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Elemental and mineralogical changes in soils due to bioturbation along an earthworm invasion chronosequence in Northern Minnesota

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ABSTRACT

Minnesota forested soils have evolved without the presence of earthworms since the last glacial retreat. When exotic earthworms arrive, enhanced soil bioturbation often results in dramatic morphological and chemical changes in soils with negative implications for the forests' sustainability. However, the impacts of earthworm invasion on geochemical processes in soils are not well understood. This study attempts to quantify the role of earthworm invasion in mineral chemical weathering and nutrient dynamics along an earthworm invasion chronosequence in a sugar maple forest in Northern Minnesota. Depth and rates of soil mixing can be tracked with atmospherically derived short lived radioisotopes ^{210}Pb and ^{137}Cs. Their radioactivities increase in the lower A horizon at the expense of the peak activities near the soil surface, which indicate that soil mixing rate and its depth reach have been enhanced by earthworms. Enhanced soil mixing by earthworms is consistent with the ways that the vertical profiles of elemental and mineralogical compositions were affected by earthworm invasion. Biologically cycled Ca and P have peak concentrations near the soil surface prior to earthworm invasion. However, these peak abundances significantly declined in the earthworm invaded soils presumably due to enhanced soil mixing. It is clear that enhanced soil mixing due to earthworms also profoundly altered the vertical distribution of most mineral species within A horizons. Though the mechanisms are not clear yet, earthworm invasion appears to have contributed to net losses of clay mineral species and opal from the A horizons. As much as earthworms vertically relocated minerals and elements, they also intensify the contacts between organic matter and cations as shown in the increased amount of Ca and Fe in organically complexed and in exchangeable pools. With future studies on soil mixing rates and elemental leaching, this study will quantitatively and mechanically address the role of earthworms in geochemical evolution of soils and forests' nutrient dynamics.

1. Introduction

Since the last glacial retreat, the forests in Northern Minnesota have evolved without the presence of earthworms. Over the last century, however, earthworm invasion of the forests has been progressing due to the expansion of agriculture, use of earthworms for fishing bait, and logging activities. Earthworms have long been thought to be beneficial to agriculture, and thus most studies on the earthworms' impacts on soil processes have been conducted on agricultural soils, however, a number of studies show that earthworms' impacts on soils in previously earthworm free regions often negatively affect forest sustainability.

Here, preliminary results are shown for elemental and mineralogical compositions in soils and extraction chemistry along a 210 m long earthworm invasion chronosequence within a sugar maple forest located in Northern Minnesota. The most heavily invaded soils occur next to a road close to a popular fishing lake. All soil pits along the transect have an aeolian deposit over glacial till. Along the transect, the population dynamics of earthworm invasion had been documented in Hale (2004), and the population monitoring resumed in 2009. It has been shown that earthworm invasion occurs as different ecological groups of earthworms arrive at different stages of invasion. Each group exhibits a unique burrowing habit associated with different mixing depths. Anecic species, such as the night crawler, are deep burrowers, epi-anecic species are A horizon to deep burrowers, epi-endogeic are A horizon mixers, and endogeic species only dwell in the litter layer (Hale, 2007).

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The least invaded soils on the transect contain a thick litter layer (~6–9 cm) underlain by A, E, and Bt horizons. As the invasion intensity increases, the litter layer disappears because earthworms disperse the organic material into underlying mineral horizons. With increased earthworm activities, A horizons thicken, and an A /E horizon is formed. Prior to the earthworm invasion, the A horizons were made of structureless single grains to weak small granules. However, with the earthworm ingestion of soil materials and deposition of their castings, the materials become strongly aggregated.

The ultimate goal is to quantify how physical (e.g., soil mixing) and chemical (e.g., oxidation change) activities of the invading earthworms affect the rates of chemical weathering and nutrient dynamics in soils. Toward this goal, this abstract focuses on presenting basic geochemistry data on the vertical distributions of elemental and extraction chemistry and mineralogical compositions along the invasion gradient. The findings presented here will guide the ongoing research activities that focus on physical movement of minerals (^{210}Pb and optically stimulated luminescence) and the leaching rates of cations and anions (chemical composition of soil water collected from lysimeters).

2. Results

2.1. Short lived isotopes

Atmospherically derived ^{137}Cs and ^{210}Pb were used to determine the depth reach and intensity of earthworm-driven soil mixing. Because the short lived isotopes strongly bind to organic matter and clays, their activities are expected to be highest in the upper centimeters of the soil, which was confirmed at a least invaded soil pit. An earthworm invaded soil, however, shows significant vertical intrusion of the radioisotopes (Fig. 1), suggesting that organic matter and clays have been incorporated to deeper depths via mixing.

2.1.1. Elemental compositions

Depending on the initial depth profiles of the elemental concentrations, vertical homogenization by earthworm-driven soil mixing produced different effects. Biologically cycled Ca and P, which abruptly decrease in their concentrations with increasing soil depth in the pre-invaded soil, experienced the reduction in their concentrations near the soil surface due to earthworm-driven soil mixing. In contrast, shallow A horizons showed significant gains in the concentrations of other cations such as K, Na, Al and Fe (Fig. 2).

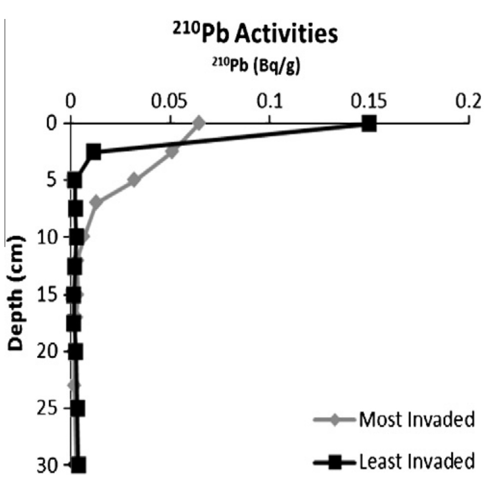

Fig. 1. ^{210}Pb activities in the soils prior to and post earthworm invasion. Note the vertical intrusion of ^{210}Pb in the earthworm invaded soil.

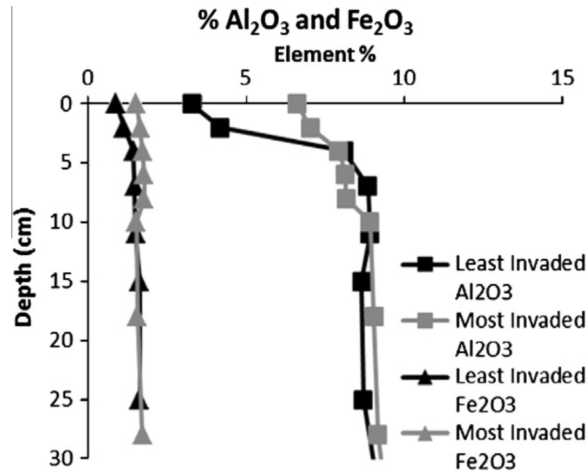

Fig. 2. Depth profiles of Al and Fe in the soils prior to and post earthworm invasion.

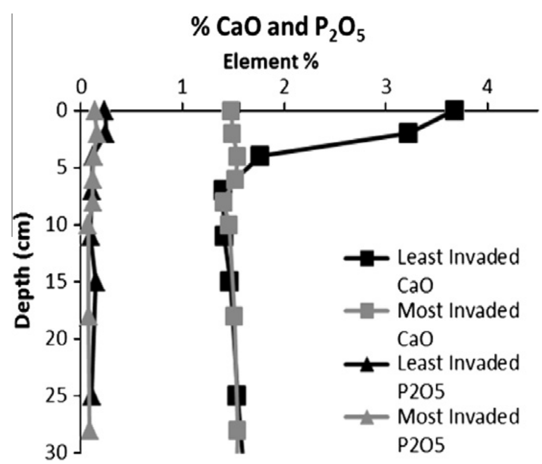

Fig. 3. Depth profiles of Ca and P in the soils prior to and post earthworm invasion.

The abundances of these elements had depth profiles that were the reverse of Ca and P (Fig. 3).

2.2. X-ray diffraction

In agreement with visual observation, XRD reveals the presence of calcite and dolomite in the C horizon made of glacial till (Fig. 4). Overlying the glacial till, the Bt and E horizons, despite their dramatically different morphology, share similar mineralogy. Up to 95% of the soil materials were explained by quartz, feldspars and plagioclase.

There are subtle differences in mineralogy that suggest the significant role of earthworm activities in modulating mineral weathering. Significant presence of the mineral opal was found only in the pre-invaded soil (Fig. 6). It also appears that the abundances of phyllosilicate clay minerals such as kaolinite and illite/smectite declined with the presence of earthworms (Fig. 7).

2.3. Extraction chemistry (Fe)

Dithionite and pyrophosphate extracts from 8 of 9 soil pits along the chronosequence were analyzed for Fe. Both the pedogenic crystalline form of Fe (dithionite extracts) and organically bound Fe (pyrophosphate) were greater in the earthworm invaded soil (Figs. 8 and 9).

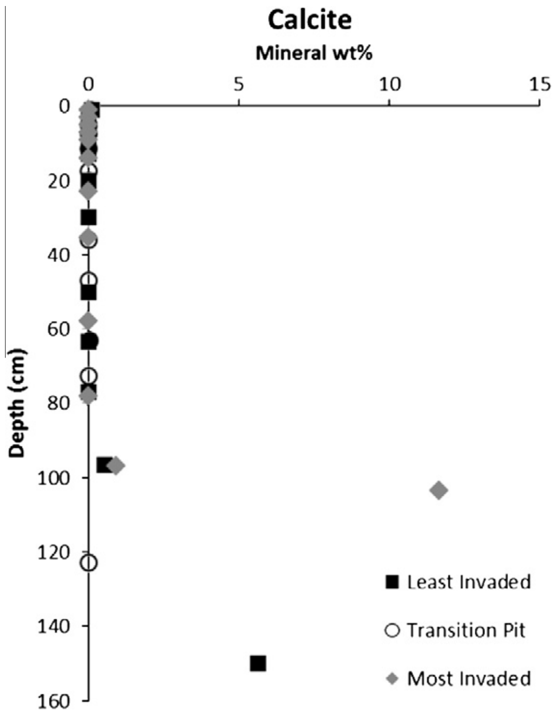

Fig. 4. Calcite depth profiles. No measurable amounts of calcite were found above the C horizons.

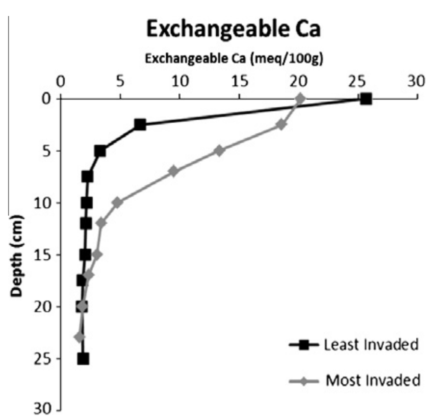

Fig. 5. Depth profiles of exchangeable Ca.

2.4. Exchangeable cations

Cation exchange capacity (CEC) is initially higher at the subsurface for the least invaded soils than in the invaded soils. With the earthworm invasion, CEC increases with depth compared to the least invaded. This trend is also seen in the exchangeable Ca data (Fig. 5).

3. Discussion

Overall, mineralogical and elemental compositions of the soils are remarkably consistent along the earthworm invasion chronosequence. This supports the basic assumption that the soils along the transect share virtually identical parent materials and soil minerals, and the only variable is the degree of earthworm invasion. Likewise, there is a strong vertical consistency in mineral compositions within the soils. This is particularly surprising because the

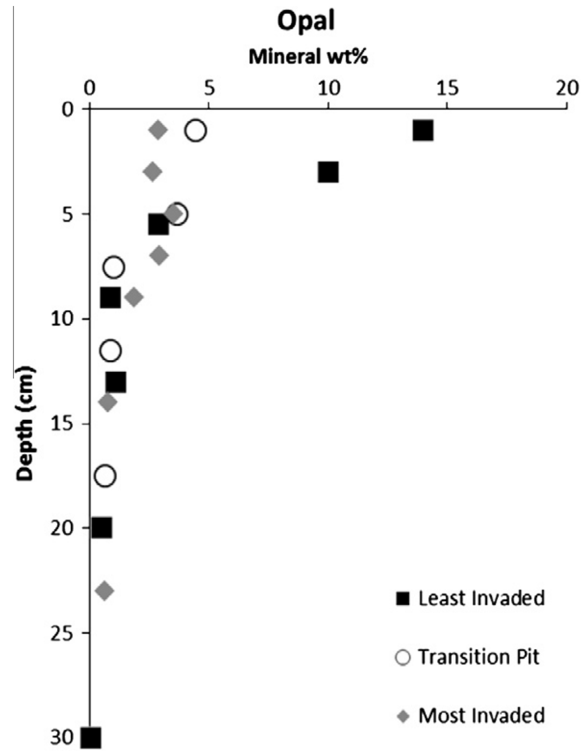

Fig. 6. Depth profiles of opal that is considered to have originated from phytoliths of sugar maple trees at the site.

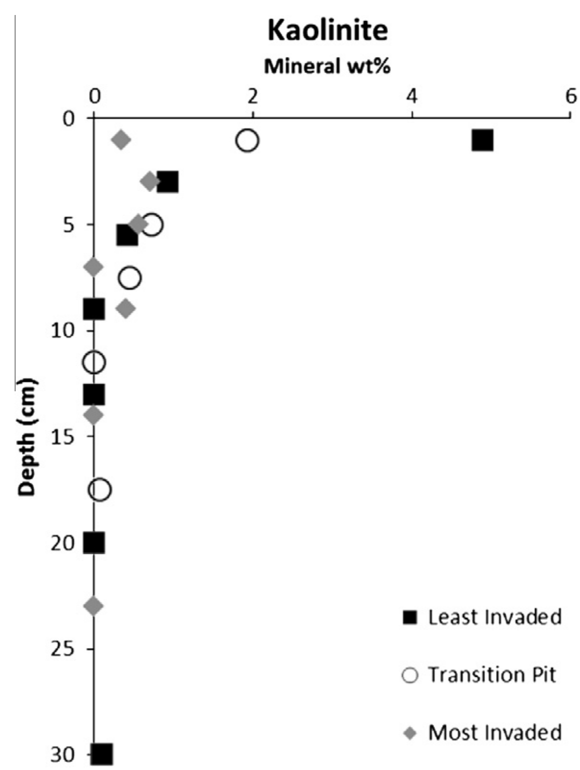

Fig. 7. Depth profiles of kaolinite concentrations.

silty homogeneous E horizon materials look very different from the underlying clay rich Bt horizon with strong pedogenic structure. This result suggests that the E horizons were derived from an aeolian deposit.

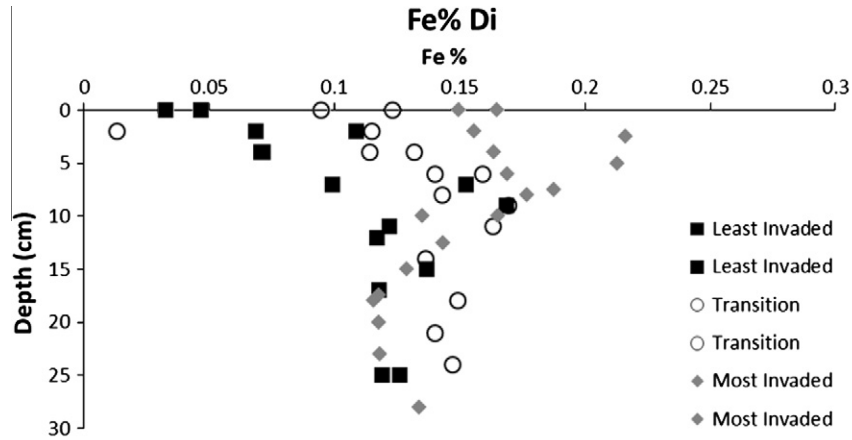

Fig. 8. Depth profiles of pedogenic crystalline Fe oxides.

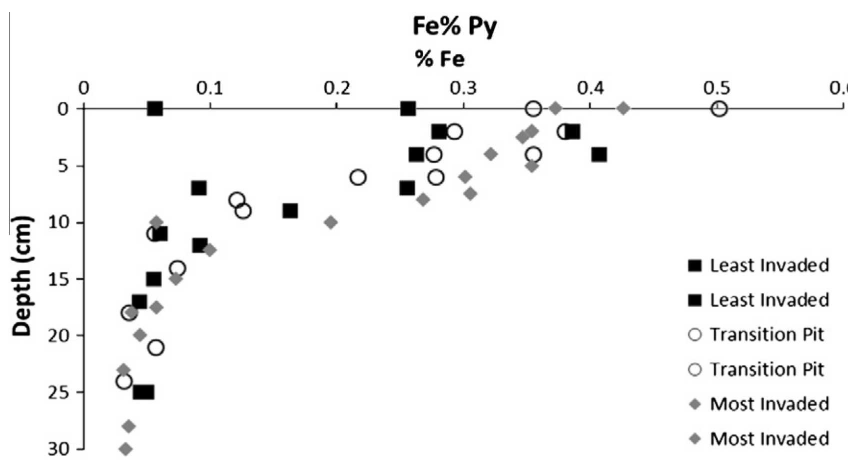

Fig. 9. Depth profiles of organically complexed Fe.

During study site visits there was concern about the fact that the depth to carbonate varies significantly from ~80 cm to over 150 cm along the transect. This concern was due to the possibility that deep burrowing anecic species may reach the deep soil zone and cause an added complexity due to the variation of the carbonate depths. However, XRD analysis, which is highly sensitive to calcite and dolomite, did not detect the carbonate minerals above the C horizons. This indicates that incorporation of C horizon materials into soils via deep burrowers does not occur along the transect.

The elemental chemistry data suggests that biological retention of Ca and P in the soil surface proceeds at rates significantly slower than soil mixing by earthworms, which exemplifies the capacity of earthworms to disrupt nutrient cycles in the forest. However, probably reflecting the intense contacts between Ca ions and organic matter within earthworms' intestines, the sizes of exchangeable and organically complexed Ca pools were greater in the earthworm invaded soils. An increase in the organically bound Ca and Fe pools may contribute to C stability. From a pedogenic perspective, secondary Fe oxides may inhibit mineral dissolution by coating the reactive surface, therefore, interfering with weathering processes.

It also appears that the combination of sugar maple and earthworm invasion may have significant impacts on the forest's silicon cycle. It is likely that the opal in the soil is from phytoliths of sugar maples which are dominant tree species at the site. Phytoliths are plant bodies, most commonly siliceous, and are found in the leaves of sugar maples. In the invaded soil, the opal contents were significantly lower, despite the likely presence of excess phytoliths as the litter layers were introduced into the A horizons. Whether the earthworm activities contributed to the dissolution of opal remains to be tested with detailed soil water chemistry data.

4. Conclusions and future work

This study confirms the major assumptions in the chronosequence approach. Because the solid state chemistry reveals the cumulative effects of earthworm invasion on soil geochemistry over the last several years to decades, they are highly informative in setting priorities in the next efforts. The data suggests that earthworm activities can affect mineral weathering through two major pathways. First, their burrowing activities physically relocated minerals and elements, thus exposing them to altered geochemical environments. Such physical relocation of elements and minerals are clear throughout the data. Second, more intimate contacts between cations, minerals, and organic matter, which occur within earthworms' intestines, appear to affect the exchangeable and organically bound pools of cations.

To constrain the physical relocation of minerals and elements, detailed measurements of ^{210}Pb activities will be conducted. In addition, major cations and anions will be determined in soil water collected from the already installed lysimeters along the transect. This will allow connecting the soil mixing with mineral dissolution/leaching. In parallel, organic C analysis will be made in conjunction with cations and minerals that are associated with them. Such integration will allow prediction of the impacts of exotic earthworms on the biogeochemistry of hardwood ecosystems in Northern Minnesota.

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