RATES OF ORGANIC CARBON ACCUMULATION IN YOUNG MINERAL SOILS NEAR BURROUGHS GLACIER, GLACIER BAY, ALASKA

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Abstract: The functional relationship between organic carbon in surface mineral horizons of fine-grained soils and time of soil development is examined in a chronosequence of soils deglaciated within 40 years of sampling. Rates of carbon accumulation increased through time in the first 4 decades of pedogenesis. Little carbon accumulated in the first 10 years, but rapid accumulation occurred over the next 22 years as alders (*Alnus crispa*) began to colonize.

Several chronofunctions of carbon accumulation are derived for the Burroughs data. A second-order polynomial function provides a good model of carbon accumulation in the first four decades of pedogenesis that is stronger and more significant than conventional exponential and power function models. A data set extended to 1000 years based on earlier studies in the region, indicates that carbon accumulation rates in this proglacial environment can be expressed by a sigmoidal curve. Several conventional chronofunctions derived from the extended data are appropriate for various stages of pedogenesis, but none provides accurate approximations over the entire 1000 years of pedogenesis. [Key words: Glacier Bay, Alaska, soil, carbon, chronofunction.]

INTRODUCTION

This paper examines soil organic carbon accumulation as a function of time in the initial decades of pedogenesis in the Glacier Bay area. Soil A horizons were sampled in proglacial environments within Glacier Bay National Park and Preserve, southeastern Alaska (Fig. 1), along a soil chronosequence produced by the rapid, well-documented retreat of the Burroughs Glacier ice margin. Percent fine organic carbon in the mineral portion of soils provides a quantitative, reproducible parameter that is a sensitive measure of pedogenesis in initial stages of soil development (Birkeland, 1984a). Soil nitrogen also increases rapidly with time, but accumulation rates depend on the ability of rhizomes to fix nitrogen, a factor which varies greatly between plant species in the Glacier Bay region (Crocker and Major, 1955). Soil pH and carbonate content change rapidly in the early stages of soil development but depend on mineralogic composition of the parent material.

The initial period of soil development is examined here to verify the existence of a carbon lag time in mineral horizons of the soil, and characterize carbon accumulation rates with quantitative models. Sample sizes are too small to develop a universal model of carbon accumulation for the region, but examination of an extended data set suggests that none of the conventional chronofunctions are appropriate at all temporal scales. Relative dating functions are also derived that express surface age as functions of organic carbon in

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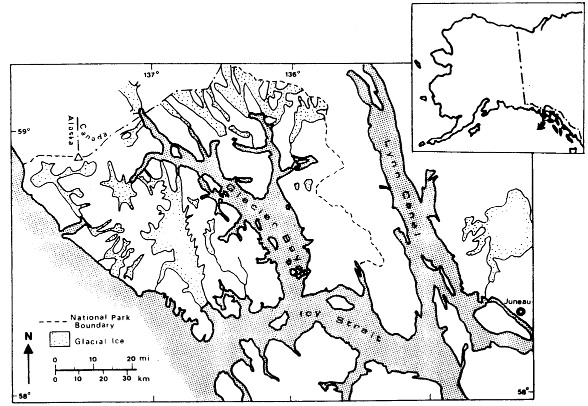


Fig. 1. Location map showing the position of Burroughs Glacier, Muir Inlet, and Glacier Bay in southeast Alaska relative to Juneau.

soils near Burroughs Glacier. These functions are used to date an outwash terrace of unknown age.

BACKGROUND

Carbon Chronofunctions

The functional method of soil analysis expresses soil development as a function of five quasi-independent factors: climate, organisms, relief, parent material, and time (Jenny, 1941; 1961). Over the last half century since the introduction of functional analysis, numerous studies have attempted to isolate univariate functional relationships between soil properties and factors controlling their development. Studies of the time factor of soil formation are frequently based on examination of a chronosequence; that is, a group of related soils in an area that differ primarily due to variations in their time of development (Jenny, 1941; 1961). Quantification of changes in a soil property allows derivation of mathematical expressions of pedogenic change as a univariate function of time, known as a chronofunction (Bockheim, 1980). When other factors can be held constant or accounted for, several soil properties can be quantified and related to the time of soil development (Birkeland, 1984a). These methods have been reviewed and critiqued elsewhere (Stevens and Walker, 1970; Vreeken, 1975; Yaalon, 1975; Birkeland, 1984a).

Chronofunctions have commanded much attention, because temporal relationships indicate pedogenic processes and provide a relative dating tool. Chronofunctions of soil organic carbon concentration are often expressed graphically as curves originating at time zero and attaining a steady-state with respect to carbon after a period ranging from a hundred to several thousand years (Birkeland, 1984a). Many studies document rapid rates of carbon accumulation as soon as surfaces stabilize (Stork, 1963; Smith et al., 1971; Caspal, 1975; Hallberg et al., 1978). Most soil chronosequence studies consider Holocene or longer time scales, and lack of data from young soils prevents resolution of initial accumulation rates.

Few studies outside of southeastern Alaska indicate lag times or accelerating rates of organic carbon development. An exception is a plot for soils on California volcanic mudflows (Dickson and Crocker, 1953). Several studies of soils in southeastern Alaska suggest a delay before any substantial accumulation of carbon begins (Chandler, 1942; Crocker and Major, 1955; Crocker and Dickson, 1957; Ugolini, 1966). Such delays are based on few samples from soils less than 50 years old, however, and are not strongly supported by studies from outside of the region. Delayed accumulation and increasing rates of carbon accumulation will be described henceforth as a lag time and accelerating accumulation, respectively.

THE STUDY AREA

Burroughs Glacier is located in Glacier Bay National Park and Preserve in southeastern Alaska (Fig. 1). The marine climate of the region is characterized by high annual precipitation in excess of 120 cm (Loewe, 1966) due to orographic uplift of westerly winds from the northern Pacific over the coastal ranges. Steep temperature gradients result from the precipitous rise of mountains from the sea, and most glaciers in the area are fed from ice fields at higher elevations. Most soils in the Burroughs area are Entisols or Inceptisols. Spodosols occur only beneath conifers (Ugolini, 1966), not beneath the alders (*Alnus crispa*) that dominate vegetation on the young surfaces in the study area.

The study area was recently deglaciated and most sites are dominated by bare ground, a crust largely of liverworts (*Lophozia badensis*) commonly called moss or black crust (Worley, 1973), Dryas (*Dryas drummondii*), willows (*Salix* sp.), or alders (*Alnus crispa*). The vegetation in older stable areas of the region is spruce (*Picea sitchensis*) forest. Stages of vegetational succession in the Glacier Bay area are summarized in Table 1. It takes about 20 to 25 years for the late pioneer stage to grade into the open thicket stage, about 30 to 35 years to reach the closed thicket stage, and about 46 years for poplars (*Populus tricocarpa*) to become well established (Decker, 1966). These generalizations agree with field observations at sample sites near Burroughs Glacier (Table 2) indicating that Alders (*Alnus crispa*) begin to invade after about 16 years (site 8), form open thickets between 18 and 24 years (sites 9–12), and form closed thickets by about 32 years (site 13).

Deglaciation in the region has been rapid over the last 200 years. The Neoglacial ice advance reached its maximum in Glacier Bay between 1660 and

Table 1. Early Vegetation Stages in the Glacier Bay Region (Decker, 1966)

Stage and duration	Dominant vegetation
Pioneer Stage, 0–20 years	
Early Pioneer Stage	Dryas (*Dryas drummondii*) (discontinuous) Willow seedlings (*Salix* sp.) Horsetail ferns (*Equisetum* sp.) Fireweed (*Epilobium* sp.)
Pioneer Stage II	Dryas (*Dryas drummondii*) (coalesced)
Late Pioneer Stage	Young alders (*Alnus crispa*) and young poplars (*Populus trichocarpa*)
Open Thicket Stage, 20–25 years	Alders (*Alnus crispa*) 2 m or higher, much open space
Closed Thicket Stage, 30–35 years	Alders (*Alnus crispa*)
Poplar-Line Stage, approx. 46 years	Poplars (*Populus trichocarpa*) 4–5 m high

1760 A.D. and the ice margin had receded to the mouth of Muir Inlet by around 1880 (Goldthwaite, 1986). Since 1880, the ice margin has retreated up Muir and Wachusett inlets at a rate averaging about 4 m per year. The Burroughs Glacier and its recent retreat from the study area have been described by Mickelson (1971; 1973; 1986), Larson (1977; 1978), and Taylor (1963; 1986). Glacial ice present in the lower Burroughs Valley in 1970 had melted by 1979 (Fig. 2), and the ice margin had retreated up-valley by 1986 when soil samples were collected.

METHODOLOGY

Research methods are grouped into four categories: sample collection, age determination, laboratory analysis, and statistical analysis.

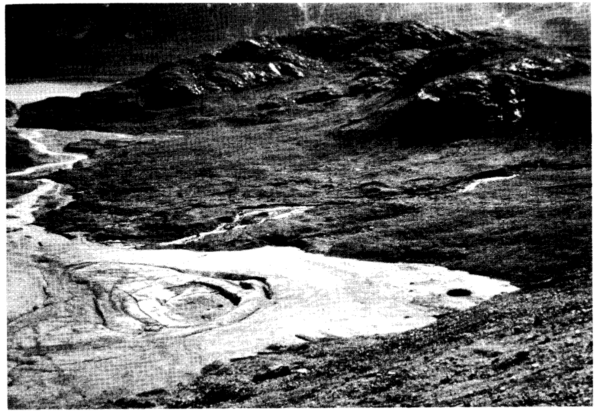
Sampling Methods

Sample sites were selected on the basis of soil textures, surface stability, and age. Deposits at sites 1 to 7 (fig. 3) are glacio-lacustrine, but deposits at other sites are till, outwash, or ice-contact stratified drift (Table 2). Cobbles and gravel dominate tills and glacio-fluvial deposits in the area and pose problems for sampling, volumetric calculations, and soil descriptions. These problems were circumvented by avoiding coarse deposits and sampling silty and sandy deposits exclusively. Only two samples had more than 4% coarser than sand by weight (Table 3). Flat areas away from slopes were sampled to avoid sites dominated by erosion or deposition. Unfortunately, flat, fine-grained sites are limited in extent and these sampling constraints severely limited the sample size.

Table 2. Sample Site Descriptions

Site[a] number	Geomorphic surface	Topographic position	Parent materials	Vegetation
1	Proglacial lake beach	3 m above lake surface closest to ice	laminated silt	very thin crust[b]
2	Proglacial lake beach	0.2 m above lake surface 50 m from #1	fine sand	very thin crust
3	Proglacial lake beach	2 m above lake surface at site #2	fine sand	none visible; orange stain
4	Proglacial lake beach	3 m above lake surface at site #2	laminated fine sand	none visible; orange stain
5	Proglacial lake beach	3 m above lake surface at site #2	laminated silt loam	none visible; orange stain
6	Proglacial lake beach	2 m above lake surface 200 m from #1	laminated fine sand	very thin crust
7	Supraglacial bouldery till	flank of small hill	silty till	thin 1 mm black crust
8	High terrace	2 m above Johns Creek water surface	loamy fine sand	crust; alders nearby, 2 m tall
9	Outwash terrace	10 m above Burroughs River near Johns Creek confluence	stratified loam	crust; alders nearby; leaves and seeds on surface
10	Outwash terrace high remnant	10 m above Burroughs River	pebbly sand over gravel and sand	alders, 4 m; crust; horse-tail ferns (*Equisetum*, sp.)
11	Ice contact stratified drift	top of large hummock	pebbly sand and gravel	open; crust; horsetails; willows and alders nearby, 4 m
12	Ice contact stratified drift	top of small ridge	thin silt-drape over gravel-sand	black crust; lichens; alders nearby, 4 m
13	Outwash terrace	top of large ridge on Burroughs River	gravelly sand	thick alders, 5 m; few poplars, 6 m; few spruce, 2 m
14	Rock till island	flank of hill; 5 m above coast	gravelly loam	moss mat, 6 cm thick; alders, 4 m; poplars, 4.5 m; many understory species

[a]Site locations are shown on Figure 3.
[b]The "crust" is primarily liverwort (*Lophozia badensis*).



A

B

Fig. 2. Photographs of Burroughs Valley southward toward Wachusett Inlet: (a) Extent of glacial ice in 1970 (by David Mickelson with permission); (b) Same site in 1986 (by Cynde English with permission).

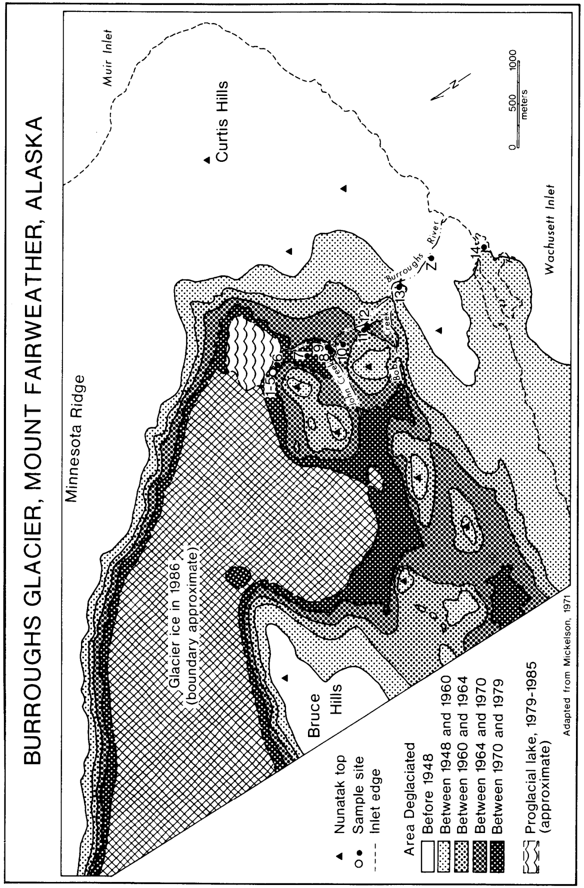


Fig. 3. The Burroughs Glacier area and sample sites. Adapted from Mickelson (1971).

Table 3. Soil Texture, Age, and Organic Carbon of Samples

Site number	Textures (wgt %)[a]			Possible year deglaciated	Age, years	Sample depth, mm	Organic carbon, percentage
	pebbles	sand	fines				
1	2.90	10.10	87.00	1979–86	6	3–8	0.000
2	0.40	68.45	31.15	1979–86	4	3–20	0.038
3	0.00	63.05	36.95	1979–86	6	0–20	0.015
4	0.71	52.73	46.56	1979–86	7	0–15	0.073
5	0.00	22.28	77.72	1979–86	7	5–20	0.000
6	0.00	44.20	55.80	1972–79	9	6–13	0.000
7	0.05	69.04	30.91	1970–72	15	1–8	0.076
8	0.00	84.53	15.47	1970–72	16	3–15	0.076
9	0.00	64.70	35.30	1970–72	16	3–20	0.073
10	3.35	88.52	8.14	1964–70	18	3–13	0.146
11	7.16	87.03	5.81	1960–64	24	2–15	0.260
12	0.00	55.58	44.42	1960–64	24	3–20	0.114
13	29.57	60.40	9.03	1948–60	32	27–47	0.409
14[b]	18.37	62.18	19.45	1929–48	46	30–50	4.717
Z[c]	4.13	76.11	19.76	1929–48	27[d]	23–38	0.303

[a]pebbles > 2 mm; 2 mm > sand > 0.063 mm; 0.063 mm > fines.
[b]Omitted from analysis (see text).
[c]Alluvial terrace site on Lower Burroughs River (see Fig. 3).
[d]Age determined by application of equations in Table 5 (see text).

Each soil profile was described in a soil pit, and the O horizon was cut from the surface with a knife. A 25 cm^2 horizontal section was then cut from the A horizon, macroscopic organic material such as rootlets were removed, and the sample was bagged and labelled for laboratory analysis. In soils less than 20 years old, a thin discolored zone extending to a depth of 2 to 5 cm was interpreted as the A horizon for sampling purposes (Fig. 4). Examination with a ten-power hand lens revealed no charcoal, coal, or graphite that would cause overestimates of soil organic carbon.

Soil Age

Soil ages are based on the difference between the date that the surface was deglaciated and the date of field work (June, 1986). A small range of possible deglaciation dates at each site was estimated by locating the sample site on a map of ice margin positions made by Mickelson (1971) (Fig. 3). Surfaces deglaciated since 1970 were dated using aerial photographs taken in 1972 and 1979 and several oblique photographs. Soil age was determined at most sites by linear interpolation between the range of possible ages according to the distance of sites from known ice margin dates (Table 3). A few young samples

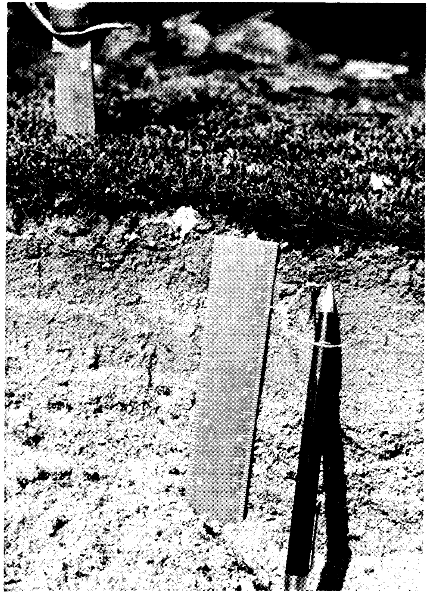


Fig. 4. Photograph of soil horizon at site #9 showing sandy parent material with thin A horizon (about 1.5 cm).

(samples 1–5) from the proglacial lake shore that may have been subject to inundation since deglaciation were assigned ages from 4 to 7 years based on proximity to the ice margin and elevation above the lake. This distinction has little bearing on results.

Site number 14 is the only site close to Wachusett Inlet and was rejected because sea spray may have added chloride ions that are assumed absent by the laboratory procedures utilized (see Sondheim et al., 1981). A floodplain sample was excluded from derivations of carbon chronofunctions, because there is no assurance that sedimentation ceased after deglaciation. It was included in laboratory analysis to obtain an age estimate from the carbon curve (Table 3; Site Z; Fig. 3).

Laboratory Procedures

Percentage organic carbon was measured by the Walkley-Black method as described by Allison (1965). Presence of carbonates up to 50% by weight does not interfere with the procedure. Samples were treated with potassium dichromate and sulfuric acid, and the unreduced chromate ion concentration was measured by titration with iron sulfate using a ferroin indicator. External heat, filtering, and grinding were not necessary. Silver sulfate (Ag_2SO_4) was not included with the sulfuric acid assuming that chloride ions were not present. Future studies of low carbon concentrations should consider dilution of titration solutions to 0.5 N for greater resolution. Percent organic carbon is not converted to total organic material due to (1) lack of consensus over the inclusion or exclusion of macrobiomass or undecayed vegetal matter in the definition of total organic material (Vaughan and Malcomb, 1985), and (2) imprecision of conversions due to variable organic carbon concentrations in organic matter both between regions and within a given soil (Allison, 1965).

Textural analysis was performed on 10 to 12 g sample splits to determine weight percentages of pebbles, sand, and fines (Table 3). Percent silt and clay were not mechanically differentiated, but hand-texturing in the field determined clay content to be uniformly low in accordance with results of mechanical analysis from a previous study of tills in the area (Mickelson, 1971).

Statistical Methods

Chronofunctions are often depicted graphically, but numerical solutions derived empirically by curve-fitting regression techniques are desirable when the proper conditions can be met. Regression analysis of the carbon data was employed to derive and evaluate various mathematical models commonly employed as chronofunctions. Previous chronofunction studies have obtained the best least squares solutions by using exponential functions (Yaalon, 1975), power functions (Birkeland, 1984b), or both (Bockheim, 1980).

Four regression models of carbon as a function of time were developed: linear, exponential, power, and second-degree polynomial functions (Table 4). The polynomial functions were derived by regression of percent organic carbon on two predictor variables: surface age to the first and second power. Samples with no measurable carbon were arbitrarily reassigned low values of carbon (0.01%) to calculate logarithms for regressions using exponential and power function models. The first stage of statistical analysis was restricted to the Burroughs Glacier data.

One objective of this study was to develop a carbon accumulation curve for relative dating of surfaces from sample percent organic carbon. Algebraic rearrangement of univariate regression models to express the independent variable as a dependent variable may give false measures of the strength and significance of regressions (Williams, 1983), so five new equations were derived by regressions with the Burroughs data using years as the dependent variable (Table 5). A second-order polynomial was derived as a function of percent carbon raised to the first and second power. High variation in carbon contents of very young soils prevents accurate predictions of surface age from soils with low carbon concentrations. Thus, another linear model for estimation of soil ages between 13 and 40 years was derived using only Burroughs Glacier samples with more than 0.05% carbon. These functions were used to determine the age of a soil developed on an outwash terrace along the lower

Table 4. Chronofunction Regression Results Ranked by Explained Variance

Model	Equation	R^2	N	$p>F^a$
	All Burroughs data from this study			
Polynomial	$\%C = 0.041-0.0065 \cdot Yr + 0.000556 \cdot Yr^2$	0.894	13	.001
Linear	$\%C = -0.0723 + 0.0121 \cdot Yr$	0.784	13	.001
Power	$\%C = 0.00119 \cdot Yr^{1.55}$	0.652	13	.001
Exponential	$\%C = -0.236 + 0.315 \cdot LogYr$	0.594	13	.01
	Step-function model with no sites < 10 years old			
Linear	$\%C = -1.86 + 0.117 \cdot Yr$	0.740	8	.01
	All Burroughs data plus 10 samples from Ugolini (1966) and Chandler (1942)			
Polynomial	$\%C = -0.284 + 0.0370Yr - 0.0000323Yr^2$	0.958	23	.001
Power	$\%C = 0.00796 \cdot Yr^{1.09}$	0.639	23	.001
Exponential	$\%C = -2.17 + 2.56 \cdot Log\ Yr$	0.630	23	.001
Linear	$\%C = 0.679 + 0.00618 \cdot Yr$	0.366	23	.001

[a]Significance of regressions (as a probability) based on the F statistic.
Yr = Years since deglaciation.
%C = Percent organic carbon.

Burroughs River that cannot be accurately dated by available aerial photographs (Table 3; sample Z).

RESULTS

The Burroughs Carbon Data

A strong positive relationship exists between percent organic carbon and age of surfaces in front of the Burroughs Glacier (Fig. 5). Accumulation rates

Table 5. Relative Dating Functions From Regressions Using Burroughs Data

Model	Equation	R^2	N	$p>F^a$	Age of Z^b
Polynomial	$Yr = 6.10 + 107 \cdot \%C - 112 \cdot \%C^2$	0.820	13	.001	28.2
Linear	$Yr = 7.76 + 65.0 \cdot \%C$	0.784	13	.001	27.5
Power	$Yr = 51.29 \cdot \%C^{0.588}$	0.639	13	.001	25.4
Exponential	$LogYr = 1.02 + 0.246 \cdot \%C$	0.630	13	.001	12.4
	Utilizing only samples with more than 0.05% carbon				
Linear	$Yr = 10.95 + 52.46 \cdot \%C$	0.714	8	.01	26.9

[a]Significance of regressions (as a probability) based on the F statistic.
[b]Age of outwash terrace surface (sample Z) based on empirical functions.
Yr = Years since deglaciation.
%C = Percent organic carbon.

increase with time over this initial period of soil development. In the first decade carbon accumulation is negligible; only two out of six samples had more than 0.02% carbon in the first decade (Table 3). A marked increase in carbon becomes apparent at around 15 years, but it is not clear if the increase occurs as a gradual transition or a step-function. The change corresponds with the colonization of alders (*Alnus crispa*) (Table 2), but this in-phase relationship does not rule out subtle increases in carbon prior to and prerequisite to alder seed germination. Carbon accumulation after 15 years is apparently related to ecological succession and the concomitant production and anchoring of organic matter as noted by earlier studies (Crocker and Major, 1955; Crocker and Dickson, 1957).

The increase in organic carbon over the first 32 years is strongly correlated with time of development, and all four regression models were significant ($p = 0.01$). The polynomial function explains the most variance in carbon ($R^2 = 0.89$; Table 4) and indicates accelerating carbon accumulation rates over this period (Fig. 5A). The linear function explains 78% of the variance in carbon, but residuals are not distributed randomly in respect to time. The power function indicates accelerating carbon accumulation during this initial period (Fig. 5B) but explains much less variance in carbon than the linear or polynomial models ($R^2 = 0.65$). The exponential function was least successful at explaining the variance in carbon ($R^2 = 0.59$). Residuals are not randomly distributed in respect to time, because, as defined, the exponential curve predicts decelerating carbon accumulation (Fig. 5B). A linear function of carbon accumulation in soils older than 10 years indicates that the average rate of carbon accumulation in A horizons between 10 and 32 years old was about 0.2% per year (Table 4). This is essentially a step-functional model assuming no carbon accumulation for 10 years followed by constant accumulation rates. None of the regression models should be extrapolated beyond the range of observations.

Relative Ages Based on Soil Carbon

Correlations of surface age using carbon as a predictor variable are all strong and statistically significant. There is very close agreement between all of the functions except the exponential model (Table 5) which is rejected because residuals are not randomly distributed through time. Based on the remaining four functions, the soil age of the terrace averaged 27.0 years old (ranging from 25.5 to 28.2) in June 1986. The terrace stabilized around 1959 $\pm$ 1.2 years (1σ), therefore, well after ice margin retreat from the site between 1929 and 1948. Ice had retreated to the head of a narrow gorge downstream of the Bobs Creek—Burroughs River confluence by 1959 (Fig. 4). High water and sediment discharges in the narrow gorge probably inundated the surface until the ice retreated further up-valley creating a sediment storage area above the gorge at which time channel incision occurred.

Changes in vegetation and microclimate are inevitable at the Burroughs Valley sites due to primary ecological succession and warming in response to ice margin retreat (Crocker and Major, 1955). Thus, as is frequently the case, complete isolation of time as the soil-forming factor is not possible. Opposi-

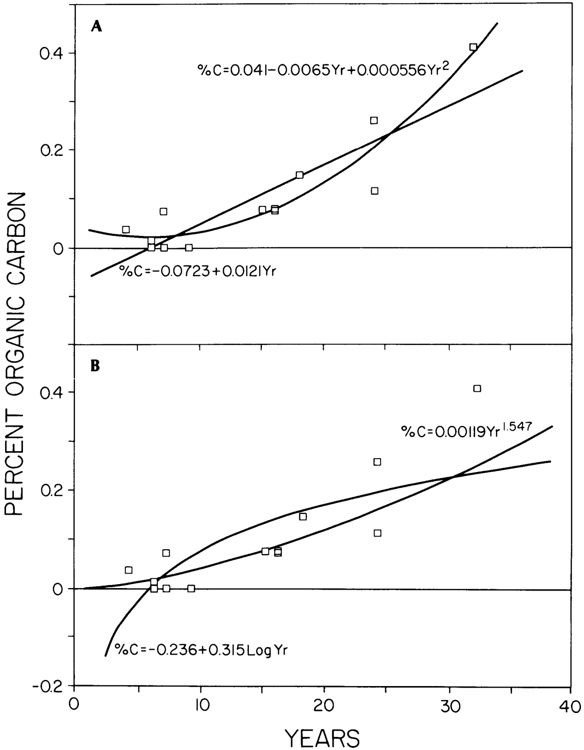


Fig. 5. Two time series plots of percent carbon for all Burroughs Glacier data, with empirically-derived functions superimposed: (a) second-order polynomial and liner functions; (b) exponential and power functions.

tion to Jenny's (1941; 1961) functional analysis method often questions the assumption that biologic, climatic, topographic, or geologic soil-forming factors can be effectively isolated from time. A polyfunctional model has been advanced that expresses pedogenesis as a function of soil-forming factors integrated over time and thus emphasizes the dependence of the other soil-forming factors on time (Stephens, 1947; 1951; cited by Stevens and Walker,

1970). Such an approach seems valid, but it is rarely applied because the number and complexity of factors involved prevent solution of the integral (Crocker, 1952). In spite of its limitations, the univariate functional analysis method remains a valuable research method employed by many researchers.

Organic carbon integrates the effects of changing vegetation and microclimate and provides an indicator of soil age potentially more reliable than biological parameters that are highly susceptible to disturbance. The changes in vegetation and microclimate are ubiquitous to retreating ice margins in the Glacier Bay region and are generally representative of the sequence of environmental changes following deglaciation. The observed rates of carbon accumulation documented here may be exemplary of soil development in many proglacial environments.

LONG-TERM CARBON CHRONOFUNCTIONS

The derivation of an appropriate general carbon chronofunction is limited by the small sample size and the lack of surfaces older than four decades in the Burroughs Glacier area. In a second stage of statistical analysis, therefore, linear, exponential, power, and polynomial models were derived by regressions on a data set extended with 10 observations made by earlier studies (Chandler, 1942; Ugolini, 1966).

Previous Studies of Organic Carbon in Southeastern Alaska

Earlier carbon chronofunction studies from the Glacier Bay region allow comparisons with this study, although only one study includes more than two samples from mineral soil horizons less than 40 years old. Four carbon chronofunction plots are presented for the Glacier Bay area by Crocker and Major (1955): two for mineral horizons and two for litter layers. The mineral soil chronofunction sketch shows carbon accumulation in the top 46 cm beginning slowly and accelerating very slightly over the first 50 to 70 years. In litter layers a pronounced acceleration in the first 25 years after establishment of alders is attributed to a strong dependence of pedogenic carbon on vegetation. Both mineral and litter layers attained constant carbon upper limits after only about 125 years. Unfortunately, Crocker and Major's (1955) data were converted to mass per unit volume and cannot be converted back to percentage of organic carbon without bulk density data.

Six A horizon samples from soils around Glacier Bay provide data comparable to this study (Ugolini, 1966). The curve for total organic carbon in O and A horizons (2 to 10 cm depth), is sketched around four observations less than 50 years old and shows accelerating carbon development in the first few decades. Carbon had not reached a steady-state after 250 years.

Four samples from shallow (0–5 cm) mineral soil horizons collected in front of the Mendenhall Glacier near Juneau provide organic carbon information from a similar environment (Chandler, 1942). Soil ages were determined by adding 15 years to tree ring counts (the 1000-year old soil age was estimated). A study in front of the Mendenhall and Herbert glaciers indicates that soil carbon had not stabilized after 200 years (Crocker and Dickson, 1957), but the data are incompatible with this study.

Theoretical Carbon Chronofunctions

Rates of soil organic carbon accumulation must eventually decrease as carbon reaches a steady-state. The attainment of equilibrium in respect to carbon apparently occurs within a hundred or a few thousand years (Holliday, 1982; Stevenson, 1982a; 1982b; Birkeland, 1984a; 1984b; Sandor, et al., 1986), although carbon stabilization in soils developed on sand may take longer (Syers, et al., 1970; Sondheim et al., 1981). To be valid over long time scales, carbon chronofunctions should include some form of decay curve. Only the exponential model expresses decreasing carbon accumulation rates over the limited period documented by the Burroughs data.

Three hypothetical carbon chronofunction types that attain an equilibrium level of carbon are shown in Figure 6. The chronosequence that is conventionally assumed is a simple saturation curve with rapid gains in carbon beginning immediately with surface stabilization (Type A). Such a trend can be expressed by several models including exponential or power functions. Accumulation of carbon in southeast Alaska is clearly not characterized by a Type A carbon chronofunction (Fig. 5).

A variation of the simple saturation curve has a lag time of zero carbon

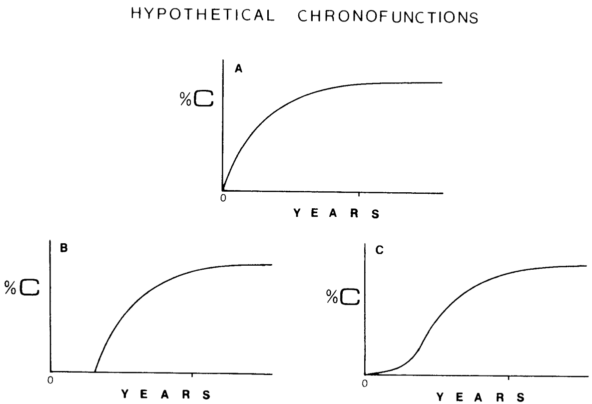


Fig. 6. Three hypothetical carbon chronofunctions (linear scales on both axes): (a) a simple exponential decay curve often assumed; (b) an exponential decay curve following a period of no carbon accumulation; (c) a sigmoidal curve depicting accelerating then decelerating accumulation.

accumulation prior to sudden onset of rapid accumulation (Fig. 6; Type B). Such a trend may represent lack of carbon production until establishment of a productive plant species abruptly initiates biological productivity. Curve-fitting techniques for such step functions require specification of where the step occurs which detracts from the objectivity of the method. Staining of mineral grains by organic acids and other traces of organic material observed in Burroughs soils less than 10 years old suggest that carbon concentrations are non-zero in initial pedogenic stages.

The third chronofunction type has an early period of slow but accelerating carbon accumulation followed by decelerating rates of accumulation as carbon reaches a steady state (Fig. 6; Type C). Sigmoidal curves such as these have been postulated for a number of pedogenic features on various time scales (Birkeland, 1974; 1984a; Yaalon, 1975), have been sketched on earlier studies of soil carbon in the region (Crocker and Major, 1955; Crocker and Dickson, 1957; Ugolini, 1966; Crocker, 1967), and have been quantitatively documented for pedogenesis on Vancouver Island (Sondheim et al., 1981). Such growth curves with asymptotes at lower and upper limits of the distribution cannot be accurately expressed throughout their range by any of the functions considered here. Second order polynomials can approximate the curve up to or beyond its inflection point, but not both. Third order polynomials can approximate the lower portion of the curve prior to attainment of steady state conditions. High-order polynomials may improve regressions, but they cannot fit an ideal logistic curve throughout its range, because they are incapable of expressing both upper and lower asymptotic limits. Furthermore, high-order polynomials may yield serious errors due to their instability.

Analysis of an Extended Data Set

Long-term carbon chronofunctions were derived by regressions using the Burroughs data augmented with data collected by Chandler (1942) and Ugolini (1966) from older sites. Carbon concentrations in young soils of those studies are slightly higher than values found in Burroughs samples, perhaps due to inclusion of macroscopic organic carbon, O horizon materials, or chloride ions. All three studies determined organic carbon in A horizons with the Walkley-Black method, and differences are assumed to be negligible. Although the extended sample size remains small (N = 23), and few observations are available for soils older than 50 years (N = 5), the data provide a test to determine if initial regression models are robust.

Equations derived from the extended data are considerably different than equations based on the Burroughs data alone (Table 4). The second order polynomial expression of the extended data set, provides an extremely strong and significant model ($R^2 = 0.96$; $p = .001$), but the parabolic form predicts decelerating accumulation with time even for very young soils (Fig. 7A). Thus, in spite of the superior fit, the model is unrealistic at both the upper and lower ends of the distribution. The extended linear model is quite weak and is no longer effective at predicting carbon in the younger soils (Fig. 7A). Exponential and power functions derived from the extended data are very different than

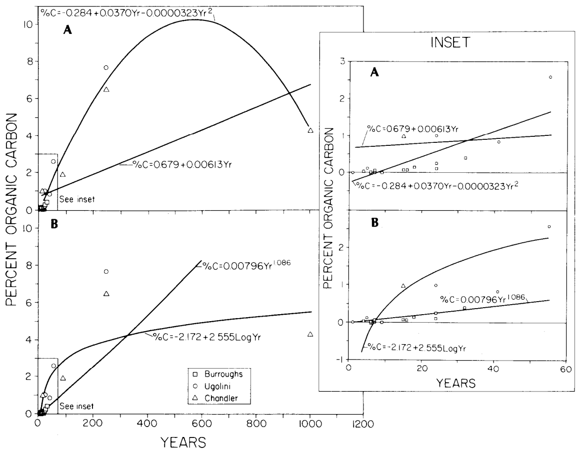


Fig. 7. Time series plots of percent carbon for Southeastern Alaska data extended with Ugolini (1966) and Chandler (1942). Empirically-derived functions are superimposed: (a) second-order polynomial and linear functions; (b) exponential and power functions.

the functions derived from the Burroughs data but explain similar amounts of variance in carbon. The extended power function is nearly linear due to domination by young samples and it provides an unrealistic prediction for old samples (Fig. 7B). The exponential curve, by definition, remains a saturation curve when fit to the extended data set, but the shape of the curve is substantially altered. Explained variance provided by the exponential curve is only slightly improved due to the dominance of young soils in this data set.

None of the models is capable of accurately modelling both the accelerating and decelerating portions of the long-term carbon curve. They all violate a basic assumption of linear regression; that is, that variance is independent of the value of the predictor variable. Most chronofunction studies have small sample sizes and observations are unevenly distributed through time. A few observations from old soils or a large number of observations occurring in clusters may dominate distributions. Caution should be exercised in using the functions to interpolate to time periods poorly represented by the data.

These limitations of Alaskan carbon chronofunctions may be relevant to other pedogenic features on longer time scales. Pedogenic features with longer periods of equilibration than carbon, such as argillic, calcic, or oxic horizons, may experience accelerating rates of development that last for tens of thousands of years (Birkeland, 1984a; p. 225). Where sigmoidal growth

curves characterize pedogenesis, chronofunctions based on simple, conventional, linearized regression models may be overly influenced by different portions of the distribution. Development of separate functions for the various areas of the curve may be warranted, or a different general model such as a logistic function may be appropriate.

The general logistic function, a three-parameter distribution, can be linearized to allow curve-fitting by linear regression techniques (Nair, 1954; Davis, 1941). The procedure is not simple, however, unless data form a continuous series (such as an annual series) or can be expressed as probabilities. The technique was not applied to the Southeastern Alaska data, because these conditions are not met, and an algorithm for the general form of the logistic function was not available. The logistic function has, however, been successfully applied to pedogenesis along a chronosequence on Vancouver Island (Sondheim et al., 1981).

CONCLUSIONS

A strong positive relationship exists between percentage organic carbon from young, shallow, mineral soils in front of the Burroughs Glacier and age of soil surfaces. A period of near-zero carbon accumulation in the first decade is followed by accelerated carbon accumulation over the next 22 years of pedogenesis. In soils between the age of about 10 and 32 years, organic carbon accumulates at an average rate of about 0.02% per year, although rates increase with the age of the surface over this period.

Carbon accumulation in the first four decades of pedogenesis can be succinctly expressed as a second-order polynomial function of time. The linear and power functions derived from the Burroughs carbon chronosequence are less adaptable than polynomial models but provide reasonable correlations. The exponential function, a conventional model for carbon accumulation and other measures of pedogenesis, was inappropriate in the initial period of pedogenesis in this pro-glacial environment, because it is incapable of adjusting to increasing rates of carbon accumulation.

Equations based on organic carbon percentages are presented for the relative dating of surfaces deglaciated near the Burroughs Glacier. These functions indicate that an outwash terrace surface in the lower Burroughs Valley stabilized about 1959, more than 10 years after the site was deglaciated, probably due to sustained high sediment loads until the glacier had retreated farther up-valley.

Long-term carbon accumulation rates in Glacier Bay are sigmoidal in trend. The validity and significance of various conventional models change with the relative number of observations of old and young soils, therefore, due to the inability of the functions to express carbon accumulation rates both accelerating initially and decelerating later on. The success of second-order polynomial functions to simulate the southeast Alaska carbon data is due to their ability to adjust to either accelerating or decelerating rates, but these functions are unstable and cannot express both trends simultaneously. Logistic curves may provide a better general model for chronofunctions extending from very young to very old surfaces in this environment. These functions will not necessarily improve predictions over other models within a range of observations restricted to the upper or lower portion of the chronofunction, but they provide a superior conceptual model and could mitigate gross errors possible when interpolations or extrapolations are based on limited data.

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