Dynamics of soil-forming processes in the Arctic

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The process of podzolization and the formation of Spodosol-like soils in well-drained tundra has been questioned. Standard chemical analyses fail to distinguish between Spodosol-like soils in boreal forest and tundra. As an alternate method to assess present soil processes, tension lysimeters were placed under the horizons of Spodosol-like soils at three sites to collect *in situ* soil solution. Soil solutions obtained by irrigating the soil with deionized water were analyzed for pH, electrical conductivity, Ca^{2+}, Mg^{2+}, K^{+}, iron, and total organic carbon. Soils from the lysimeter sites were analyzed for pyrophosphate and dithionite extractable Fe and Al. In the boreal forest, solid phase and soil solution analyses indicate that the process of podzolization has occurred and is currently occurring. In the boreal forest and tundra transition site, analyses show that podzolization occurs sporadically in wet years. In the tundra, conventional analyses indicate that podzolization has occurred; soil solution indicates a weak expression of this process. This study reveals the existence of latitudinal pedogenic gradients related to climate, productivity and biomass degradation, and mineral weathering. Tension lysimetry permits evaluation of soil development rates in the Arctic for the first time.

On s'est penché sur le processus de la podzolisation et sur la formation de sols ressemblant à des spodosols dans la toundra bien drainée. Des analyses chimiques courantes n'ont pas permis de distinguer les sols ressemblant à des spodosols de la forêt boréale de ceux de la toundra. Une autre méthode d'étude des processus pédologiques en cours a consisté en l'installation de lysimètres sous les horizons de sols ressemblant à des spodosols pour recueillir *in situ* les solutions du sol. De telles solutions, obtenues par irrigation du sol avec de l'eau déionisée, ont été soumises à des mesures de pH, de conductivité électrique et de teneur en Ca^{2+}, en Mg^{2+}, en K^{+}, en fer, et en carbone organique total. Les échantillons des lysimètres ont été soumis à des analyses de la teneur en Fe et en Al extractibles par le pyrophosphate et le dithionite. Dans la forêt boréale, les analyses des phases solides et aqueuses des sols indiquent que le processus de la podzolisation s'est déjà produit et se poursuit; dans la zone de transition entre la forêt boréale et la toundra, les analyses indiquent que le processus de la podzolisation peut se produire sporadiquement pendant les années humides; dans la toundra, des analyses conventionnelles indiquent qu'il y a eu podzolisation, ce que révèlent faiblement les solutions de sol. Cette étude montre l'existence de gradients pédogénétiques latitudinaux liés aux conditions climatiques, à la productivité du sol, à la dégradation de la biomasse et à l'altération minérale. Les essais lysimétriques ont permis d'évaluer pour la première fois dans l'Arctique la vitesse de développement des sols.

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Introduction

In the arctic and subarctic regions poorly drained soils prevail because of the presence of ice-cemented permafrost that forms an effective barrier to downward water percolation during the thaw season (Tedrow *et al.* 1958). These poorly drained soils are affected both by gleying processes and cryoturbation. However, recent soil mapping in arctic Alaska shows that, within the continuous permafrost zone (Figure 1), including the Brooks Range, Arctic Foothills, and Arctic Coastal Plains, well-drained soils comprise nearly 22 per cent of the land surface, exclusive of mountainous land and similar areas which lack soil development (Rieger *et al.* 1979). These well-drained soils, in spite of representing a minor portion of the total landscape, are of special value from pedological, archaeological, biological, and engineering standpoints.

The well-drained soils that develop on stable landscapes receive the full impact of the regional climate and biota, and thus acquire maturity. They allow us to trace a thread of continuity from the well-drained mature soils of lower latitudes to those of the Arctic. The well-drained soils are also those used preferentially by both historic and prehistoric cultures and are, therefore, potentially important areas for the identification and preservation of archaeological sites. Biologically, these soils are important because of the absence of ice-cemented permafrost throughout the thaw season. They are warmer than the adja-

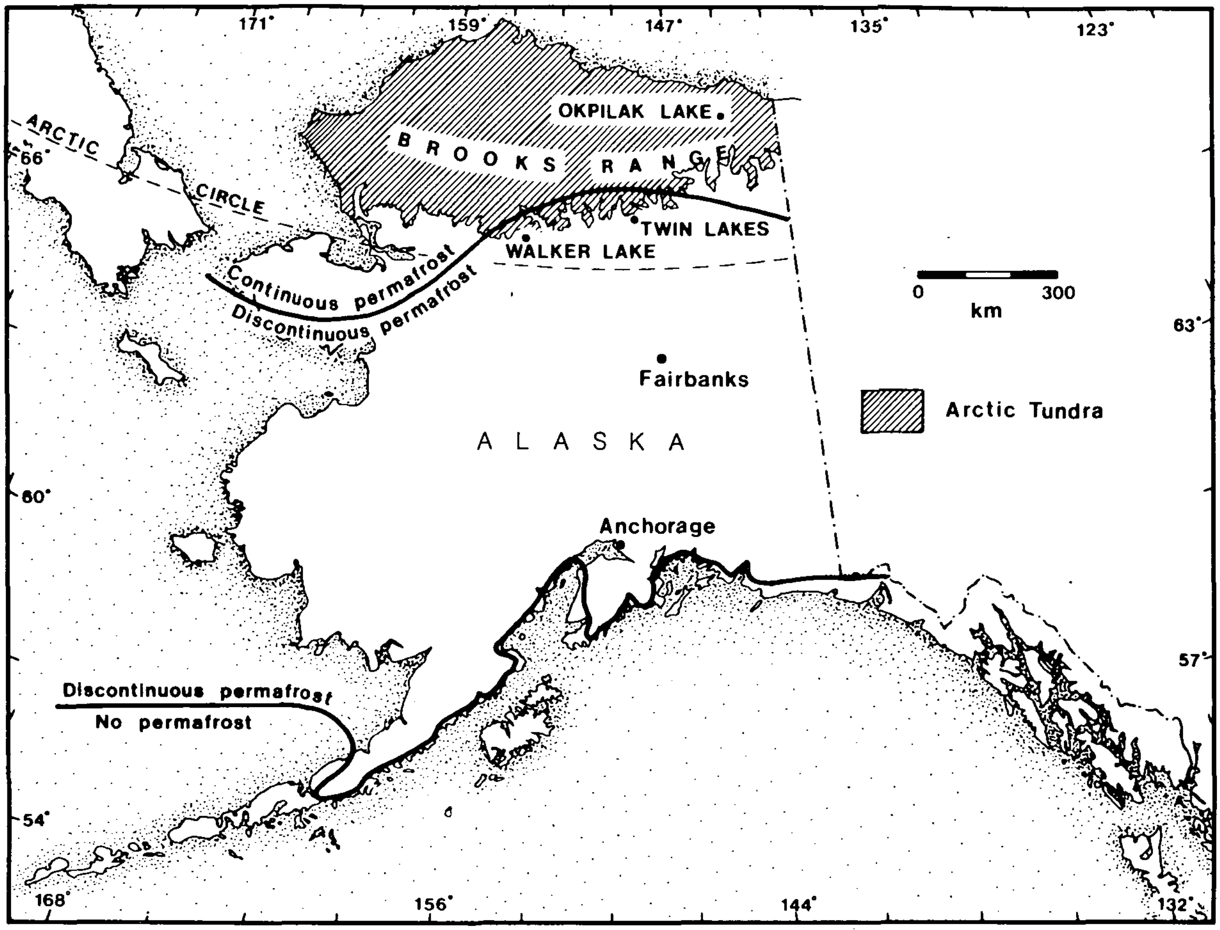

FIGURE 1. Locations of the Walker Lake, Twin Lakes, and Okpilak Lake sites, Brooks Range, Alaska. (Permafrost distribution *after* Brown and Péwé 1973).

cent wet tundra soils and remain unconsolidated (Drew *et al.* 1958) and therefore harbour many burrowing animals that otherwise could not dwell or den in the wet tundra. For engineering purposes, the well-drained soils offer relatively unrestricted drainage, an absence of near-surface ice-cemented permafrost during the thaw season, and a low incidence of frost heaving. For these reasons they provide optimum sites for roads, sources of material, and other construction activities. To gain a comprehensive understanding of the soil-landscape of the Arctic, it is necessary, therefore, to understand the soil processes operating at these well-drained sites.

In 1958, Tedrow and his associates (Tedrow *et al.* 1958) suggested that no qualitative difference exists between soil-forming processes in the boreal forest and those in the well-drained arctic tundra; rather, that podzolization weakens polewards as the Podzols (Spodosols) in the forest are replaced by Arctic Brown soils (Cryochrepts) in the tundra. Consequently, Podzols were expected and found in the boreal forest and Arctic Brown soils in the arctic tundra. However, since that time Podzols have been repeatedly reported in a number of arctic tundra environments including Greenland, eastern Canada, Siberia, northern Alaska, and northern Norway (Brown and Tedrow 1964; Ellis 1980; Everett 1979; James 1970; Larsen 1972; Moore 1974; Payette 1973; Tedrow 1977; and Ugolini 1966). In each case these Podzols were beneath lichen mixed-heath vegetation and were intermixed with Arctic Brown soils. In northern Alaska, Podzols were found more than 350 km beyond the present tree-line at sites which had evidently never been occupied by trees (Everett 1979). Tundra Podzols, thus far reported, experience cold semi-arid climates. Despite the fact that relative humidity is high in the Arctic and moisture accumulates in the soil by condensation (Gorodkov 1939), soil moisture typically remains insufficient for intensive leaching (Tedrow *et al.* 1958). This observation raises the question whether the process of podzolization is current or whether tundra Podzols are relict from a time when conditions were more conducive to their formation. Establishing the contemporaniety of podzolization in arctic Alaska can shed some light on post-glacial climatic trends.

Although raised previously by Brown and Tedrow (1964), this question has not yet been satisfactorily answered in arctic pedology. Additionally, the conventional pedological approach which involves the physical, chemical, and mineralogical analyses of soil samples cannot evaluate contemporaniety of processes (Ugolini *et al.* 1981). Such studies can only reveal that certain processes have occurred over time. The most effective means of evaluating the current soil-forming processes is by analysis of soil solutions collected *in situ*. As stated by Mubarak and Olsen (1976) and supported by others (Adams 1971; Kittrick 1971; Pearson 1971; van Breemen and Brinkman 1976), the composition of the soil solution reflects the actual processes occurring in the soil. Although this approach represents a departure from conventional pedology; recent research has shown that this is a most powerful and direct way for evaluating contemporary soil-forming processes (Dawson *et al.* 1978; Singer *et al.* 1978; Ugolini *et al.* 1977*a*, 1977*b*). These authors, working in the subalpine zone of the Cascade Mountains of Washington, have characterized the podzolization process as it occurs in a cool, humid coniferous forest. At this locale, podzolization is dominated by soluble organic compounds originating in the canopy and/or in the surficial humus layer. These compounds lower the pH, suppress the dissociation of carbonic acid, make complexes of the iron, aluminum, and other metals, and move them into the B2ir soil horizon where these metal-organo-complexes accumulate. Below the B2ir horizon, the removal of organic acids causes the pH to increase, carbonic acid dissociates, and the bicarbonate governs the transport of ions. Mobile fulvic acids were detected in the soil solution of the organic and A2 horizons, but were subjected to 60 to 70 per cent reduction across the B2ir horizon. Podzolization trends, as seen in the composition of the soil solution, can be summarized as a decrease in concentration of iron, aluminum, major cations, and fulvic acid across the B horizon boundaries. The utility of these studies in determining present-day soil genetic processes suggested that the analysis of soil solutions, collected *in situ*, could be used to assess the unresolved question of whether or not podzolization is a present day process in the Arctic.

Study Area

The Brooks Range is the northernmost extension of the Rocky Mountains and consists of a series of east–west trending belts of metamorphic, sedimentary, and intrusive rocks. The sedimentary rocks of Paleozoic and Mesozoic age are folded, faulted, and locally metamorphosed. Limestone, graywacke, chert, shale, and shist are common. Dark intrusive rocks from the Jurassic–Cretaceous period as well as other intrusive bodies of granite and diorite exist in the range (Black 1969). Repeated glaciations have left broad U-shaped valleys. The range lies entirely north of the Arctic Circle and experiences an arctic climate. The northernmost extension of the boreal forest occurs on the southern flanks of the Brooks Range (*see* Figure 1).

In general, the climate of the Brooks Range is characterized by cold, dry winters and short, cool summers with light rains. July is the warmest month of the year.

Three diverse sites were selected for this study: Walker Lake, Twin Lakes, and Okpilak Lake (*see* Figure 1). The nature of the parent material was a critical factor in selecting sites for this study. Podzolization preferentially occurs on acidic rocks such as granite. The sites selected for this study were located in glaciated valleys covered by unconsolidated Quaternary deposits with acidic igneous or metamorphic lithologies. These sites form a transect from the boreal forest to the arctic tundra across the Brooks Range.

Walker Lake, the southern site at 67°09'N and 154°22'W, is located at the northern margin of the boreal forest where white spruce (*Picea glauca*) dominates the well-drained sites and black spruce (*Picea mariana*) predominates in the poorly-drained sites. The ground cover consists of ericaceous species including blueberry (*Vaccinium uliginosum*), Labrador tea (*Ledum decumbens*), crowberry (*Empetrum nigrum*), mountain cranberry (*Vaccinium vitis-idaea*), and lichens (*Cladonia* sp. and *Cetraria* sp.).

The Walker Lake area is underlain by Paleozoic schists; the study site, however, is located at approximately 600 m on a late-Pleistocene moraine of Itkillik (Wisconsin) age (Hamilton and Porter 1975). The glacial drift consists of locally derived quartz–mica schists and granitic material of more northern provenance.

Walker Lake is in the Interior Basin climatic division of Alaska and is characterized by cold, dry winters and relatively warm and moist summers (U.S. Environmental Data Service 1977). The mean annual temperature of Bettles, the nearest meteorological station some 120 km east, is −5.9°C. July is the warmest month (mean temperature of 14.4°) and the range of average summer temperature is between 5 and 25°C. Average winter temperatures range from −1 to −35°C. The annual precipitation is 35.5 cm (U.S. Environmental Data Service 1977).

The Twin Lakes site is located at 67°33'N and 149°03'W on the south flank of the Brooks Range at 670 m in elevation (*see* Figure 1). The study site is in the transition zone between the boreal forest and arctic tundra and is sparsely vegetated (60 per cent) by clumps of birch (*Betula glandulosa*), Labrador tea (*Ledum decumbens*), blueberry (*Vaccinium uliginosum*), and a cover of lichens (*Cladonia* sp.). Unvegetated areas are covered by desert pavement. The soil profile and lysimeter installation were located under a birch shrub and a cover of lichens. The soil studied has developed on kame-terrace deposits of Itkillik age (Hamilton 1978; Hamilton and Porter 1975). The parent material consists of mixed metamorphic and granitic lithologies.

Discontinuous climatic records (between 1964 and 1978), obtained from Chandalar (67°30'N and 148°30'W) some 25 km east of Twin Lakes, indicate a mean annual temperature of −9.6°C and precipitation of 23.5 cm.

Okpilak Lake, on the north side of the Brooks Range (69°26'N and 144°02'W), is at about 610 m elevation. The Okpilak site is in the arctic tundra and the vegetation consists of lichen mixed-heath assemblage including alpine bearberry (*Arctostaphylos alpina*), crowberry (*Empetrum nigrum*), Labrador tea (*Ledum decumbens*), mountain cranberry (*Vaccinium vitis-idaea*), and lichens (*Cladonia* sp. and *Cetraria* sp.). The parent material consists of granitic glacial deposits with an admixture of shale. These deposits have been correlated with the Alapah Mountain glaciation (Sable 1977). Hamilton (1979) has recently assigned a late Itkillik age to the type deposits of this glaciation, and has given an age of 12,800–12,500 yr B.P. to the late-Itkillik readvance in the Sagavanirktok and Anaktuvuk valleys in the central part of the Brooks Range (Hamilton 1981). Therefore it is likely that the Okpilak site was deglaciated about 12,000 years ago. Soils of this valley have been previously described by Brown and Tedrow (1964) and Brown (1966). Only limited meteorological data have been recorded for this area (Tedrow and Brown 1962). The annual precipitation has been estimated to be 15 to 20 cm, half of which falls during the summer. The mean annual temperature is near −11°C, with a July mean temperature between 7 and 12°C (Conover 1960; Tedrow 1977). Happy Valley camp, along the TAPS haul road, may be climatologically comparable to the Okpilak site. Records from Happy Valley (from 1975 to 1978) show a mean annual temperature of −11°C, with a range of average summer temperature between 3 and 19°C and winter temperatures between −40 and −15°C. The mean annual precipitation is approximately 11.5 cm (water equivalent), most of which falls between June and October (Brown and Berg 1980).

Materials and Methods

At three selected sites, representative soil profiles were chosen for this study. Soils at these sites display the morphology of Spodosol-like soils. This term is used throughout this paper rather than Spodosol because, in spite of having the morphology and chemistry of Spodosols, the soils studied here fail to meet the strict spodic horizon criteria established by the *Soil Taxonomy* (Soil Survey Staff 1975). These soils all have eluvial albic horizons and correspond to miniature podzols in Tedrow's classification (Tedrow *et al.* 1958). They are well drained and apparently not recently disturbed by frost action. The lack of cryoturbation in these well-drained profiles is in part due to the depth of the permafrost table, which is controlled locally by the complex interaction of such factors as topography, vegetation cover, and soil texture (Washburn 1980). Although these particular profiles were not excavated to the frost table, nearby profiles at Walker Lake encountered ice-cemented permafrost at a depth of 1 m and profiles adjacent to the ones studied at Okpilak Lake and Twin Lakes encountered ice-cemented permafrost at less than 1 m depth under thicker vegetation cover. An active layer thicker than the solum allows good internal drainage, and provides a relatively dry solum only slightly susceptible to frost action processes during freeze-up. Active layer thickness is therefore in part responsible for the stability of these soils and for their usefulness in this study.

The profiles were described following the standard methods presented in the *Soil Survey Manual*, the *Supplement*, and the *Soil Taxonomy* (Soil Survey Staff 1951, 1962, and 1975). Descriptions are provided in Table 1. Following profile description and sampling, tension lysimeters were placed under each genetic horizon, and the resultant data represent the concentration of solutions as each left their respective horizons. At Walker Lake tension lysimetry and soil sampling were done on separate but adjacent profiles. The lysimeter apparatus (Figure 2) consists of fritted glass filter discs (Kimble #2820M) 60 mm in diameter with medium porosity (nominal pore size 10 to 15 μm). These glass filters were placed in machined plexiglass holders and held in place by nylon screw-

TABLE 1. Soil profile descriptions for the Walker Lake, Twin Lakes, and Okpilak Lake sites, Brooks Range, Alaska

Horizon	Depth (cm)	Colour (moist)	Texture	Structure	Consistence	Roots	Boundary
Walker Lake							
01	9-4						
02	4-0						
A1	0-3	2.5YR 2/2	sicl	lfcr	fr, so,po	3vf&f,1co	aw
A2	3-10	5YR 4/2	sl	lfcr	fr,ss,sp	3vf&f	aw
B21hir	10-14	5YR 3/4	l	lfpl→lfsbk	fr,ss,sp	2vf&f	aw
B22ir	14-18	7.5YR 4/4	l	lfsbk	fr,ss,sp	2vf&f	cs
C	18-32*	10YR 4/4	l	lfpl→lfabk	fr,ss,sp	2vf&f	ab
Twin Lakes							
01+02	4-0						
A2	0-7.5	N6/	gsl	lfpl→lfsbk	fr,so,po	2f	ab
B2ir	7.5-14	5YR 4/8	gsl	lfsbk→lfcr	fr,so,po	1f	cw
B3	14-21	10YR 4/4	gls	lf-vfpl→fcr	fr,ss,sp	1f	cb
C	21-43+	7.5YR 5/6	vgls	M	lo,so,po	2vf&f	
Okpilak Lake							
01+02	3-0						
A2	0-11	10YR 6/2	l-sl	lfpl	fr,so,po	3vf,2f	ab
B2ir	11-19	7.5YR 4/4	l	lfpl→f-mcr	fr,ss,sp	3vf,2f	aw
B3	19-29	10YR 4/3	gsl	lfpl→lfcr	fr,so,po	3vf,1f	ai
C	29-44+	10YR 6/2	gsl	M→lfcr	fr,so,po	1f	

Abbreviations:

Texture: v-very; s-sand, sandy; si-silty; c-clay; g-gravelly; l-loam, loamy.

Structure: 1-weak; vf-very fine or thin; f-fine or thin; m-medium; pl-platy; cr-crumb; M-massive; abk-angular blocky; sbk-subangular blocky; → breaking to.

Consistence: fr-moist, friable; lo-moist, loose; so-wet, nonsticky; ss-wet, slightly sticky; po-wet, nonplastic; sp-wet, slightly plastic.

Roots: 1-few; 2-common; 3-many; vf-very fine; f-fine; co-coarse.

Boundary: a-abrupt; c-clear; s-smooth; w-wavy; b-broken; i-irregular.

* This profile extends to 62 cm depth through unfrozen buried horizons unrelated to this study. The complete description is given in Ugolini *et al.* (1981) p. 370.

caps. The lysimeters were connected to a vacuum system with teflon tubing. The vacuum was maintained at 10 kPa (0.1 bar) by a Cartesian manostat. Soil solutions held below this tension were drawn through the lysimeter plates into the collection system. Because of the lack of available moisture, soil solution collection was facilitated by irrigating the sites. Stream water collected in plastic carboys was deionized with ion-exchange columns (Barnstead D8902) and measured volumes of water slowly applied to a delineated area. Aliquots of deionized water were retained in order to confirm the adequacy of the deionization process. Generally, water was applied intermittently over a three-day period, the time required to collect 250 ml of solution. Irrigation and soil solution collection were performed from July 1 to 16, 1978. Collection was in sequence starting from the southern site and moving northward to minimize the seasonal differences and thus attempt to sample the soils at the same position in the summer thaw cycle. Solutions collected were refrigerated in the field and analyzed in the laboratory for pH, electrical conductivity, major cations (Ca^{2+}, Mg^{2+}, and K^{+}), total organic carbon (TOC), and soluble iron.

Prior to analysis the solutions were passed through a filter with 0.45 μm millipores, with the exception of the TOC samples. The pH was measured using a Corning model 12 pH meter and electrical conductivity with a Yellow Springs model 31 conductivity bridge. Calcium, Mg^{2+}, and K^{+} were determined on an Instrumentation Laboratory model 353 atomic absorption spectrophotometer. Total organic carbon was determined on a Dohrmann DC-50 TOC analyzer, using a 30-μl acidified sample (Dawson *et al.* 1978). Soluble iron was determined by atomic absorption spectrophotometry. In addition, air-dry soil samples (<2 mm) collected from individual horizons were used for iron, aluminum, and carbon extractions. Both metals were extracted with sodium dithionite (Jackson 1969) and sodium pyrophosphate (McKea-

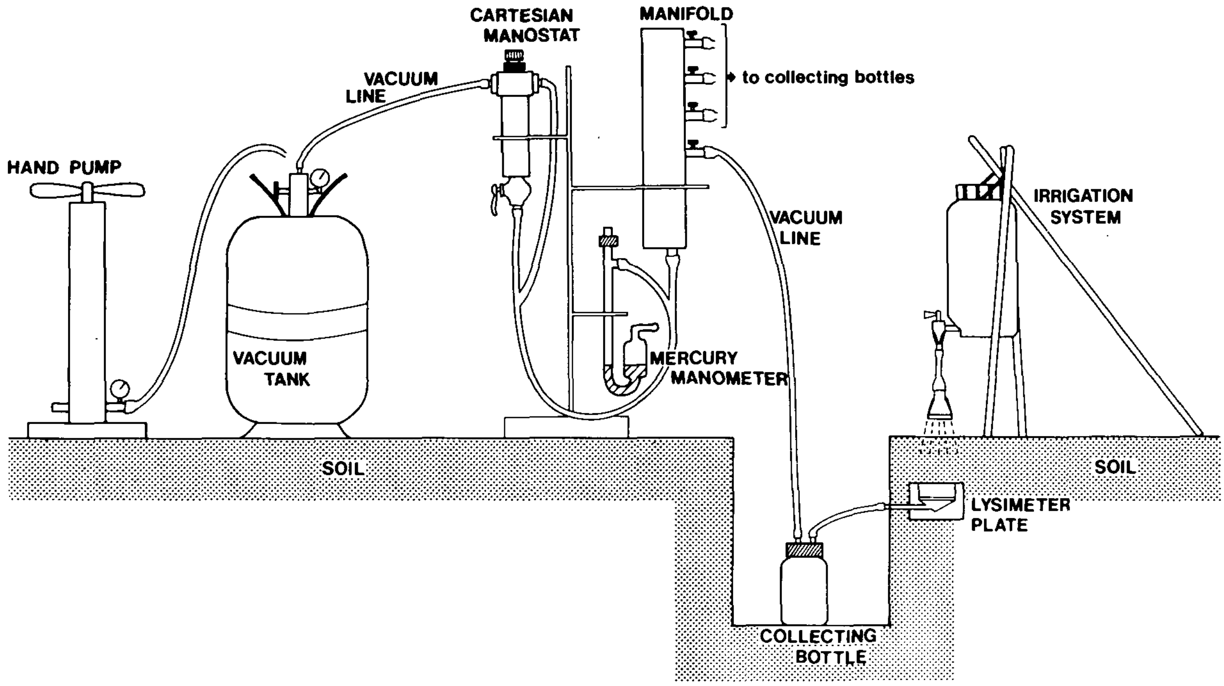

FIGURE 2. Tension lysimeter apparatus.

gue 1967) and were assayed by atomic absorption spectrophotometry. Organic carbon (C) was determined by the modified Walkley–Black procedure reported by Allison *et al.* (1965). The humified carbon (C_p) was extracted by sodium pyrophosphate (McKeague 1978) and determined on the Dohrmann TOC analyzer.

Results and Discussion

Factors Affecting Solution Collection

In contrast to similar studies utilizing tension lysimetry (e.g. Cole 1958; Singer *et al.* 1978; Ugolini *et al.* 1977*a*) soil solutions from these arctic soils could be extracted only when the soil was artificially irrigated. At Walker Lake, even after persistent rainfall, solutions could not be obtained at the 10 kPa tension without artificial irrigation.

The textural and structural characteristics of the soils, as judged qualitatively in the field, vary both between sites and within a given profile. Thus, the water retention characteristics and, most importantly, the hydraulic conductivities differ between the sites. These differences are further modified by the distribution and degree of humification of organic materials within the individual profiles. At this point it is difficult to specify the direct impact of these differences on the compositions of the soil solutions extracted. Certainly, the hydraulic conductivity influences the contact time between solutions and minerals or organo-mineral complexes, and consequently influences the magnitude of dissolution or reaction processes. Under irrigation the concentrations in the pore waters may be diluted with respect to the true soil solution, and the degree of dilution may vary between sites. The authors contend that the behaviour of soluble organic and inorganic species or their complexes, mobilized by artificial infiltration can reflect current soil genetic processes. Hydraulic conductivity and water retention differences within individual profiles have existed during the development of the profile, and such differences therefore do not unnaturally affect the results presented here. It is, however, premature to discuss in quantitative terms absolute species concentration differences between sites without further evaluation of the factors which may cause concentrations in artificially induced soil solutions to depart from those in natural soil solutions. Laboratory studies are now in progress to evaluate these factors and assess their effects.

Solution Composition

The pH values for the three sites vary from strongly to slightly acid (Table 2 and Figure 3) and show the general trend of increasing with depth. The Walker Lake site, situated directly under a spruce tree, shows a low pH value; probably reflecting a more-leached regime in addition to more-abundant biomass and more-active decomposition than at the other two sites. The Okpilak site, with the least biomass, presumed lower decomposition rate, and lower precipitation, has the highest pH.

Electrical conductivity values (*see* Table 2) generally support the podzolization trend for these soils, showing higher ionic loads in the solutions percolating from the 02 and A2 horizons and lower values for solutions leaving the B and C horizons, thereby indicating ionic accumulation in the B horizons. The Twin Lakes site shows a remarkably high conductivity value for the A2 horizon, which is confirmed by the cation determinations.

Similar patterns are also evident in the cation concentration data (*see* Table 2 and Figure 3). Walker Lake site shows a definite podzolization trend indicating removal of cations from the surface and their arrest in the B horizon. This is a trend previously observed in soil solutions of strongly podzolized soils in the Cascades of Washington (Singer *et al.* 1978; Ugolini *et al.* 1977*b*).

The Twin Lakes site is geomorphically distinct from the other two sites in that the Spodosol-like soil is situated on top of a windswept and dry kame terrace. Accordingly, the high cationic values may result from irrigation induced flushing of soluble ions, produced by surficial weathering and decomposition reactions, that have accumulated because of normally low leaching intensities. The distribution of these cations within the profile, however, shows the podzolization trend.

Soil solutions from Okpilak Lake show, to a lesser extent, the flushing effect due to irrigation. The removal of the cations is, however, less than at the other sites, reflecting the less vigorous weathering regime and the weaker podzolic trend in this most northerly soil.

Total organic carbon in soil solution from the Walker Lake site depicts the podzolization trend (*see* Table 2 and Figure 3). Mobile organic compounds are produced in the forest floor, temporarily stored on the surface of the mineral soil, mobilized by percolating water, and then arrested by the sesquioxides in the B horizons.

The Twin Lakes profile displays a similar trend, but with elevated values. These high concentrations could result from the thick organic cover, accelerated decomposition, or from the unique composition of the birch litter. The mobile organic compounds are stored in the A2 horizon and flushed into the B2ir horizon where they accumulate. Again this curve depicts the expected podzolization trend.

Soil solutions from the Okpilak Lake site show lower concentrations of total organic carbon than the other sites. However, in spite of reduced levels, the podzolization trend is still evident. The authors suggest that, at this northern site, conditions for the production of mobile organic compounds are less favourable because of the short frost-free season, the small biomass, and low biological activity.

At Walker Lake soluble iron (<0.45 μm) closely parallels the distribution of total organic carbon (*see* Table 2 and Figure 3). The authors infer that the iron in solution is organically complexed and moves in conjunction with the soluble organic phase. As pre-

TABLE 2. Soil chemical parameters for the Walker Lake, Twin Lakes, and Okpilak Lake sites, Brooks Range, Alaska

Profiles	Soil chemical parameters																	
	Solution composition									Solid phase composition								
	Depth cm	pH	EC μmho/cm	Ca ppm	K ppm	Mg ppm	Ca + K + Mg $(meq/l) \times 10^{-2}$	Fe ppm	TOC ppm	pH	C %	C_p* %	Fe_d* %	Fe_p* %	Al_d* %	Al_p* %	C/C_p*	Fe_p/C_p*
Walker Lake																		
02	4-0	5.03	9.0	0.353	1.03	0.044	4.76	0.19	18.8									
A2	3-10	4.80	11.8	0.395	0.896	0.095	5.04	0.20	25.2	4.3	10.70	3.38	2.03	0.75	0.26	0.24	3.17	0.22
B21hir	10-14	4.78	10.5	0.220	0.295	0.092	2.61	0.19	17.6	3.9	3.11	2.69	2.41	0.89	0.43	0.33	1.16	0.33
B22ir	14-18	5.20	7.35	0.343	0.133	0.103	2.90	0.01	8.8	5.1	2.35	1.97	2.17	0.74	0.61	0.41	1.19	0.38
C	18-32									4.8	1.93	1.78	1.93	0.73	0.63	0.46	1.08	0.41
Twin Lakes																		
02	4-0	5.20	13.5	0.739	1.66	0.206	9.63	0.59	32.0									
A2	0-7.5	5.77	53.0	5.75	1.08	2.00	47.9	2.80	52.0	5.6	0.86	0.29	0.32	0.17	0.08	0.07	2.97	0.59
B2ir	7.5-14	5.78	12.4	0.635	0.896	0.554	10.0	0.25	18.0	5.4	0.34	0.31	1.21	0.11	0.18	0.10	1.10	0.35
B3	14-21	6.50	11.1	0.968	0.451	0.372	9.04	0.06	14.8	5.9	0.25	0.38	1.11	0.05	0.23	0.10	0.66	0.13
C	21-43 +									5.9	0.28	0.37	0.76	0.06	0.21	0.12	0.76	0.16
Okpilak Lake																		
02	3-0	5.70	8.6	0.374	1.01	0.054	4.89	0.12	7.2									
A2	0-11	6.18	6.3	0.207	0.698	0.020	2.98	0.10	14.4	5.1	2.46	0.94	0.49	0.15	0.10	0.10	2.62	0.16
B2ir	11-19	5.70	5.17	0.426	0.126	0.048	2.84	0.14	10.4	5.6	0.97	0.86	0.52	0.22	0.17	0.13	1.13	0.26
B3	19-29	5.95	5.45	—	—	—	—	0.01	11.2	5.5	0.47	0.54	0.58	0.12	0.22	0.11	0.87	0.22
C	29-44 +									5.9	0.16	0.17	0.42	0.04	0.12	0.07	0.94	0.24

*Subscript *p* indicates sodium pyrophosphate extractable form, subscript *d* indicates sodium dithionite extractable form.

Note: Solution composition data points are values for solutions exiting the denoted horizon.

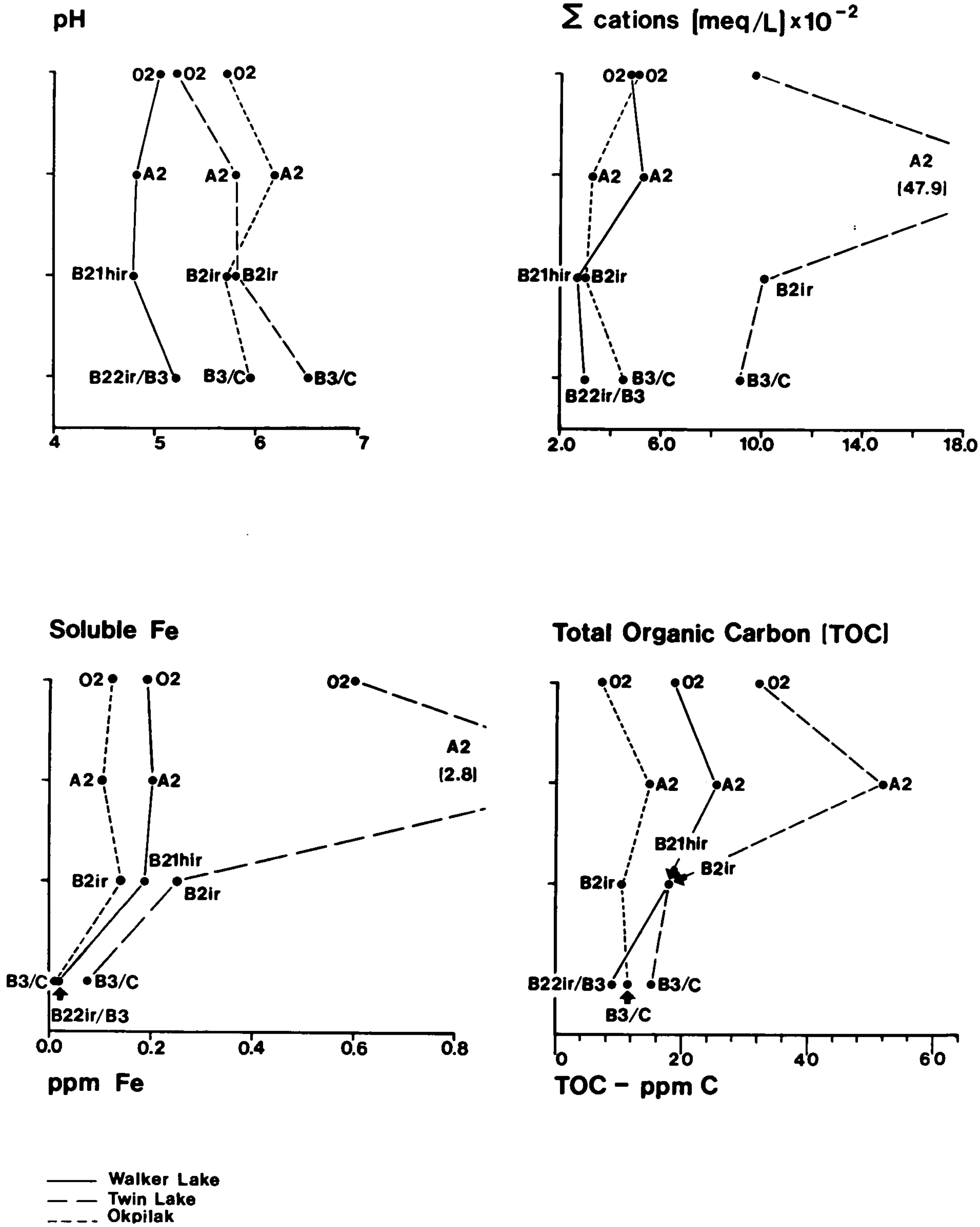

FIGURE 3. Selected soil solution parameters for Walker Lake, Twin Lakes, and Okpilak Lake lysimeter sites, Brooks Range, Alaska. Data points are values for solutions exiting the denoted horizon.

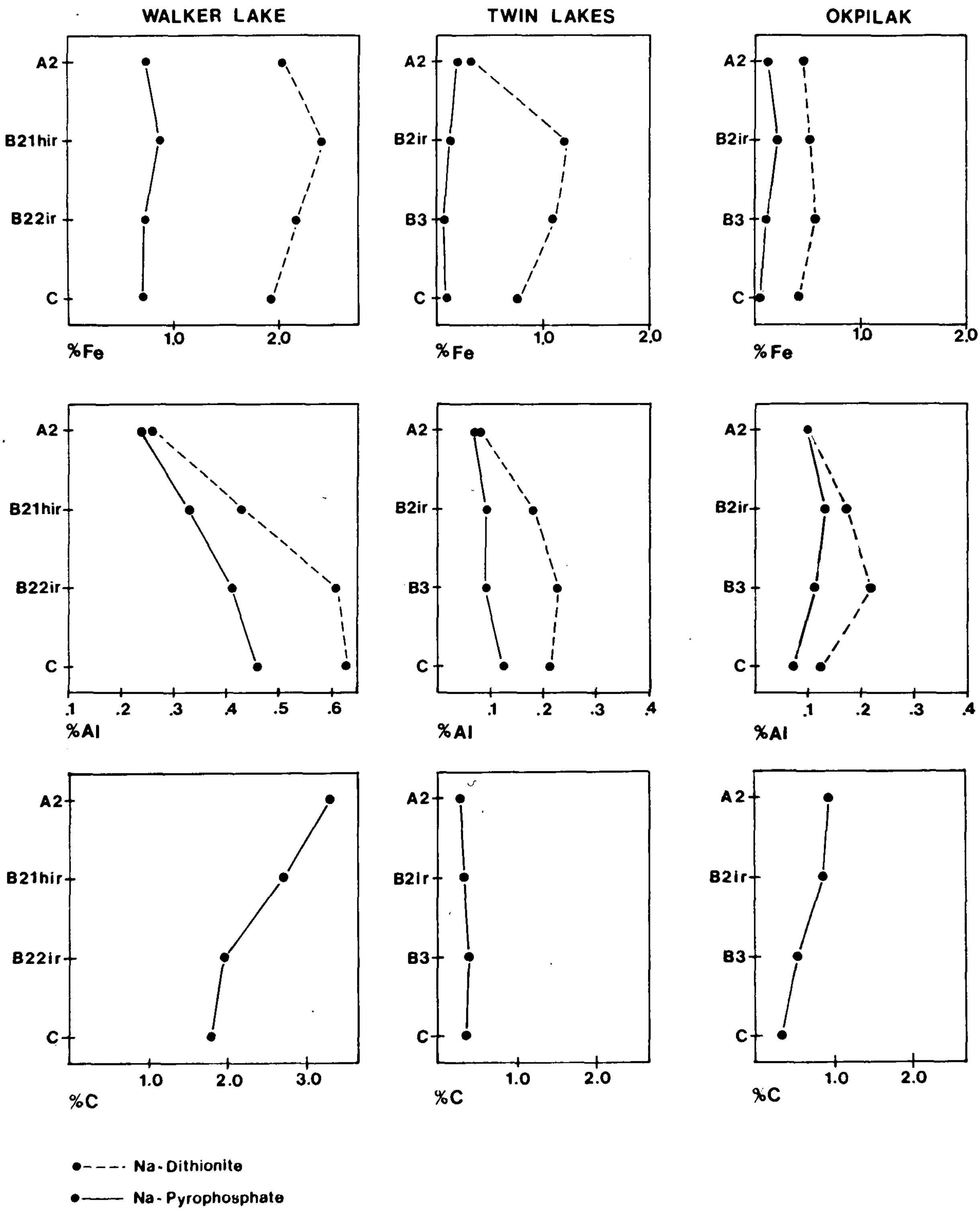

FIGURE 4. Dithionite and pyrophosphate extractable iron, aluminum, and carbon from Walker Lake, Twin Lakes, and Okpilak Lake lysimeter sites, Brooks Range, Alaska.

viously found in the temperate regions (Dawson *et al.* 1978), the B2ir horizon of the arctic Spodosol-like soils appears to be the most effective horizon for arresting organically bound iron.

The concentrations of soluble iron at Twin Lakes are high in the 02 and A2 horizons, but decrease considerably across the B2ir horizon. This distribution again seems to indicate a flushing effect due to the applied irrigation water.

Soluble iron in the tundra soil (Okpilak) is the lowest, suggesting slow release of iron by weathering and, consequently, low amounts available for translocation. The podzolization process is only weakly displayed.

Solid Phase Composition

Dithionite extractable iron (Fe_d) shows an accumulation in the B horizons at all sites (Figure 4 and *see* Table 2). The Walker Lake profile contains the largest percentage of extractable iron in the C horizon, the increase in the B horizons is intermediate between the other two sites. Pyrophosphate iron (Fe_p) shows slight enrichment in the B horizons of the Walker Lake and Okpilak profiles, but just a steady decrease with depth and generally low levels in the Twin Lakes profile. The lack of an Fe_p peak in the B horizons of the Twin Lakes profile is inconsistent with the levels of soluble iron recorded in the soil solution. This apparent discrepancy may relate to the dry conditions common to this site. Under these xeric conditions the organic-iron complexes which form at the surface are translocated at depth only sporadically when sufficient snow melting or heavy rainfall occurs. Irrigating this soil artificially induced such a flushing. Extended periods between natural translocation events may allow decomposition of the organic compounds in the B horizons and, thus, the conversion of organic-iron complexes into inorganic iron.

By comparing the percentages of Fe_p in the B horizons of Walker Lake and Okpilak it appears that the Fe_p is between four and six times higher at Walker Lake. By examining the concentrations of soluble iron in the soil solutions at these two sites it is also apparent that higher concentrations of iron are transmitted into the B horizons at Walker Lake than at Okpilak Lake. Further scrutiny of the soluble iron distribution of these two sites shows that the B21hir horizon at Walker Lake and the B2ir horizon at Okpilak are not very effective in arresting the movement of the percolating soluble iron at the translocation rates imposed by irrigation. The arrest of this metal occurs in the B22ir horizon of Walker Lake, but in the B3 horizon of the Okpilak site. The accumulation of soluble organic-iron complexes in a particular horizon depends on the presence of iron hydroxides already in that horizon (Dawson *et al.* 1978; Schnitzer 1969). Weathering of mafic minerals and the associated iron release proceeds more intensively in the soils of the boreal forest than in the tundra. Since, at the tundra site, mineral weathering and iron release is less intense, a thicker layer of soil is required for the arrest of the percolating soluble organic-iron complexes. In both boreal forest and tundra, there appears to be a downward growth of the B horizons, a process also observed in well-developed Spodosols of the Washington Cascades (Dawson *et al.* 1978).

In comparison to the C horizon, the horizon least affected by pedogenesis, the A2 and B21hir horizons at Walker Lake show losses of both dithionite and pyrophosphate extractable aluminum (Al_d, Al_p) presumably due to leaching (*see* Table 2 and Figure 4). At Twin Lakes the leaching seems to have affected the A2 and B2ir horizons to a lesser extent and at Okpilak Lake only the A2 horizon has been leached. At all three sites the aluminum in the A2 horizons is virtually all organically bound whereas in the C horizons approximately half is organically complexed. In the B horizons of Twin Lakes and Okpilak Lake almost half of the aluminum is organically complexed, but a much smaller fraction is organically complexed at Walker Lake. Because aluminum was not determined in the soil solution, comments cannot be made about current transfer of this element in the soil.

Pyrophosphate extractable carbon (C_p) represents the humified portion of the soil organic matter and, in part, the mobile carbon associated with the organo-metallic complexes responsible for podzolization. Both the Walker Lake and Okpilak profiles show uniform decreases in C_p with depth (*see* Table 2 and Figure 4). The Walker Lake horizons have considerably greater amounts of C_p than do those from Okpilak, reflecting the increased biomass and rate of decomposition of the boreal forest site. The high C_p values in the A2 horizons probably result from carbon physically mixed in from the directly overlying A1 horizons. High values of readily oxidizable carbon in Walker Lake A2 horizons have been reported previously (Ugolini *et al.* 1981). The uniformly low amounts of C_p in all horizons at Twin Lakes support the contention that leaching occurs only sporadically, allowing sufficient time between flushings for degradation of the translocated organic material. Pyrophosphate extractable carbon from B and C horizons of all three sites generally follows the trends observed for pyrophosphate iron. The ratio of Fe_p to C_p for a given horizon indicates the relative amount of iron associated with the organo-metallic complexes (*see* Table 2). Both the Okpilak Lake and Twin Lakes sites have higher Fe_p/C_p ratios than does the Walker Lake site. The lower Fe_p/C_p ratio at Walker Lake may result from either an excess of organic compounds from greater biomass and decomposition at this southern site or from the low availability of Fe for translocation.

Additional information on the genesis of these soils can be obtained by comparing the organic carbon determined by wet oxidation (C) (Allison *et al.* 1965) and the pyrophosphate extractable carbon (C_p). At Walker Lake the larger values of C over C_p (*see* Table 2) indicate more-abundant dead and living biomass relative to humic substances than at Twin lakes and Okpilak Lake. At these two sites, except at the surface, the carbon in the soil is mostly made of humic substances extractable by pyrophosphate. This suggests either a low supply of fresh organic matter to these soils, implying sporadic growth followed by intervals of decomposition, or preferential translocation of mobile organic compounds from the surface. Although root concentrations (*see* Table 1) are estimates of below-ground biomass, they do not show systematic relationships to either the carbon fractions measured here (C, C_p) or to ratios of these fractions. It must be concluded that carbon in the living roots is not accurately measured by either of these procedures, since it is neither humified nor readily oxidizable. Furthermore, since the soil was sieved prior to analysis, root masses which did not pass the 2-mm mesh were excluded from these determinations.

Summary

At Walker Lake, the southern site, the climate is milder and wetter, larger amounts of biomass are present, and it is inferred that the rate of decomposition must be higher than at the other two sites. Spodosol-like morphology is displayed, and both the conventional and soil solution analyses indicate that the process of podzolization has occurred and is currently occurring.

At Twin Lakes, located in a more continental climate and at a xeric site, Spodosol-like morphology is displayed, but the conventional analyses indicate extremely low levels of organically bound iron in the B horizon. However, soil solution compositions show translocation of large amounts of mobile organic compounds and iron into the B horizons under irrigation, indicating that iron complexing occurs, but there is probably insufficient water under most natural conditions to move these compounds through the profile. The translocation may be intermittent and the process of podzolization may occur sporadically in wet years, followed by intervals of inactivity during which degradation of the translocated organic compounds could occur.

The Okpilak Lake site is the northernmost of the three on the transect. It is colder than the other sites, but probably not as dry as the Twin Lakes site; biomass is slight and production of mobile organic compounds is low due to the reduced rate of decomposition. Spodosol-like morphology is displayed and the conventional analyses indicate that the process of podzolization has occurred. The soil solution composition indicates low levels of soluble iron and organic compounds suggesting that a low-intensity podzolization could presently occur, provided input of sufficient precipitation.

Rates of Pedogenesis

In addition to an understanding of current processes active within soil profiles, soil solution analysis provides an opportunity to estimate rates of soil development in the Arctic. At Okpilak Lake, for example, by determining the amount of iron translocated annually into the B horizons, it can be determined whether or not the process has occurred at modern intensities since deglaciation about 12,000 years ago.

Assuming an hypothetical soil column with a cross-sectional area of 1 cm^2 and a depth of 18 cm corresponding to the combined thickness of B2ir and B3 horizons, the soil column measures 18 cm^3 volume. The concentration of soluble iron entering these B horizons is 0.10 ppm, while the concentration leaving the B horizons is 0.01 ppm (*see* Table 2). This leaves 0.09 ppm in the soil column, so that 0.09 ppm represents 2.7×10^{-6} g of iron remaining in the B horizons. Assuming that the amount of applied water, 30 cm, has dissolved the entire quantity of iron available to be moved annually into the B horizons, then 2.7×10^{-6} g represents the annual iron added to the B horizons. Over a 12,000-year period this results in a predicted value of 3.2×10^{-2} g of iron accumulated in the B horizons of the Okpilak Lake profile.

The actual amount of organically complexed iron, determined as pyrophosphate extractable iron, is 0.22 per cent for the B2ir and 0.12 per cent for the B3 (*see* Table 2). Assuming a bulk density of 1.4 g/cm^3, this results in 4.14×10^{-2} g of iron in 18 cm^3 of the B horizons. This value compares favourably with that predicted, 3.2×10^{-2} g, the discrepancy is due in part to artificial conditions imposed by irrigation or to organically complexed iron formed *in situ* in the B horizons. It must be mentioned, however, that the Okpilak site received in 1978, in addition to 30 cm of irrigation water, the natural precipitation falling at the site from January to July. The combined inputs could easily have doubled the mean annual precipitation.

Conclusions

This study indicates the existence of latitudinal pedogenic gradients which are related to climate, biomass productivity and decomposition, and mineral weathering. The initial analysis of *in situ* soil solutions gathered under irrigation by tension lysimeters suggests the contemporaneity of the soil processes and morphology. In addition the use of lysimetry is conducive to quantification of rates of soil development.

It appears from this study that modern pedogenic processes in well-drained arctic tundra soils, even if occurring weakly and sporadically, may be responsible for the genesis of Spodosol-like soils beyond the present limit of trees. There is less reason to question the genetic authenticity of such soils, as has been the case in the past (Brown and Tedrow 1964). Further studies using natural solutions will answer this long-standing question conclusively.

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