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Carbon–mineral interactions along an earthworm invasion gradient at a Sugar Maple Forest in Northern Minnesota

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ABSTRACT

The interactions of organic matter and minerals contribute to the capacity of soils to store C. Such interactions may be controlled by the processes that determine the availability of organic matter and minerals, and their physical contacts. One of these processes is bioturbation, and earthworms are the best known organisms that physically mix soils. Earthworms are not native species to areas previously glaciated, and the introduction of earthworms to these regions has been associated with often dramatic changes in soil structure and geochemical cycles. The authors are studying C mineral interaction along an approximately 200 m long earthworm invasion transect in a hardwood forest in northern Minnesota. This transect extends from the soils where earthworms are absent to soils that have been invaded by earthworms for nearly 30–40 years. Pre-invaded soils have an approximately 5 cm thick litter layer, thin (~5 cm) A horizon, silt rich E horizon, and clay-rich Bt horizons. The A and E horizons formed from aeolian deposits, while the clay-rich Bt horizons probably developed from underlying glacial till. With the advent of earthworm invasion, the litter layer disappears and the A horizons thicken at the expense of the O and E horizons. In addition, organic C contents in the A horizons significantly increase with the arrival of earthworms. Simultaneously, measured mineral specific surface areas suggest that minerals' capacities to complex the organic matter appear to be greater in soils with active earthworm populations. Based on the data from two end member soils along the transect, mineral specific surface areas in the A and E horizons are larger in the earthworm invaded soil than in the pre-invasion soil. Additionally, within < 5 a of earthworm invasions, A horizon materials are turned from single grain to a strong medium granular structure. While A horizon organic matter content and organic C-mineral complexation increase after earthworm invasion, they are also more vigorously mixed. This growing data set, when ultimately combined with ongoing measurements of (1) the population dynamics of earthworms along the invasion transect, (2) C-mineral association (via surface adsorption and physical collusion in mineral aggregates) and (3) dissolved organic C will show how and how much soil capacity to store C is affected by burrowing organisms, which are often the keystone species of given ecosystems.

1. Introduction

Earthworms are not native to glaciated regions of North America, however, human activities, such as dumping of unused fishing bait and movement of soils containing earthworms or earthworm cocoons, have introduced exotic earthworm species to areas previously free of earthworms. Most notably, redistribution of leaf litter deep into the soils, which involves the reduction of O horizons while increasing A horizon thicknesses, has been associated with the invasion of exotic earthworms. Earthworms, based on their mixing behavior, are classified into several functional groups. Epigeic earthworm species live and feed in the litter layer and are typically found in surface litter. Endogeic and anecic earthworm species both feed at the surface, ingesting the litter layer and organic-rich soils, but dwell within the mineral soil. Endogeic species live and burrow in the topsoil and anecic species live and burrow in deep soils (up to 2 m depth), creating permanent burrows. It is the burrowing of endogeic and anecic species that mix organic and mineral soil, thus relocating organic C.

In the absence of vertical mixing, leaf litter remains on the soil surface. Bioturbators, such as earthworms, may however translocate organic matter into deeper soil zones where the organic matter can interact with minerals. Likewise, physical vertical mixing may translocate clay minerals from the B horizons and allow

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contact with organic matter. When complexed onto minerals, organic C is better stabilized (Oades, 1988). Therefore, it is hypothesized that the advent of earthworm vertical soil mixing may lead to greater C mineral complexation and thus slower mineralization of organic matter.

Hardwood forests in the Great Lakes Region, when perturbed by exotic earthworms, have been shown to experience changes in soil structure and the storage and availability of nutrients. However, changes in C storage following earthworm invasions are not well understood. Earthworm ability to remove litter may result in a decline of total soil C. On the other hand, the expansion of the A horizon and formation of A/E horizon may compensate for the loss of C in the O horizon (Hale et al., 2005; Bohlen et al., 2004). Therefore, examining the effect of earthworms on the amount of C in litter layers and A horizons, the rate and depth of soil mixing, and the rate of C mineralization, will elucidate the overall rate of C loss/gain due to earthworm invasion in hardwood forests.

Taking advantage of a well-studied earthworm invasion chronosequence that stretches approximately 200 m (where the distance is measured from a heavily invaded location near a paved road) (Hale, 2004), the authors are exploring the relationship between earthworms, C storage in leaf litter and mineral soils, mineral specific surface area, and soil mixing rates.

2. Results

2.1. Earthworm biomass along the transect

The earthworm invasion forefront advanced significantly from the year 2009 to year 2010. In 2010, epigeic earthworms were found at 160 and 180 m, where no earthworms had been found in 2009. In 2009 the anecic species' forefront was found at the distance of 60 m while endogeic species' forefront was at 100 m. Both forefronts have migrated to 120 and 150 m, respectively. Earthworm biomass varies significantly but abruptly decreases at 130 m (Fig. 1).

2.2. Earthworm species compositions along the transect in the years 2009 and 2010

In 2009, the largest fraction of the total biomass was explained by anecic species (40%), followed closely by epi-anecic (23%) and epigeic (19%). Epi-endogeic species were responsible for only 6% of the total biomass. Such species composition largely persisted in the 2010 survey, with the exception of epi-anecic and endogeic which showed increases in their biomass (Fig. 2).

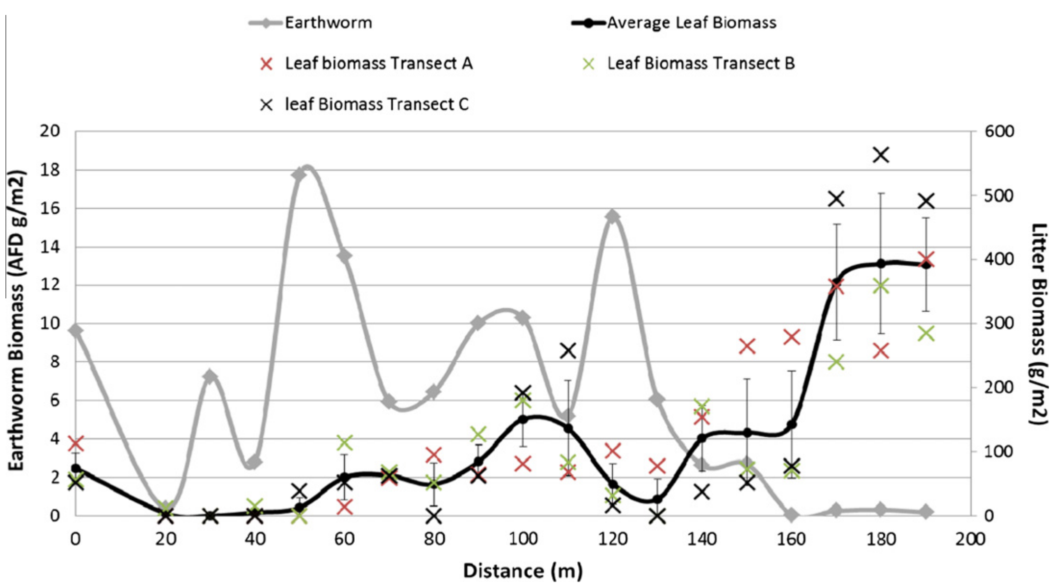

Fig. 1. Biomass of earthworms and leaf litter along an earthworm invasion transect. At 0 m soil is heavily invaded by earthworms and at 200 m earthworm populations are minimal. Litter samples were taken from three different invasion transects, while earthworms from transect B were identified. Significant increase of litter biomass at 160 m is associated with a decrease in earthworm biomass.

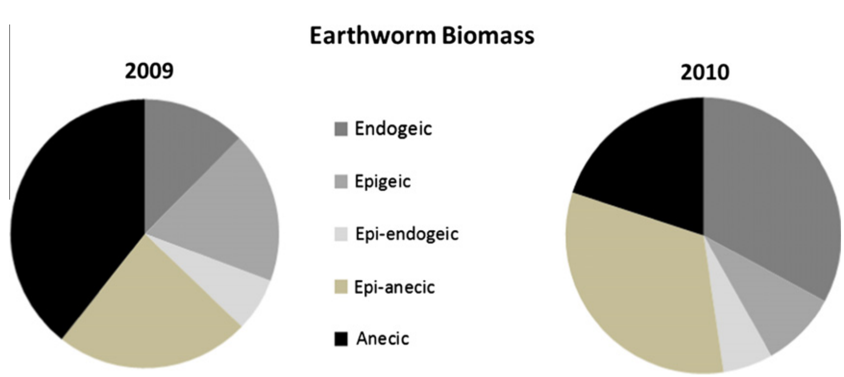

Fig. 2. Earthworm biomass by functional groups in the years 2009 and 2010.

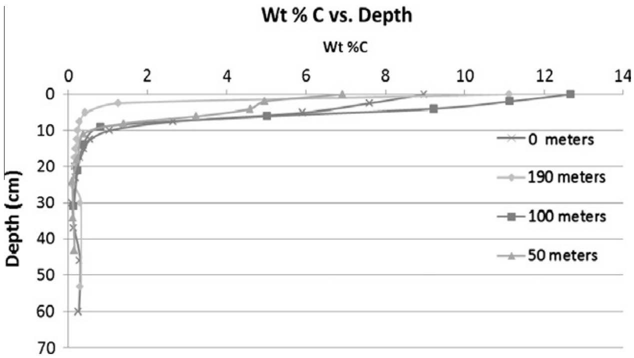

Fig. 3. Weight % C versus depth at four different pits along an earthworm invasion transect. At 0 m, the soil is heavily invaded by earthworms, while the earthworm population is minimal at 190 m. Soils with low earthworm biomass and high litter biomass are associated with a rapid decrease in % C with soil depth.

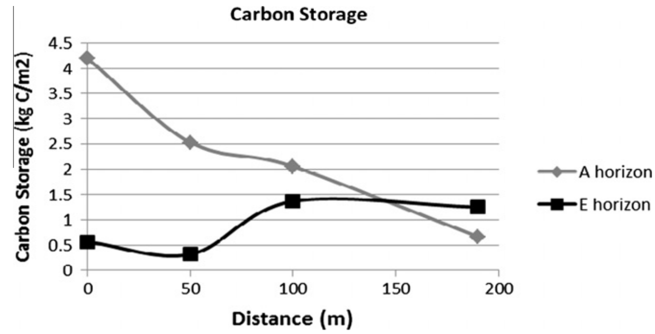

Fig. 4. Carbon Storage along an earthworm invasion transect. The longer the soil has been invaded by earthworms, the greater the C storage in the A horizon, which is partly compensated by the reduction of C storage in the E horizons.

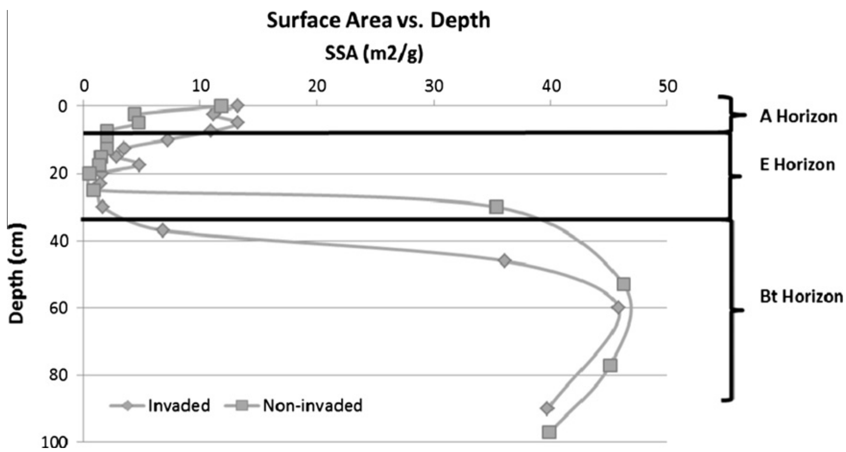

Fig. 5. Soil specific surface area versus depth along an earthworm invasion transect.

2.3. Litter layer biomass

Litter biomass, although varying slightly in the first 130 m, abruptly increases at 130 and 160 m (Fig. 1). An earthworm survey showed that the endogeic species invasion front was at 100 and 150 m in 2009 and 2010, respectively, suggesting that this group plays the most important role in reducing the litter layer.

2.4. Soil organic carbon contents and storage

Where high litter biomass is present, soil organic C content rapidly decreases with increasing depth (Fig. 3). In earthworm invaded soils, organic C contents decrease less dramatically with increasing depth than in the pre-invaded soils. Earthworm-invaded areas with higher organic content throughout the A horizon are associated with little or no litter biomass (Figs. 1 and 3). Lastly, C storage in the A horizon increases with the introduction of earthworms (Fig. 4).

2.5. Mineral specific surface areas

Mineral specific surface areas in the A horizons are greater in the earthworm invaded soil (0 m distance) than in the non-invaded soils (at 190 m) (Fig. 5), which is also true in the upper E horizon.

3. Discussion

Soils that have been heavily invaded by anecic and endogeic species have significantly lower litter biomass, but higher organic matter contents to depths of 12 cm where the A horizon thickens, and mixed zones of A and E horizons (A/E) appear. These data support the findings from other studies that earthworm invasions into pristine soils result in the incorporation of surface organic matter into the A horizon (Alban and Berry, 1994; Bohlen et al., 2004).

Earthworm activities increase mineral specific surface area in the organic matter rich A horizons. First, as earthworms travel between the A and Bt horizons, they may bring up clay minerals from the Bt horizon. The preliminary analysis of ^{210}Pb activities in the soil, however, suggests that earthworm burrowing activities in the Bt horizon may be minimal. Secondly, when minerals pass through earthworm intestines, they may be ground up and thus new mineral surface area is produced (Suzuki et al., 2003). Third, it was found that earthworm-worked soil materials have a greater amount of crystalline pedogenic Fe oxides (dithionite citrate extracted), which is known to have higher specific surface area.

Regardless of the mechanisms involved in mineral surface generation, the increase of mineral specific surface area in invaded soils may have increased organic matter complexation onto mineral surfaces. The next step is to understand (1) how earthworms affect mineral specific surface area and (2) how much of the increased organic matter in the earthworm affected A horizon is complexed with mineral surfaces.

4. Conclusions

While the data set continues to grow, early findings suggest that earthworms have great impacts on soil C storage in ecosystems that have developed free of native earthworms. The earthworm invasion in northern hardwood forests has led to changes in the location of organic C and mineral specific surface area within the soils, which may influence soil capacity to store C. Further investigation of organic C contents and surface area measurement from nine different soil pits along the invasion chronosequence will allow determination of the overall effects of earthworms on C-mineral complexation. Changes in the manner and intensity of mineral contact with organic matter along the invasion chronosequence will also be investigated, which will elucidate the long term ability of soils to store C.

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