The methods were: (i) regression analysis of CO_2-C release from a 341 day incubation of unamended soils; (ii) results of C analysis procedures including determinations of soluble C, microbial biomass C and light fraction C; and (iii) CENTURY model simulations of equilibrium values of soil C pools.

Soil mineralogy did not have a significant effect on CO_2-C release, expressed as a proportion of total organic C, during incubation. However, allophanic soils had significantly higher total organic C, soluble C and light fraction C than soils of smectitic, kaolinitic or oxidic mineralogies. Clay and sand contents significantly correlated with cumulative proportional CO_2-C release.

The active C pool, as determined by the CENTURY equilibrium method and measurements of soluble plus microbial biomass C, were less than the active C pool estimated by the incubation–regression method. Measured light fraction C was smaller than estimates from the CENTURY equilibrium method and incubation–regression estimates. Total organic C, soluble plus microbial biomass C and light fraction C had the highest correlations with cumulative incubation CO_2-C release. Of the CENTURY model C pool estimates, only the slow C pool estimate correlated with incubation CO_2-C release.

The use of C analyses as soil C pool estimates for model simulations of the long-term incubation resulted in an underestimation of actual incubation CO_2-C release. This underestimate was caused by a smaller slow pool estimated by light fraction analysis. In addition, structural and metabolic C pools were not measured and they have a large short-term effect on CO_2-C release. Use of CENTURY equilibrium estimates, including estimates of structural and metabolic C, resulted in simulated CO_2-C release comparable to actual CO_2-C release patterns. However, the use of the CENTURY equilibrium method may be limited by the difficulty of obtaining adequate soil, plant and climatic information to run model simulations and by the validity of CENTURY model assumptions for factors controlling soil C pools under tropical climatic conditions.

INTRODUCTION

Soil organic matter (SOM) plays an important role in nutrient cycling and soil productivity in tropical ecosystems. However, no direct relationship between SOM contents and soil fertility has been established for soils in the tropics (Sanchez and Miller, 1986). This lack of correlation may be partially explained by the large proportion of highly-weathered, nutrient-poor soils with large amounts of soil organic matter present in the tropics (Sanchez and Logan, 1992). In addition, the common methods used for measuring and characterizing SOM, such as total organic C and humic acids, may be inadequate to explain SOM dynamics and nutrient availability because they do not directly measure biologically-active C fractions.

Several conceptual and mathematical models have proposed the existence of discrete soil C pools with varying decomposition or turnover rates (Jenkinson and Rayner, 1977; McGill *et al.*, 1981; Parton *et al.*, 1987). For example, the CENTURY SOM model contains an active C pool with a turnover time of 1–5 yr, a slow C pool with a turnover time between 20–40 yr, and a passive C pool with a turnover time between 200–1500 yr (Parton *et al.*, 1987). The active pool is possibly composed of live microbes, microbial products and labile organic substrates (Parton *et al.*, 1987). The slow and passive pools may be C fractions resistant to decomposition either because of their chemical form or through physical protection (Parton *et al.*, 1987).

The CENTURY model also includes two plant residue metabolic and structural C pools. These pools represent shoot and root residues that have either 0.1–1 yr (metabolic) or 1–5 yr turnover times (structural) before transfer into soil C pools (Parton *et al.*, 1987). The division of residue into these two pools is controlled by the lignin:N ratio of the material. The higher the lignin:N ratio, the higher the proportion of residue C that goes into the structural C pool.

An advantage of this soil C pool approach is the use of first-order kinetics of observed biological decomposition patterns. These patterns appear to describe decomposition for a wide range of soils under either tropical or temperate environmental conditions (Jenkinson and Ayanaba, 1977; S. Singer, unpubl. Ph.D. thesis, University of Hamburg, 1993). This approach also has potential agronomic applicability for predicting nutrient release from SOM decomposition because the soil C pools are estimated based on their biological lability (Sanchez *et al.*, 1989).

Physical or chemical methods for estimating kinetically-defined soil C pools have not been clearly established since biological lability is not dependent solely on the chemical or physical forms of soil C (Duxbury *et al.*, 1989). It also depends upon the interaction of soil C with other soil constituents and environmental conditions. Furthermore, many methods are time-consuming, costly and may not reflect climatic, biological and physical conditions present in field situations.

Some methods proposed to estimate soil C or N pools include procedures to determine microbial biomass C or N as a measure of the active pool (Paul, 1984), light fraction or particulate organic matter C or N as a measure of the slow pool (Cambardella and Elliott, 1992; Janzen *et al.*, 1992), and biologically-active soil N through isotopic dilution (Duxbury *et al.*, 1991). Davidson *et al.* (1987) recommended the use of a 7 day incubation to measure available or active C. Long-term incubations of *ca* 1 yr or more have also been used to determine active and slow C or N pools from multiple compartment first-order kinetics (van Veen and Paul, 1981). Another approach is to estimate equilibrium levels of soil C pools through long-term simulations (2000–3000 yr) with models. This approach has been used with the CENTURY model to parameterize initial active, slow and passive C pools for forested sites at different elevations in Hawaii (Parton *et al.*, 1989) and for long-term organic-amended cultivated plots in Sweden (Paustian *et al.*, 1992).

Our objective was to compare three methods for estimating soil C pools for tropical soils with a wide range of soil clay content and mineralogy. These methods were: (i) regression analysis of CO_2-C release from a long-term soil incubation; (ii) results of several soil C analysis procedures; and (iii) model simulations of equilibrium values of soil C pools. Model simulations of the long-term incubation were also used to examine the effects of differences between estimated C pools from each method and actual incubation results.

MATERIALS AND METHODS

Soil sampling and characteristics

Thirteen soils representing four mineralogical classes (smectitic, kaolinitic, oxidic and allophanic) were collected in 1991 from forest sites in Costa Rica, Colombia, Peru and Brazil. Soils were sampled by horizon to a depth of 1 m. Three field replicates for each soil were sampled from soil pits located *ca* 50 m apart. For this research, results are presented for analyses of samples from the top soil mineral horizon. Soil names, classification, vegetation type, sampling depth, and chemical and physical characteristics are given in Table 1. All soil was sieved (4 mm). A portion of each soil was then air-dried and sieved (2 mm) for chemical and mineralogical analyses. The remaining soil was kept at its field moisture content and stored at 4°C for 11–14 months.

Mineral identification of the clay fraction ($<2\ \mu m$) was determined by X-ray diffraction, citrate–dithionite and acid–oxalate extractions, and differential thermal analysis (Jackson, 1979). With the exception of the allophanic soils, soils were treated at 100°C with NaOAc for carbonate removal and with NaOCl for organic matter removal during clay separation. Allophanic soils were not treated to avoid dissolution of amorphous components. Soil texture was determined on non-allophanic soils using the pipette method (Gee and Bauder, 1986). Texture was not measured in allophanic soils because conventional procedures for texture analysis are not applicable for soils with non-crystalline or short-order mineralogy. Soil bulk density was measured on duplicate samples from one soil pit per site using the core method (Blake and Hartge, 1986). Soil pH was determined in water (2.5 soil:1 water v/v) and soil ECEC by summing exchangeable cations (Al, H, Ca, Mg and Na by 1 M KCl and K by 0.5 M $NaHCO_3$).

Long-term incubation method

Field-moist soil samples from each field replicate were sieved (2 mm) and mixed with acid-washed sand (1:1 w/w). Duplicate 100 g samples of each soil:sand mixture were then placed in Falcon filter units (150 ml bottle-type) fitted with moistened 51 mm Gelman SUPOR-200 polyethersulfone 0.2 μm membrane filters and 47 mm extra-thick glass fiber prefilters. Membrane filters are important in controlling soil moisture content (MacKay and Carefoot, 1981) and the polyethersulfone filter avoided potential biological degradation of the filter over time. A 70 mm Whatman glass microfiber filter was placed on top of the soil to avoid dispersion during leaching. Filter units were then leached initially with 100 ml of minus-N nutrient solution (Nadelhoffer, 1990) under 80 kPa suction for 1 h and kept in incubation chambers at 35°C. Subsequent leachings were with 50 ml of solution. The rate of CO_2-C evolution was measured in the sealed head space of filter units using gas chromatography (Nadelhoffer, 1990) at 2, 7, 14, 21, 28, 35, 42, 49, 56, 63, 70, 78, 92, 106, 119, 133, 147, 175, 211, 276 and 341 days after the start of the incubation.

Non-linear regression analysis of incubation results was performed using the PROC NLIN procedure and the Marquardt iterative method from the

Table 1. Characteristics of soils by site and mineralogy

Site name (country)	Vegetation type	Soil classification	Mineralogicial class	Soil depth (cm)	Bulk density ($Mg\ m^{-3}$)	Clay content ($g\ kg^{-1}$)	pH (H_2O)	ECEC ($cmol_c\ kg^{-1}$)
			Smectitic					
Burriga (Colombia)	Bamboo forest	Vertic Ustropept	Smectitic	0–20	1.10	264	6.69	18.76
Rio Paila (Colombia)	Bamboo forest	Typic Ustropept	Smectitic	0–12	1.24	225	6.47	14.18
Santa Ana (Costa Rica)	Semi-decid. woodland	Typic Pellustert	Smectitic-Kaol.	0–12	1.08	598	6.48	31.59
CEPEC† (Brazil)	Tropical forest	Typic Argiudoll	Smectitic–Kaol.	0–8	1.14	261	6.31	11.87
			Kaolinitic					
Yurimaguas (Peru)	Tropical forest	Typic Paleudult	Kaolinitic	0–8	0.90	143	3.91	4.00
Manaus (Brazil)	Tropical forest	Xanthic Hapludox	Kaolinitic	0–8	0.83	752	4.21	3.02
Colonia (Brazil)	Tropical forest	Typic Hapludox	Kaolinitic	0–8	0.61	432	4.38	3.84
			Oxidic					
Valença (Brazil)	Tropical forest	Typic Hapludox	Oxidic–Kaol.	0–12	1.17	230	4.92	2.96
Ouro Preto (Brazil)	Tropical forest	Rhodic Kandiustalf	Oxidic-Kaol.	0–12	1.25	150	5.73	3.80
Una (Brazil)	Tropical forest	Typic Kandiudox	Oxidic	0–12	0.86	579	4.33	2.93
			Allophanic					
Birrisito (Costa Rica)	Tropical forest	Thaptic Hapludand	Hall.-Ox.-Allo.	0–10	0.39	—	4.83	6.58
Tierra Blanca (Costa Rica)	Tropical forest	Typic Udivitrand	Allophanic	0–8	0.86	—	5.72	10.12
Popayan (Colombia)	Oak forest	Acroudoxic Melanudand	Allophanic	0–14	0.52	—	4.98	3.25
			Site $LSD_{(0.05)}$		0.12	51	0.35	2.12
			Mineralogy		***	NS	***	***

***Significant at the 0.001 probability level; NS = not significant.
†Centro de Pesquisa de Cacau.

SAS statistical program (SAS Institute, Inc, 1988). The regression model was of the form: $Y = C_1\exp(-k_1 t) + C_2\exp(-k_2 t)$ where $Y = \%$ of total soil organic C remaining; $t =$ time; and $C_2 = 100 - C_1$ (van Veen and Paul, 1981). The coefficients, C_1 and C_2, were considered as estimates of the active and slow plus passive pools, respectively. The coefficients, k_1 and k_2, are rate constants for each corresponding C pool. This model assumes that the passive soil C pool is not significantly affected during the 1 yr incubation because of the long turnover time of the passive C pool (Parton *et al.*, 1987).

Soil carbon analysis method

Total soil organic C was determined on air-dried soils using a CHN analyzer. Microbial biomass C was determined for field-moist soils by the $CHCl_3$ fumigation–direct extraction method (Vance *et al.*, 1987). All soils were fumigated for 5 days because tests had showed this amount of time resulted in maximum C extraction in wet, high-clay soils. Carbon contained in 0.5 M K_2SO_4 extracts was measured with a wet oxidation diffusion procedure (Snyder and Trofymow, 1984). The conversion factor (k_{EC}) used to convert C flush to microbial biomass C was 0.35 (Sparling *et al.*, 1990). Carbon contained in the 0.5 M K_2SO_4 extract of unfumigated soils was considered to be a measure of soluble C. The sum of microbial biomass C plus soluble C was used as an estimate of the active C pool.

Light fraction C was determined using a modification of the method of Greenland and Ford (1964). Air-dried soil (1 g) was suspended in 20 ml of sodium polytungstate (density of 1.85 g cm^{-3}). The suspension was sonicated for 60 s at an energy level of 5.57 J s^{-1} using a probe-type ultrasonic unit. The output energy was calibrated by measuring the temperature change produced by sonication of a known mass of deionized water for a specified time (North, 1976). Tests had shown this level of sonication maximized light fraction recovery. After dispersion, the soil suspension was evacuated for 10 min under 70 kPa suction to remove entrapped air from soil pore space. The soil suspensions were left for 12 h at room temperature. The light fraction material was then aspirated from the surface of the tubes, trapped on an ashed glass microfiber filter (GF/A), rinsed with deionized water, and the filter plus sample analyzed for total organic C (Snyder and Trofymow, 1984). The amount of light fraction C was used as an estimate of the slow C pool.

The passive C pool was not measured directly; it was calculated as the total organic C minus the active plus slow pools.

Equilibrium simulation method

Estimates of equilibrium soil C pools (i.e. metabolic, structural, active, slow and passive) were made for non-allophanic soils using the CENTURY SOM and forest submodels, version 3.0 (Parton *et al.*, 1987, 1989; Sanford *et al.*, 1991). Required input values for the SOM and forest submodels are monthly minimum and maximum air temperatures, precipitation, soil texture, and forest production measurements (Parton *et al.*, 1989; Sanford *et al.*, 1991). Allophanic soils were excluded because soil texture is a necessary input for the CENTURY model and soil texture was not measurable for those soils. Climate data for each site were obtained either directly from agricultural experimental stations near where the site was located or from the World Weather Disk (Weather Disk Associates Inc., 1993) for adjoining towns or airports with weather stations. Production data for tropical forest were obtained from Sanford *et al.* (1991) and amended according to recent modifications (William M. Pulliam, 1993, pers. commun.). All model simulations were for 3000 yr and excluded disturbance events such as hurricanes and fire. No adjustment was made in the CENTURY model for the varying soil depths to which soils were collected. All CENTURY estimates were based on a 20 cm depth.

Incubation simulations

The CENTURY model was also used to simulate long-term soil incubation in order to examine the effects of differences in C pool estimates obtained by applying the different methods. These 1 yr simulations were done using the soil incubation mode (MICOSM = 1) of the CENTURY model. An initial cultivation disturbance event was simulated to account for soil disturbance during sample handling and processing.

Data analysis

Analysis of variance (ANOVA) was determined by PROC GLM (SAS Institute Inc., 1988). The multiple comparison test used was Fisher's (protected) LSD at a 0.05 significance level. Linear correlations were calculated using the PROC CORR SAS procedure.

RESULTS AND DISCUSSION

Soil carbon and correlation with other soil properties

Total soil organic C contents of collected soils ranged from 12.4 to 120.0 g C kg^{-1} soil (Table 2). In general, allophanic soils had significantly higher ($P < 0.001$) total organic C, soluble C and light fraction C than the soils of smectitic, kaolinitic or oxidic mineralogies. Microbial biomass C was the only soil C fraction measured which did not correlate with total organic C and which was significantly higher in smectitic and allophanic soils compared to others soils. Higher organic C contents in allophanic soils have been attributed to the stabilization of organic colloids through interaction with allophane surfaces (Martin and Haider, 1986).

Clay content of non-allophanic soils (Table 1) was positively correlated with total organic C content ($r = 0.59^{***}$, $n = 30$) and soluble C ($r = 0.78^{***}$, $n = 30$), but not with microbial biomass C and light

fraction C. Increasing soil clay content is considered a factor that promotes C stabilization (Paul, 1984; Oades, 1988) through several potential bonding mechanisms of organic colloids with mineral surfaces (Mortland, 1970). Soil pH was positively correlated with microbial biomass C ($r = 0.32^{*}$, $n = 39$) and negatively correlated with soluble C ($r = -0.53^{***}$, $n = 39$). Soil ECEC only correlated with soluble C ($r = -0.43^{**}$, $n = 39$). No correlations between light fraction C and soil pH or ECEC were observed. This result is in contrast to Amato and Ladd (1992) who observed a highly-significant correlation between microbial biomass C and clay content, CEC, and soil pH of 23 soils classified as Vertisols, Alfisols, Mollisols and Entisols. As in our study, they did not find a correlation between soil total organic C and soil pH or CEC. However, their study did not include Oxisol and Ultisol soil orders and soils with a pH below 6.0.

C release patterns

No significant differences ($P < 0.05$) in CO_2-C release between soil mineralogies averaged over soils were observed at any of the sampling dates (Fig. 1). However, within each soil mineralogy, certain soils did have significantly greater ($P < 0.05$) CO_2-C release than others over the duration of the incubation (Fig. 1). These soils include Birrisito in the allophanic mineralogy, Ouro Preto in the oxidic mineralogy, CEPEC in the smectitic mineralogy, and Yurimaguas in the kaolinitic mineralogy. Carbon loss after 341 days, expressed as a proportion of the initial total soil organic C, ranged from 6.7 (Santa Ana) to 15.5% (CEPEC).

This result is in contrast to findings by T. F. Muamba (unpubl. M.S. thesis, North Carolina State University, 1992) who observed lower C release in allophanic (2% of initial total organic C) and oxidic (13.2–19.8%) soils compared to smectitic (25.7–32.8%) and kaolinitic (21.9–33.3%) soils after 900 days of incubation. However, in contrast to our study, he did not add nutrient solution to the soils during incubation. Nutrient additions have been shown to increase CO_2-C losses from allophanic soils (Munevar and Wollum, 1977).

Of the chemical and physical soil characteristics measured, only clay ($r = -0.66^{***}$, $n = 30$), sand ($r = 0.61^{***}$, $n = 30$), and total organic C ($r = -0.44^{**}$, $n = 39$) contents correlated significantly with proportional C loss. Clay content (Table 1) accounted for 43% of the variation observed in C loss from non-allophanic soils expressed as a proportion of the initial total organic C.

There were notable exceptions to the effect of clay content on C loss among the kaolinitic and oxidic mineralogies. Among the kaolinitic soils, the Manaus soil (752 g clay kg^{-1} soil) had the same C release pattern as the Colonia soil (432 g clay kg^{-1} soil) [Fig. 1(D)]. Similarly, among the oxidic soils, Una (579 g clay kg^{-1} soil) had the same C release pattern as Valença (230 g clay kg^{-1} soil) [Fig. 1(B)]. These similarities between soils are not explained by their C contents, since the soils with lower clay content tended to have a higher proportion of total organic C in soluble, microbial and light fraction C (Table 2). For example, the Manaus soil had a total of 180 g C kg^{-1} organic C in soluble, microbial and light fraction C compared to 224 g C kg^{-1} organic C in the Colonia soil. Also, the Una soil had a total of 118 g C kg^{-1} organic C in these C fractions compared to 240 g C kg^{-1} organic C in the Valença soil.

Table 2. Soil carbon fractions by site and mineralogy

Site name	Total org. C	Soluble C	Microbial C	Light fraction C
	(g kg^{-1} soil)			
		Smectitic		
Burriga	27.6	0.056	0.663	1.77
Rio Paila	28.8	0.061	0.864	2.75
Santa Ana	33.7	0.136	0.433	2.00
CEPEC	26.9	0.071	0.880	3.42
		Kaolinitic		
Yurimaguas	14.3	0.166	0.357	2.86
Manaus	33.3	0.520	0.182	5.29
Colonia	45.3	0.319	0.699	9.22
		Oxidic		
Valença	22.3	0.154	0.488	4.49
Ouro Preto	12.4	0.082	0.343	1.83
Una	32.3	0.389	0.440	2.71
		Allophanic		
Birrisito	53.8	0.525	0.631	13.12
Tierra Blanca	48.2	0.134	0.313	24.35
Popayan	120.0	0.897	0.882	52.29
Site $LSD_{(0.05)}$	13.2	0.105	0.313	6.35
Mineralogy	***	***	**	***

**, ***Significant at the 0.01 and 0.001 probability levels, respectively; NS = not significant.

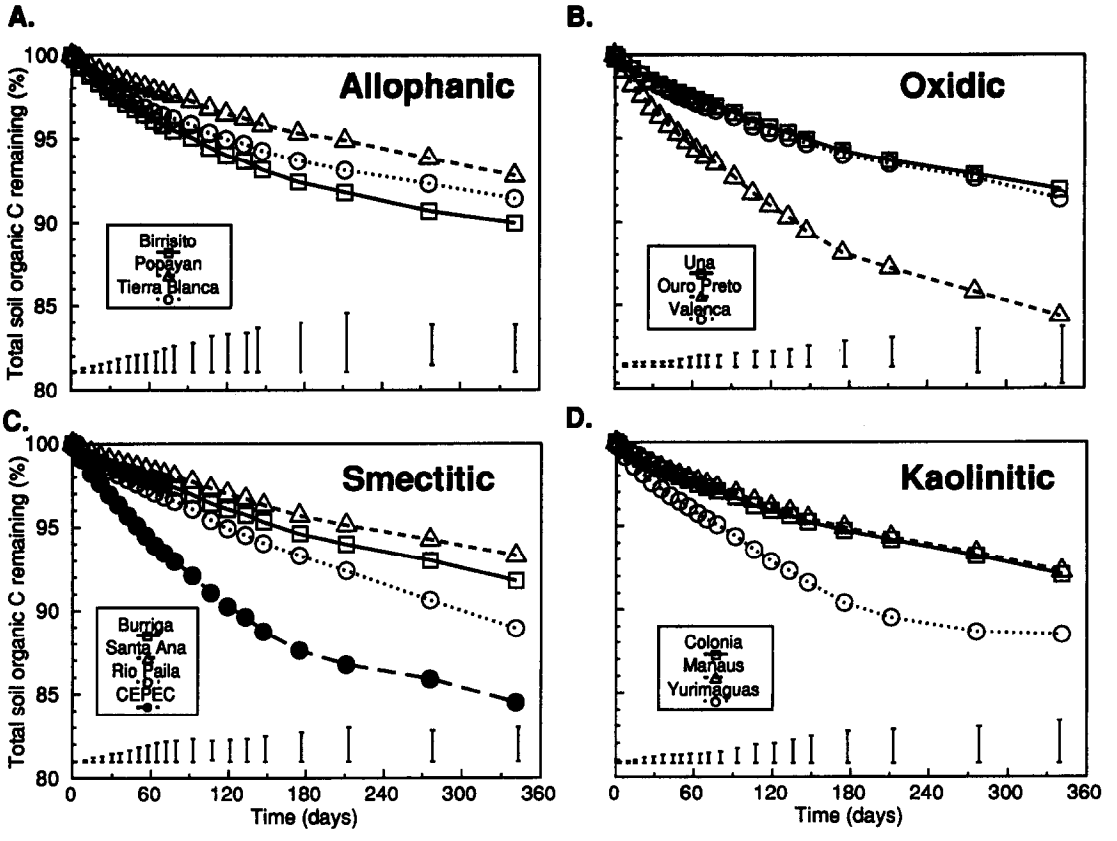

Fig. 1. Cumulative CO_2-C loss during a long-term incubation expressed as a proportion of remaining initial total organic C for soils with (A) allophanic, (B) oxidic, (C) smectitic and (D) kaolinitic mineralogies. Bars indicate $LSD_{(0.05)}$ values at each sampling time.

Estimates of soil C pools

The CENTURY model equilibrium simulation estimates of the active C pool and soluble and microbial biomass C were generally less than the first regression coefficient (C_1) of the incubation–regression procedure (Table 3). This underestimation was particularly evident for the CEPEC, Yurimaguas and Ouro Preto soils (Table 3). The CENTURY slow C pool estimates and the regression C_2 estimates were also higher than light fraction C. This result suggests that the slow pool includes more than just light fraction C or that the extraction method we used does not fully extract light fraction C of tropical soils. A. K. Metherell (unpubl. Ph.D. thesis, Colorado State University, 1992) also observed that the C extracted as light fraction or particulate organic matter was less than the CENTURY slow pool.

Regression slow pool estimates (C_2) included the passive C pool because C_2 was calculated as the difference between total organic C and C_1. Therefore, C_2 would be an overestimate of the actual slow pool. One problem in determining the slow pool using incubations and 2- or 3-pool regression models is that 1 yr incubations may be too short to distinguish between the slow or passive pools. Amato and Ladd (1992) concluded that 66 weeks of incubation was insufficient to determine relationships between C dynamics and soil properties for acidic soils. Sorensen (1981) incubated soils of differing clay content for 1600 days to determine C release after addition of ^{14}C-labeled cellulose.

CENTURY model estimates of structural C ranged from 19 to 44 g C kg^{-1} organic C (Table 3). Estimates of metabolic C ranged from 0.032 to 0.067 g C kg^{-1} organic C (Table 3). Estimated structural C material in all soils, except Santa Ana, was larger than the active C pool estimated by the CENTURY model. However, sieving the soils before incubation may have removed an unknown proportion of the structural C material. As shown by electron microscopy, some of this structural C may be included in light fraction extraction (Spycher *et al.*, 1983; Cambardella and Elliott, 1992), which may complicate the distinction between structural and slow C pools using light fraction separation procedures.

Rate constants for the active soil C pool (k_1) as determined by regression did not correlate with the active C pool rate constants as determined by the CENTURY model (Table 3). The CENTURY slow C pool rate constant used for all soils was consistently

Table 3. Estimated soil carbon pools and decomposition rate constants for the active (k_1) and slow (k_2) pools

Site name	Regression estimates				Carbon analysis†		CENTURY estimates					
	C_1 (g C kg^{-1} total C)	C_2	k_1 (day^{-1})	k_2	SM-C	LF-C	Active C (g C kg^{-1} total C)	Slow C	Metab. C	Struc. C	k_1 (day^{-1})	k_2
						Smectitic						
Burriga	19	981	0.015	0.00020	26	64	18	563	0.047	30	0.0076	0.00054
Rio Paila	30	970	0.011	0.00025	32	96	17	585	0.052	33	0.0096	0.00054
Santa Ana	28	972	0.0066	0.00013	17	59	20	433	0.036	19	0.0028	0.00054
CEPEC	150	850	0.0080	0.00004	35	127	19	630	0.057	36	0.0091	0.00054
						Kaolinitic						
Yurimaguas	130	870	0.0060	0.00005	37	200	19	689	0.067	40	0.010	0.00054
Manaus	30	970	0.011	0.00015	21	159	16	418	0.032	19	0.0047	0.00054
Colonia	30	970	0.013	0.00015	23	204	16	553	0.050	31	0.0089	0.00054
						Oxidic						
Valença	34	966	0.014	0.00016	29	201	16	645	0.065	41	0.013	0.00054
Ouro Preto	110	890	0.00090	0.00018	34	147	16	670	0.056	42	0.014	0.00054
Una	50	950	0.00090	0.00010	27	84	17	501	0.043	27	0.0070	0.00054
						Allophanic						
Birrisito	70	930	0.0105	0.00015	21	244	—	—	—	—	—	—
Tierra Blanca	42	958	0.015	0.00014	9	505	—	—	—	—	—	—
Popayan	40	960	0.0080	0.00010	15	436	—	—	—	—	—	—

*C_1 = first regression coefficient; C_2 = second regression coefficient. C_2 includes slow plus passive C pools.
†SM-C = soluble C plus microbial biomass C; LF-C = light fraction C.

higher than regression slow C pool rate constants (k_2) estimated for each soil.

Correlations among C pool estimates indicated that most of the C analyses correlated significantly with C_1 regression estimates and the total C released during incubation (Table 4). Of the C analysis procedures compared, total organic C, soluble plus microbial C and light fraction C had the highest correlations ($r = 0.91$***, $r = 0.87$*** and $r = 0.87$***, respectively) with total incubation C release (Table 4). This result is comparable to the significant correlations that Janzen *et al.* (1992) observed among microbial biomass C, light fraction C, total organic C and soil respiration in cultivated soils from Canada. Total organic C, soluble C, soluble plus microbial C and light fraction C also correlated significantly with regression C_2 estimates.

CENTURY model equilibrium estimates of the active and slow C pools did not correlate well with regression C_1 estimates, but did correlate significantly with regression C_2 estimates (Table 4). Of the CENTURY model C pool estimates, only the slow C estimate correlated significantly ($r = 0.64$*) with C release during incubation. The failure of CENTURY estimates to correlate with the regression C_1 estimate is attributable to the relatively large regression C_1 estimates for the CEPEC, Yurimaguas and Ouro Preto soils (Table 3).

Model incubation simulations

CENTURY model simulations of the soil incubation were done to compare C pool estimates from each method and determine the effects of initial pool size on C release patterns. Use of C analysis results as initial C pool estimates in the incubation simulation caused underestimates of actual incubation CO_2-C release patterns. No correlation between simulated and actual incubation results was observed [Fig. 2(A)]. This underestimation can be explained by the relatively lower amounts of light fraction C compared to regression C_2 or CENTURY slow pool estimates (Table 3) and by the lack of estimates of metabolic and structural C. Including CENTURY estimates of metabolic and structural C with the C analysis results in the incubation simulations caused an increase in CO_2-C release for all soils [Fig. 2(B)]. However, simulated total CO_2-C release still underestimated and did not correlate with actual CO_2-C release.

In contrast, the use of CENTURY equilibrium C

Table 4. Linear correlation coefficients among carbon pool estimates and total CO_2-C released during incubation after 341 days

Methods	Regression estimates† C_1	Regression estimates† C_2	Total CO_2-C released
	(r)		
Analysis‡			
Total organic C	0.67*	0.99***	0.91***
Soluble C	0.58*	0.82***	0.73**
Microbial C	NS	NS	0.60*
Soluble + microbial C	0.70**	0.85***	0.87***
Light fraction C	0.67*	0.94***	0.87***
CENTURY model§			
Active C	NS	0.96***	NS
Slow C	NS	0.87**	0.64*
Metabolic C	NS	0.76*	NS
Structural C	NS	0.68*	NS

*, **, ***Significant at the 0.05, 0.01, and 0.001 probability level, respectively; NS = not significant.

†Regression estimates (C_1 and C_2) and total CO_2-C release expressed as g C kg^{-1} soil.

‡$n = 13$ and values expressed as g C kg^{-1} soil.

§$n = 10$ and values expressed as g C kg^{-1} soil (excludes allophanic soils).

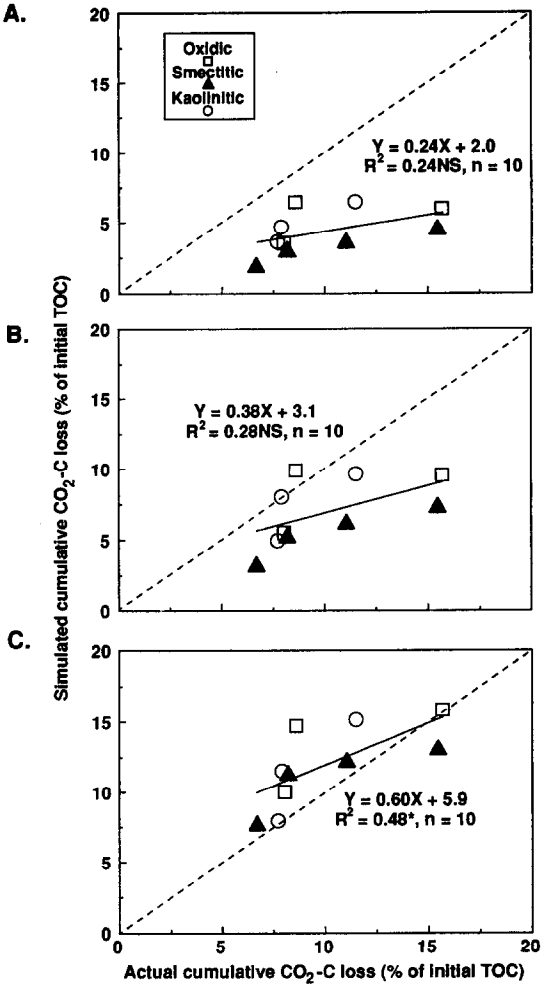

Fig. 2. CENTURY model incubation simulations of CO_2-C loss compared to actual incubation cumulative CO_2-C loss expressed as a proportion of initial total organic C for oxidic, smectitic and kaolinitic soils using (A) soluble C plus microbial C as a measure of the initial active C pool and light fraction C as a measure of the initial slow pool; (B) same as (A) but including estimates of initial metabolic and structural C pools from CENTURY equilibrium estimates; and (C) using CENTURY equilibrium estimates for estimates of the initial active, slow, metabolic and structural C pools. Solid line indicates linear regression of actual versus simulated incubation data. Dotted line indicates line of one-to-one correspondence. * indicates significance at the 0.05 probability level; NS = not significant.

pool estimates, including metabolic and structural C, resulted in simulated incubation release patterns which were comparable in magnitude and significantly related ($R^2 = 0.48$*) to the actual incubation results [Fig. 2(C)]. Release of CO_2-C in the CENTURY model is controlled largely by soil texture when soil temperature and moisture are held constant (Parton *et al.*, 1987). This pattern was observed for all soils during the actual incubation except for Valença (230 g clay kg^{-1}) and Colonia (432 g clay kg^{-1}), which both had intermediate clay contents in their mineralogical grouping (Table 1), but had CO_2-C release patterns similar to CO_2-C release of the soils with the highest clay contents (Fig. 1). This suggests that soil texture was not the dominant factor controlling CO_2-C release from those two soils. In addition, among the smectitic soils, simulated CO_2-C release underestimated CO_2-C release from the CEPEC soil and overestimated CO_2-C release from the Burriga soil.

Such differences between simulated values and actual CO_2-C release for certain soils may indicate the difficulty of obtaining adequate background data (i.e. climate, plant production, litter quality and soil texture) on individual sites to run CENTURY model simulations. In addition, disturbances, such as fire and hurricanes, may have a large effect on C pool cycling in tropical forest ecosystems (Sanford *et al.*, 1991). These disturbances may also need to be included in determining equilibrium estimates using the CENTURY model when such site information is available.

Conclusions

We used several methods to estimate C pools for native soils from tropical forests. Regression analysis of long-term incubations provides estimates of rates of CO_2-C release from individual soils under controlled conditions. Therefore, regression analysis directly measures CO_2-C release kinetics which are the theoretical basis of the existence of separate C pools. However, incubations are time-consuming and costly. Difficulties may also arise in selecting the appropriate time of incubation and regression models to differentiate between slow and passive pools in unamended soils. Carbon analysis methods, such as soluble C, microbial C and light fraction C, isolate a measurable C fraction in a relatively short period. However, these C analyses provided no better relationship with C release than measuring total organic C for the native forest soils we studied. In comparison to CENTURY equilibrium estimates and incubation–regression estimates of slow C, analysis of light fraction C underestimated the slow C pool. Model simulations of soil incubations indicated that CENTURY equilibrium estimates came closest to predicting actual CO_2-C release of incubated soils. Such simulations have the advantage of providing estimates of metabolic and structural C pools which appear to have a large effect on short-term CO_2-C release. However, this approach requires extensive knowledge of site characteristics. Also it depends upon the validity of CENTURY model assumptions for the effects of factors controlling C flow and CO_2-C release under tropical climatic conditions, such as moisture, temperature and soil texture.

For most of the soils we studied, soil texture was the major factor controlling soil CO_2-C release. However, certain soils did not follow this pattern. These disparities could not be explained by other soil characteristics such as soil mineralogy or the proportion of C in different measured C fractions. This suggests that other factors may have a greater influence on C stabilization in these soils.

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