Calcium carbonate precipitation–dissolution along a forest primary successional sequence on the Tanana River floodplain, interior Alaska

G.M. MARION
U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory,
72 Lyme Road, Hanover, NH 03755, U.S.A.

K. VAN CLEVE
Forest Soils Laboratory, University of Alaska Fairbanks,
Fairbanks, AK 99775, U.S.A.

AND

C.T. DYRNES
USDA Forest Service, Institute of Northern Forestry, 308 Tanana Drive,
Fairbanks, AK 99775, U.S.A.


Calcereous (alkaline) soils exist along the river floodplains of interior Alaska. In calcereous soils, the balance of CaCO₃ reflects net system acidification–alkalinization. The objectives of this study were to determine the origin of the CaCO₃, quantify CaCO₃ precipitation–dissolution, and quantify net system acidification–alkalinization along a forest primary successional sequence (250 years) on the Tanana River floodplain of interior Alaska. The CaCO₃ concentrations in the initial soil profiles were positively correlated ($r^2 = 0.883$) with silt concentrations. Differences in CaCO₃ concentrations in the early soil profiles/cores of similar age, between forest successional stages, and among soil horizons within a profile are primarily due to differences in silt concentrations, which are controlled by the alluvial deposition process. There is a curvilinear decrease in CaCO₃ content along the forest successional sequence, suggesting that the CaCO₃ originated with the alluvial material and was not formed in situ. The loss of CaCO₃ was equivalent to a loss of acid-neutralizing capacity of 10.6 keq·ha⁻¹·year⁻¹, which is a high rate of soil acidification. These forested, relatively pristine ecosystems are dominated by internal sources of acidity.


On retrouve des sols calcereux (alkalins) dans les zones inondées des berges des rivières situées dans la partie intérieure de l'Alaska. Dans les sols calcereux, le niveau de CaCO₃ indique si un système s'acidifie ou s'alkalinise. Les objectifs de cette étude consistaient à identifier l’origine du CaCO₃, à quantifier la réaction de précipitation et de dissolution du CaCO₃ et à déterminer quantitativement si le système s’acidifie ou s’alkalinise, le long d’une séquence successielle primaire (250 ans), dans une forêt située dans une zone inondée de la rivière Tanana dans la partie intérieure de l’Alaska. La concentration de CaCO₃ dans les profils du sol d’origine était positivement corrélée ($r^2 = 0.883$) avec la concentration de limon. Les différences dans la concentration de CaCO₃ dans les profils du sol d’origine entre des stades d’âge semblables, entre les étapes de succession de la forêt et entre les horizons dans un même profil de sol sont principalement dues aux différences dans la concentration de limon qui est contrôlée par les processus de dépôt des alluvions. Il y avait une diminution curviligne du contenu en CaCO₃ en fonction de la séquence successielle; ce qui suggère que le CaCO₃ a été apporté par les alluvions plutôt que d’avoir été formé in situ. La perte de CaCO₃ équivalait à une perte de capacité de neutralisation d’acide de 10.6 keq·ha⁻¹·an⁻¹, ce qui constitue un taux élevé d’acidification du sol. Les sources internes d’acidité dominent dans ces écosystèmes relativement intacts, occupés par la forêt.

Introduction

Calcereous (alkaline) soils exist under forest vegetation along the river floodplains of interior Alaska (Wilde and Krause 1966; Krause and Wilde 1966; Rieger et al. 1979; Van Cleve and Vierreck 1981; Marion et al. 1991; Marion et al. 1993, this issue). Generally forest vegetation is associated with environments where precipitation exceeds evapotranspiration and soils are acidic (Jenny 1980; Birkeland 1984). The occurrence of alkaline soils in areas of forest vegetation in Alaska is one of many paradoxes produced by the subarctic environment (Wilde and Krause 1960; Krause and Wilde 1966). Only recently have efforts been made to ascertain either the origin of the CaCO₃ or processes controlling the precipitation–dissolution of CaCO₃ in these forested ecosystems (Marion et al. 1991; Marion et al. 1993, this issue).

The net system balance of CaCO₃ within these forested ecosystems is an indicator of soil acidification–alkalinization processes. The recent worldwide attention on acid rain has led to considerable work on both anthropogenic and natural sources and sinks for H⁺ (Ulrich 1980; Van Bremen et al. 1984; Van Miegroet and Cole 1985; Ulrich and Matzner 1986; Binkley and Richter 1987). Because H⁺ reacts readily and stoichiometrically with CaCO₃, mineral weathering rates are easily assessed in calcereous soils (Van Bremen and Protz 1988); and since mineral weathering is the dominant sink for H⁺ (Van Bremen et al. 1984), the rate of CaCO₃ removal should reflect net ecosystem acidification.

The objectives of this study were to (i) determine the origin of the CaCO₃ (geologic or pedogenic), (ii) quantify CaCO₃ precipitation–dissolution, and (iii) quantify net system acidification–alkalinization along a forest primary successional sequence (250 years) on the Tanana River floodplain of interior Alaska.
The research site

The research site was in interior Alaska along the Tanana River near Fairbanks (Van Cleve et al. 1993, this issue). The mean annual temperature, precipitation, and potential evapotranspiration for Fairbanks are -3.4°C (Muller 1982), 285 mm, and 473 mm (Slaughter and Viereck 1986), respectively. The soil parent material (Holocene in age, Beikman 1980) is glacial-outwash alluvium consisting primarily of sand- and silt-sized particles (Rieger et al. 1963). This alluvial material has been reworked through alternating periods of deposition and erosion along the Tanana River and always contains CaCO₃ (calcite) and sometimes CaSO₄ (gypsum) at the beginning of the primary successional sequence (Marion et al. 1993, this issue). The soils are classified as Typic Cryorthods (Rieger et al. 1979).

Two replicate research plots were located in four stages of plant succession; these eight plots are the "intensive" sites where most of the work associated with the Salt Crust Project was done (Van Cleve et al. 1993, this issue). The stages sampled were stage I (bare alluvium), stage II (open willow), stage V (poplar-alder), and stage VIII (white spruce). The stage III stands are dominated by Salix spp. and Equisetum spp., the stage V stands are dominated by balsam poplar (Populus balsamifera L.) and thimble alder (Alnus tenuifolia Nutt.), and the stage VIII stands are dominated by white spruce (Picea glauca (Moench) Voss) (Viereck et al. 1993, this issue). Three plots in stages I, III, and V were near the gravel pit on the Bonanza Creek Experimental Forest and are located on sites I-A, III-A, and V-A, respectively; three plots in stages I, III, and V were on Sam Charley Island and are located on sites I-B, III-B, and V-B, respectively; and the two stage VIII plots were located along Sevenmile Slough and are located on sites VIII-B and VIII-D. All plots sampled for this paper were from undisturbed areas. The approximate ages (years) of these stands at the time of field sampling, based on tree ring counts, were as follows: I-A = 0, I-B = 0, III-A = 4, III-B = 4, V-A = 33, V-B = 29, VIII-A = 170, and VIII-D = 250.

In addition to the eight intensive plots, supplemental data from 16 previously sampled "extensive" plots along the Tanana River will be used to help characterize the successional sequence. These 16 extensive plots included sites from stage I (1), stage IV (1), stage V (3), stage VI (2), stage VII (5), and stage VIII (4). The dominant vegetation in the stage I, V, and VIII stands was described previously. The stage IV plot is a closed alder stand; stage VI plots are poplar–spruce–alder stands; and stage VIII plots are dominated by poplar–spruce. For a complete description of the vegetation and soils along this successional sequence, refer to Viereck et al. (1993, this issue).

Methods and materials

Field sampling

Within each of the eight intensive plots, five randomly selected soil pits were dug, described, and sampled by soil horizons. The sampling intensity in the 16 extensive plots was two soil pits per plot. A total of 72 soil pits were excavated, representing 24 different stands. Among the field properties measured for all soil horizons were horizon thickness and bulk density.

Laboratory analyses

Chemical analyses were done on air-dried soil samples and reported on an ovendried (at 105°C) soil basis. Calcium carbonate concentration was measured with a manometric method (Nelson 1982). Soil texture (sand, silt, and clay) was measured using the hydrometer method (Day 1965).

The CaCO₃ contents

The CaCO₃ contents (kg/m²) of the soil profiles were estimated with the equation

\[ \text{CaCO}_3 \text{ content} = \Sigma C \cdot BD \cdot 0.1D \]

where \( C \) is the CaCO₃ concentration (%), BD is the bulk density (g/cm³), and D is the soil depth interval (cm). The summations are to a standard depth of 60 cm.

Results

Calcium carbonate concentrations and contents

The initial patterns of CaCO₃ concentration (stages I and III) show considerable variation, especially between the A and B plots (Fig. 1). Since these early stages (0–4 years) have not been exposed long enough for current pedogenic processes to have significantly altered the profiles, their patterns of CaCO₃ concentration are largely influenced by the depositional process.

Both stages V and VIII show patterns suggesting the influence of pedogenic processes. The stage V profiles indicate that CaCO₃ is being preferentially removed from the surface soil (Fig. 1). The stage VIII profiles suggest a general loss of CaCO₃ throughout the soil profile. Interestingly, the stage VIII profiles show a zone of moderately high CaCO₃ in the surface horizon (Fig. 1); this surface zone of CaCO₃ accumulation is believed to be due to the 1967 flood, which deposited new calcareous alluvium on these sites.

There was a high correlation between CaCO₃ and silt concentrations in the early stages (Fig. 2). Apparently, the CaCO₃ is primarily associated with the silt-sized fraction.

Ideally, we would like to evaluate how CaCO₃ content changes with succession. For this reason, it is necessary that the successional sequence be a chronosequence (a sequence of sites where all state factors other than time (i.e., climate, biota, topography, and parent material) are constant). It is clear that the stage I plots are fundamentally different from the older stages with respect to soil texture (Fig. 3). The nonvegetated stage I plots are predominantly sandy textured, whereas the older vegetated stages are predominantly silt textured. Given the strong correlation between CaCO₃ and silt concentrations (Fig. 2), it is not surprising that CaCO₃ contents in the stage I plots (0 years) are out of line with respect to the trends for the older stages (Fig. 4). Because of the differences in parent material (texture), the stage I plots are excluded from the chronosequence.

Discussion

The origin of the calcium carbonate

The ultimate source of the CaCO₃ in these ecosystems is either through weathering of carbonate rock (primary) or through pedogenic processes (secondary). The CaCO₃ contents declined exponentially over the successional sequence (Fig. 4), which suggests that the CaCO₃ is inherited with the alluvial material.

The ultimate source of the alluvium is glacial weathering from the Alaska Range of predominantly Paleozoic and (or) Precambrian metamorphic rocks such as schist, gneiss, and quartzite (Wahrhaftig 1965; Beikman 1980). In the Tanana–Kuskokwim lowland physiographic region, of which the Tanana River valley is a part, scattered low hills of granite, ultramafic rocks, and Precambrian schist rise above the glacial outwash; the Yukon–Tanana upland physiographic region is dominated by Precambrian schist and gneiss on its southern flank where it borders the Tanana River (Wahrhaftig 1965). There are no known major deposits of carbonate rock in the areas bordering the Tanana River valley. However, calcite is a minor, but pervasive, constituent of metamorphic rock types in the Alaska Range; in addition, localized calcite accumulations are often associated with active fault zones (M.A. Wiltsie, personal communication, 1989). So, a rock carbonate source exists in the Alaska Range.
In a recent paper, the stable C and O isotopes in CaCO₃ were used to evaluate pedogenic mechanisms for CaCO₃ precipitation in these soils (Marion et al. 1991). The stable isotope analyses showed that two pedogenic processes, namely surface evaporation of water and transpirational loss of water, altered the isotopic composition of soil CaCO₃ over the successional sequence. However, the lack of any variation in stable isotope composition with soil depth in the initial soil profiles (stage III) suggested that CaCO₃ was inherited with the alluvial material.

In another recent paper, a high correlation was found between total soluble salt content and average silt concentration in the early stages (I, III, and V) and a significant loss of soluble salts by the late stage VIII (Marion et al. 1993, this issue). These findings support the argument that soluble salts were inherited with the alluvial material.

The CaCO₃ contents (Fig. 4), stable isotopes (Marion et al. 1991), and soluble salts (Marion et al. 1993, this issue) suggest that CaCO₃ and soluble salts are primarily inherited with the alluvial material. The extent to which this alluvial material may have been altered from the primary rock source by pedogenic processes through alternating cycles of deposition and erosion along the Tanana River is unknown at present. Conceptually, the earlier cycles of soil development might be inferred from examining sites longitudinally upriver, with the current glacial outwash serving as the time-zero material for soil formation. This well-known principal of substituting space for time in constructing chronosequences (Jenny 1980) might resolve the unknowns concerning the development of soil CaCO₃ in the Tanana River floodplain of interior Alaska.

**Variation in CaCO₃ content**

There was considerable variation in CaCO₃ contents even among plots of similar age (Fig. 4). Most of the variation in the early stages is due to differences in the initial concentrations of silt (Fig. 3), which is highly correlated with CaCO₃ concentrations (Fig. 2). In turn, the silt concentration of the alluvial material is probably largely controlled by the position of the plot relative to the river and the magnitude of the flooding event. I-B, III-B, and V-B are on a point bar, which probably receives the direct force of the river during flooding,
whereas I-A, III-A, and V-A are along a quieter reach of the river (Van Cleve et al. 1993, this issue). The greater the force of the river during flooding, the coarser the texture will be of the particles that settle from suspension. The depositional history of a site by controlling silt concentrations and, subsequently, CaCO₃ concentrations can lead to significant differences, especially in the early stages, between sites (A versus B), between stages (I versus III, V, and VIII), and among soil horizons within a profile (Figs. 1-3). Studies dealing with ecosystem properties dependent on soil CaCO₃ content, such as soil acidification, must explicitly consider the significant variation in soil texture and CaCO₃ concentrations that exists in these floodplain soils.

**Soil acidification**

The rate of CaCO₃ dissolution (the slope) apparently declines with increasing age (Fig. 4). An average rate for the successional sequence can be ascertained by dividing the difference in CaCO₃ contents for the 4- and 250-year-old stands (12.34 kg/m²) by 246 years, which gives 0.0502 kg·m⁻²·year⁻¹. This rate is similar to rates of removal cited by Van Breemen and Proz (1988) for soil chronosequences weathering from CaCO₃ parent rock in the Hudson Bay and James Bay areas of Canada (0.024–0.050 kg·m⁻²·year⁻¹).

Van Breemen et al. (1984) have separated ecosystems into three classes based on rates of soil acidification: (i) low rates of soil acidification (<2.5 kequiv·ha⁻¹·year⁻¹), (ii) intermediate rates of soil acidification (2.5–7.5 kequiv·ha⁻¹·year⁻¹), and (iii) high rates of soil acidification (>7.5 kequiv·ha⁻¹·year⁻¹). The loss of CaCO₃ from the Tanana River ecosystems over time is equivalent to a loss of acid-neutralizing capacity of 10.0 kequiv·ha⁻¹·year⁻¹. This is a minimum estimate of the H⁺ flux through the ecosystem because other reactions, leaching, and deeper soil depths were not considered. The Tanana River floodplain ecosystems show a high rate of soil acidification typical of calcareous soils (Van Breemen et al. 1984).

The acidic input in precipitation in the study area was not measured; but if one assumes a precipitation pH of 5.0 and a mean annual precipitation of 285 mm (Slaughter and Vierreck 1986), then the calculated annual precipitation H⁺ input would be 0.03 kequiv·ha⁻¹·year⁻¹, which is insignificant relative to the minimum H⁺ flux through the ecosystem (10.0 kequiv·ha⁻¹·year⁻¹). The Tanana River ecosystems are clearly dominated by an internal source of acidity, which is probably mainly carbonic acid production in these calcareous, alkaline soils (Van Breemen et al. 1984).

The loss of CaCO₃ from these ecosystems over time offers the potential to accurately assess the role of various stages of plant succession on soil acidification processes. For example, alder is known to be a strong soil acidifier (Crocker and Major 1955; Van Miegroet and Cole 1985). Stage IV is dominated by alder (Vierreck et al. 1993, this issue). A judicious selection of research plots would allow one to assess the role of plant species and plant succession on soil acidification. Generally, mineral weathering is the dominant sink for H⁺ and the most difficult part of the H⁺ budget to quantify (Van Breemen et al. 1984; Binkley and Richter 1987). However, CaCO₃ reacts readily and stoichiometrically with H⁺, which greatly facilitates assessing the role of mineral weathering as a sink for H⁺ in calcareous soils. These CaCO₃-bearing soils of the Tanana River floodplain are essentially base-calibrated ecosystems, which offer a unique opportunity for examining processes of soil acidification under natural, relatively pristine conditions.

**Acknowledgements**

We thank Charles Black, Terry Griffin, Kesh Prasad, and Craig Turner for assistance with the field collections and laboratory analyses. We thank Milton A. Willse, Alaska Geological and Geophysical Survey, for providing information on the bedrock geology of the Alaska Range. We thank Dr. Helga Van Miegroet and an anonymous reviewer for constructive reviews of the final draft. This research was supported by the following National Science Foundation grants to the University of Alaska Fairbanks: BSR-8405269 dealing with salt-affected soils and BSR-8702629 supporting the taiga Long-Term Ecological Research program. The research was also supported by the USDA Forest Service Pacific Northwest Research Station, the McIntire-Stennis Forestry Research Program, the State of Alaska, and the University of Alaska Fairbanks Agriculture and Forestry Experiment Station.


