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Effects of Exotic Earthworms on Northern Hardwood Forests in North America

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Introduction

There are 36 species of exotic earthworms reported in North America and 26 of them originate from Europe and the others from Asia (Reynolds, 1995). The first introduction of the former occurred during the late 19th and early 20th centuries, when many European plants were imported. These plants likely contained earthworms or earthworm cocoons in the soil (Minnesota Worm Watch, 2002-2003). More recent introductions of various earthworm species were distributed from fishing activities, as they were used as bait. Many earthworms were released into lakes and rivers and found their way to their favorable habitats (Minnesota Worm Watch).

"Worms chomp and churn leaf litter so rapidly that soil life is altered, nutrient cycling is changed and erosion becomes a problem," said Cindy Hale, a researcher at the University of Minnesota, Department of Forest Resources (U of M Extension Service News, 2003). The degradation of the Northern hardwood forest floor ecosystems caused by earthworms is of great concern to conservation and restoration scientists; however, developing strategies to counteract this invasion have been very difficult because their activity is primarily belowground. As the physical and chemical composition of the soil surface is altered by earthworms, the diversity and composition of herbaceous ground plane vegetation is impacted. (Interview with A Holdsworth, 2003). Declines in diversity and abundance of forest herbaceous plants is likely due to multiple stressors, in addition to earthworms, such as over-predation by white tail deer, disease, inbreeding (Frelich et al. 1999), and soil disturbance (Burtelow et al. 1998; Lawrence et al. 2003; Xuiong et al. 2002; Gange, 1993). Issues of earthworm invasions in North American hardwood forest are complex and relate to types of the species, reproduction habits and life cycles of earthworms. Comparison of forest conditions and decomposition patterns with and without earthworms reveals the great consequences of the earthworm invasions. Therefore, this issue must be dealt with new techniques that enable to remove the earthworms and forest restoration techniques that allow rebuilding the forest floor ecosystems.

Ecosystem Changes After Earthworm Invasion

The regions that were once covered by Pleistocene glaciations developed various ecosystems without earthworms for approximately 10,000 years (Reynolds, 1995). Among these post-glaciation ecosystems, are Northern American deciduous forests which are dominated by broad-leaved, deciduous trees such as sugar maples (*Acer saccharum*), oaks (*Quercus spp.*) and basswoods (*Tilia americana*). These forests generally consist of different vertical layers of canopy, sub-canopy, saplings and ground plane. This vertical layering and species diversity are the most visible indicators of the forest health; however, less visible biological activity on and under the forest floor are much more complex and fundamental to the well-being of the forest ecosystem (Hendlix, 1995).

Since native earthworms were eradicated during glaciation, those forests without earthworms have adapted to conditions with slower decomposition processes and thicker and more nutrient rich organic soils than those recently invaded by exotic earthworms. Figure 1 shows forest floor profiles with and without earthworms. The forest floor without earthworms is covered with seedlings and other sedges, mosses and herbaceous plants. The forest floor with earthworms, on the other hand, has the least under-story plants and organic soils, leaving the mineral soils exposed. Thus, earthworms are known as "ecosystem engineers", disturbing the forest floor environments through their consumption of the soil organic matter. Their consumption habits are not only causing elimination of the organic matter, but they are also altering the decomposition characteristics, the nutrient cycles of the forest system affecting from under-story to over-story species growth (Burtelow et al. 1998; Lawrence et al. 2003; Xuiong et al. 2002; Gange, 1993), and the seed bank and germination availability (Frelich, 1995).

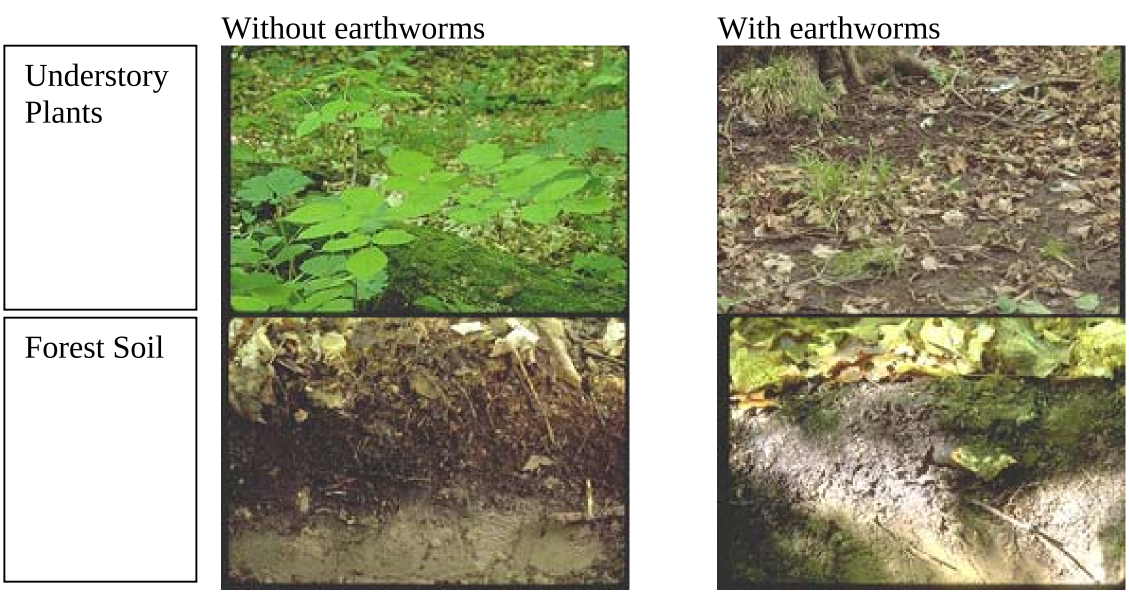

Figure 1: Photo Credits: University of Minnesota, Agricultural Experiment Station Minnesota Worm Watch <http://www.nrri.umn.edu/worms/>

Earthworms: Their Biology and Behavior

Among many exotic earthworm species present in North America, the species are generally categorized into three groups of epigeic, endogeic and anecic (Minnesota Worm Watch, 2002-2003; Clive, 1998). These species groups differ in their behaviors and the degree and type of potential impact on hardwood forests (MN Worm Watch, 2002-2003). Epigeic species are small reddish worms and about 2 to 7 cm in length. They live in the topsoil and consume decomposing litter and fungi. For example, *Lumbricus rubells* consumes the decaying organic matters quite rapidly causing the disappearance of the organic soil horizons. Endogeic species are whitish gray worms living in the soil or under logs. They consume organic matter inside of the soil and rarely come out to the surface. Thus, they lack red pigment used for camouflage. Anecic species are large reddish worms such as *Lumbricus terrestris* (night crawlers). They can grow up to 10 to 15 centimeters long and feed on fresh litter at the surface and burrow deep into the soil, sometimes reaching to 2 meters below the soil surface. Since activities of anecic species extend more vertically than the other species, they mix organic and mineral soils and aerate the soil. Their intensive consumption habits also cause exposure of inorganic soil, and the aerated soil causes a forest floor susceptible to erosion (Minnesota Worm Watch, 2002-2003). Since each type of the species affects the forest floor in different vertical layer, many of the northern American hardwood forests that contain combination of these three types of earthworms may have significant affects to the forest floor ecosystems.

Earthworms are typically hermaphrodites possessing both male and female reproductive organs, with few exceptions of species like *Dendrobaena octaedra* that can reproduce individually and spread faster than the others. Most earthworms require a mate of the same species to reproduce and trends of their population increase may relate to their habits of reproduction; general life spans of earthworms; rates of the annual fertility, juvenile survivals and migration; availabilities of the their predators (Clive, 1998). When clitellum changes color from pinkish to red-orange, two earthworms line up in a head to tail fashion and interchange sperm cells to be fertilized with the ova into the capsule, cocoons (Figure 2). One or more juvenile hatch per a cocoon and the incubation time greatly varies, depending upon soil temperature and seasonal variation of the soil moisture contents relates to delay in timing of the hatching (Clive, 1998).

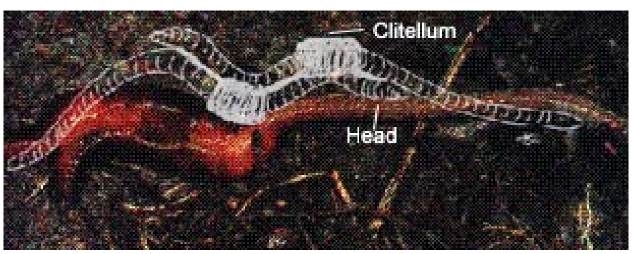

Figure 2. Mating of Earthworms (Graphic by Satoko Muratake).

Clive (1998) explains that the incubation time of the cocoons takes at least three months and it largely changes, depending on the temperature. Cocoons of some species like *Lumbricus castaneus* and *Aporrectodea caliginosa*, according to the Scotland field experiment, had capability to persist through the winter with 14 to 11 months of the incubation time (Clive, 1998). Relationships between soil moisture and the cocoons hatching timing are also introduced that species like *Aporrectodea longa* in New Zealand had their cocoons persisting the dry season even though the adults died down from the heat. When the season shifted to wet spring and autumn, hatching of these cocoons were observed (Clive, 1998). Therefore, cocoons of earthworms can tolerate various temperatures until soil moisture becomes right for their cocoons to hatch.

Life span of earthworms varies among by species (Figure 3). *Lumbricus terrestris*, for example, matures in about a year and can live for about seven years while the other species like *Aporrectodea caliginosa and A. longa* live for average 1.25 to 2.6 years. (Clive, 1998). Numbers of reproduction per year also varies, depending on species types. For example, anecic species like *Aporrectodea caliginosa*, *A. longa* and *Octolasion cyaneum* produced 3-13 cocoons per a year and epigeic species like A. chloratica produced 25 – 27 cocoons per a year, while species living near the surface like *Lumbricus rubellus* produced 42-106 cocoons per a year. Thus, the depth of their habitats relates to juvenile survival abilities affected by the temperature variations, moisture availability and predation (Clive, 1998).

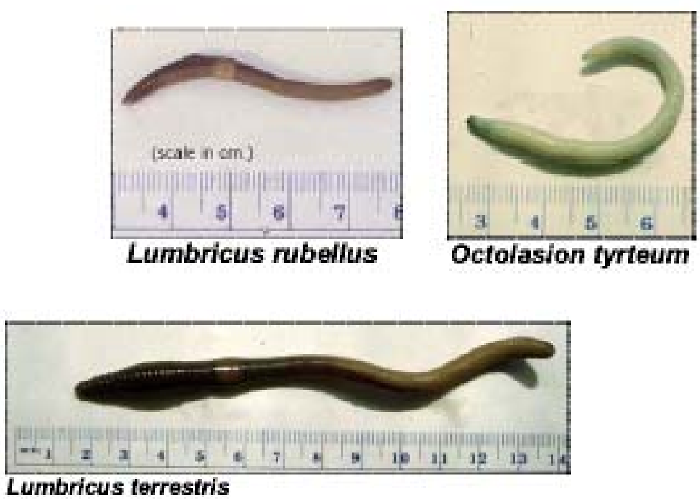

Fig. 3: Photo Credits: Cindy Hale from University of Minnesota, Extension Service <http://www.extension.umn.edu/yardandgarden/YGLNews/YGLN-

Predation of earthworms in the North American hardwood forests is not fully understood. For example, observations by Reynolds et al. (1977) reported that woodcocks in eastern North America might consume quantities of earthworms equal to their their own body weight per day (Reynolds et al. 1977). This predation pressure was not enough, however, to stress to limit the earthworm population. Earthworms are preyed on by mammals, as well as birds. Foxes in England (*Vulpes vulpes*), for example, detect sound of *Lumbricus terrestris* movements at night when they emerge to the surface. Once the presence of earthworms at the burrows is detected, a fox grasps earthworms its their mouth and carefully pulls its prey from the burrows. These techniques are taught to their cubs (Clive, 1998); thus regions with longer history of earthworm inhabitations may have established the prey-predator relationships comparing to North American hardwood forest ecosystems. Unknown relationships of earthworm predation reveal questions of whether populations of earthworms in the North American forests can be controlled by predation.

Decomposition

Recent studies indicate that earthworm activities accelerate decomposition processes and this phenomena leads to greater problems with the nutrient cycles. The faster rates of decomposition mean that organic nutrients are mineralized faster than the production of the organic matter and the plant uptake of those available nutrients. As a result, organic matter on the forest floor decreases and over-mineralized nutrients become susceptible to leaching. Thus, earthworm invasions alter the dynamics of the nutrient cycle within the hardwood forest ecosystem (Burtelow et al. 1998; Lawrence et al. 2003; Xuiong et al. 2002; Gange, 1993; Tomplin et al. 1995). Furthermore, many researchers are concerned that alteration of soil formation and function caused by earthworms may lead to greater problems such as: 1) limitation of phosphorus for some species like *Acer saccharum* (Lawrence et al. 2003); 2) loss of the nitrogen and carbon in the soil (Burtelow et al. 1998; Xuiong et al. 2002; Gange, 1993); and 3) degradation of biodiversity (Burtelow et al, 1998; Lawrence et al. 2003; Xuiong et al. 2002; Gange, 1993; Tomplin et al. 1995).

Cortez et al. (1997) compare decomposition characteristics without earthworms (microbiota decomposition) and with earthworms (lumbrico-microbiota decomposition) in order to explain differences in the soil formations (Cortez et al. 1997). He explains that "microbiota" decomposition processes such as in native North American hardwood forest soils fully depends on fungi and microbial activities and some meso-faunas like white tail deer. Microbial activity is sensitive to seasonal variation in temperature and moisture; overall litter decay rate is controlled by the climatic conditions but also by litter age. Since organic and inorganic soils are not highly mixed in forests, slowly mineralized nutrients are held within the organic matter and slowly released for plant uptake (Cortez et al. 1997).

However, decomposition processes in ecosystems with earthworms very much depend how they digest food. For instance, a study of Lawrence et al. (2003) who investigated impacts of earthworm invasion in North America sugar maple forest concluded that presence of earthworms in forest floor dominates the decomposition processes through organic matter consumption that cause loss of environments that mycorrhizal fungi inhabit (Lawrence et al. 2003). In order to explain how earthworms dominate the decomposition processes, Cortez et al. (1997) defines the decomposition processes in three stages; "the pre-oral stage", "the earthworm digestion stage" and "the post-anal stage" (Cortez et al. 1997).

"The pre-oral stage" occurs at a surface of the forest floor and is an initial break down of organic matter into sizes transportable through earthworms' burrows (an entrance of which the earthworms dig into the ground). Earthworms like *L. terrestris* consume and break down fresh litters like leaves and small twigs into small pieces. They push those pieces towards the burrow mouth and create temporal accumulations of the fresh litter pieces. At the same time, feces of the earthworms are mixed with organic matters, minerals and soil microbes producing casts and the casts are left behind around the burrow mouth. As a result, soil microbes increase their activities at the accumulated fresh litter pieces and the casts of earthworms (Cortez et al. 1997); therefore, soil microbes become more actives at the soil surface when earthworms are present in the forests. This phenomenon was also observed by Xuyong et al. (2002) who found that increase of soil microbe activities at the forest floor surface in response to the earthworm invasions (Xuyong et al. 2002).

After the initial break down of the organic matter at the surface, earthworms push those litter pieces into their burrows and further ingest and digest them. The digestion processes also accelerate decomposition rates because the guts of the earthworms contain high bacterial activities (Cortez et al. 1997). Through earthworms' diets, large quantity of organic matters is converted into inorganic forms causing huge loss of Carbon and Nitrogen *in situ* (Cortez et al. 1997). Similar findings are reported from experiments in the northern hardwood forests of New York state: readily mineralized carbon, microbial biomass carbon and nitrogen increases in relation to earthworm abundance, large carbon and nitrogen fluxes (Burterlow et al. 1998). The pH and moisture content of the soils can also be modified through the earthworm digestion (Cortez et al. 1997). The experiments of Burterlow et al. (1998), for instance, did not report soil moisture flux but increases of soil pH and denitrifying enzyme in the forest soil. As a result, the study raised potential concerns of increase in denitrification in the forest soil as a significant long-term consequences for the forests invaded by exotic earthworms (Burterlow et al. 1998).

When their feces are released and the casts are incorporated into the soil, microbial activities at the cast also increase and progress further decomposition of the organic matters. This further decomposition of the casts is called "post anal stage" (Cortez et al. 1997). The casts are distributed along the burrow attracting soil microbes. Soil microbes further break down the casts and produce more mineral nutrients either being used by plants or most likely being leached. Thus, the earthworms play significant roles of how organic matter is broken down and nutrient cycles change in the forest ecosystem.

What is Forest Restoration?

Rates of earthworm expansion are crucial to predict the future impacts and the restorative application. The rate of earthworm expansion is about five meters per year so their expansion is slow in the regional scale (Minnesota Worm Watch, 2002-2003). In the scale of a forest floor patch mosaic, however, it is questionable whether the rates of expansion is slow enough, since migrations of five meter can colonize a good size patch of the forest floor and may alter heterogeneity of the forest floor (Figure 4).

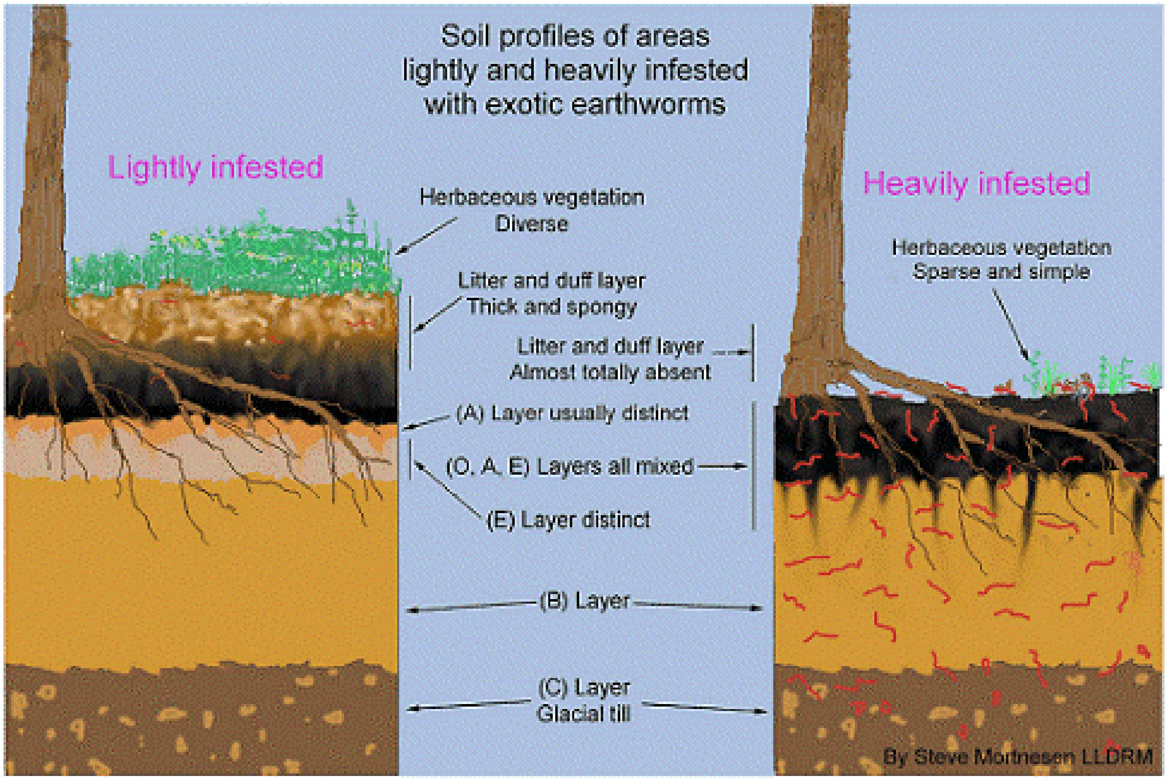

Fig. 4.: Diagram by Steve Mortensen. Minnesota Worm Watch
http://www.nrri.umn.edu/worms/

Among diverse fields of forest restoration, silvicultural treatments are the most common techniques, incorporating sustainable industrial alternatives such as mixed harvesting, thinning trees and establishing snags, logs and woody coarse materials. These silvicultural treatments can maintain similar structural characteristics of the mature hardwood forests, but the relationship of the mature forests to rare plant species have not been fully investigated (Hale et al. 1999). Frelich et al. (1999) also notes a misconception that the recolonization of under-story vegetation will occur with time as long as vertical layers and diversity of tree species are established (Frelich et al. 1999). Many under-story plants like herbs, mosses and sedges often require special microhabitats of light, moisture and nutrient availability (Frelich et al. 1999). If earthworms are the key species destroying the moisture and nutrient content of the forest soils, diversity of these plants will be endangered. In addition to the destruction of the microhabitats, if the seed bank or rootstock of rare species is destroyed, the native species will not be able to persist and will be locally extinct (Frelich et al. 1999).

The traditional approaches to establishing vertically diverse forest structure are still significant in terms of diversifying light availability and stimulating mature tree growth. However, more restorative methods are needed in order to establish heterogeneity of the forest floor (Frelich et al. 1999). Frelich et al. (1999) introduces an idea to mimic the patch mosaic and spatial patterns of natural vegetation in order to create variety of the special microhabitat patches for the under-story vegetation. Habitat requirements of native under-story species may vary depending on light requirements, growth rates and seed supplies. For example, some species mature more quickly and demand more light than others, while some other species are more shade tolerant but grow slower, and the rest may have limited seed supply. Thus, creating patches that satisfy these requirements is recommended in order to stimulate spreads of these species and diversify compositions of the forest floor (Frelich et al. 1999).

This approach to restore patches of the under-story vegetation makes great sense, because it is more cost efficient than large-scale plantings of under-story species and it also encourages heterogeneity of the forest floor. However, it must also be noted that problems with establishing and maintaining the organic soil required for the microhabitat still remains while earthworms are present at the site.

Challenges of removing earthworms from hardwood forest ecosystems

Currently, there is no effective method to control earthworm population in the North American hardwood forests, but some researchers are currently investigating ways to make it possible. Andy Holdsworth, a PhD candidate in Forest Resource at the University of Minnesota, is currently investigating applications of “electroshocking methods” in order to reduce earthworm densities. This idea is to electroshock plots that are size of 3 x 6.5 m each in order to remove maximum amounts of earthworms. According to Holdsworth, the similar experiments in the past in an agroecosystem of Ohio successfully reduced earthworm densities by approximately 75%. After creating patches with low earthworm densities, they are amended with soil organic matters and planted with the appropriate native species. Then these sites are monitored for two years to see levels of reestablishments of forest floor vegetations and the diversifications of the forest floor ecosystems due to the reduced earthworm densities and absence of whitetail deer (Holdsworth, in progress).

Prior to electroshoking the experimental sites, Holdsworth also monitored under-story plant recoveries by excluding white tail deer contacts for four years. His four years of experiments so far suggest little recovery of the under-story plants leading him to suspect more significant relationship between limits of the plant establishment and earthworm activities than whitetail deer (Holdsworth, in progress).

The results of this test will not be revealed until 2004, but this experiment will open many questions. What are the side effects of the methods? To what extent will electroshocking be applicable to maximize reductions of the earthworm density from the targeted site, while the side effects to the other micro organisms are kept at a minimum? If microhabitat patches that encourage the under-story plants establishments with the least earthworms were created, how can they be prevented from future earthworm migration and reproduction?

There are no solutions to prevent further earthworm expansions at this point. Hale and Holdsworth recommend use of wood-chip mulch in order to protect erosion prune forest soils resulted from the earthworm invasions (Holdsworth, 2003; Minnesota Extension Service News, 2003 and personal communications). Wood-chip mulch seems to be avoided as a food by earthworms and allow germination of some under-story plants (Holdsworth, 2003, personal communication). However, Holdworth points out that wood chips can also become obstacles to some plants like sedges that may not be able to sprout through heavier and harder organic layers like wood chips. Earthworm introduction by use as fishing bait is still significant. University of Minnesota extension service news also cautions against the transplant of plants from common gardens to woodlands in order to prevent further earthworm distribution (University of Minnesota extension service, 2003). Thus, there is no directly effective prevention for earthworm population increases today.

Conclusion

In conclusion, it is clear that soil disturbance caused by exotic earthworms is problematic to conserve rare native species and restore diversity of the North American hardwood forest floor. Many studies suggest large consequences of carbon, nitrogen and phosphorus loss in the forest ecosystem due to the accelerated decomposition of the soil organic matter caused by the earthworm activities. The below ground soil composition is also modified by the deep-burrowing species like *L. terrestris* that remove the organic horizon, enrich nutrients of the inorganic soil and aerate the soil. Such shifts in the chemical and physical compositions can relate to significant loss of habitats for the native ground plain vegetations. In addition, concerns of herbivory by white tail deer that tends to consume young under-story vegetation add complexity to the issues of how the native under-story vegetation can be conserved, restored, and enhanced.

Effective forest restoration strategies need to be developed. How can the forest soil be amended to promote heterogeneity of the forest floor vegetation without encouraging growth of the earthworm population? If not all, can some native forest ground plain species adapt to the altered soil (nutrient rich inorganic soil with low organic matters)? Can new technologies be developed in order to eliminate earthworms without hurting the soil fauna in the forest ecosystem? Even if it is only possible to reduce density of the earthworm population, how quickly will the population bounce back? Thus, these issues need to be addressed from multiple perspectives before the earthworm removal and the forest floor restoration can become applicable to the field of restoration ecology.

Literature Cited

Burtelow, A. E., P. J. Bohlen, and P.M. Groffman, 1998. Influence of exotic earthworm invasion on soil organic matter, microbial biomass and denitrification potential in forest soils of the northeastern United States. *Applied Soil Ecology* 9: 197-202.

Clive, AE. c1998. *Earthworm ecology.* St. Lucie Press, Boca Raton, Fla.

Cortez, J., M. B., and Bouche. 1997. Field decomposition of leaf litters: earthworm-microorganism interactions –the ploughing-in effect. *Soil Biology and Biochemistry* 30: 795-804

Frelich L and K, Puettman. (1999) Restoration Ecology. In Maintaining biodiversity in forest ecosystems. pp. 499-524.. Cambridge, UK ; New York, NY, USA., Cambridge University Press.

Gange A. C. 1993. Translocation of mycorrhizal fungi by earthworms during early succession. *Soil Biology and Biochemistry* 25: 1021-1026

Hale, C. M., J. Pastor, and K. A. Rusterholz. 1999. Comparison of structural and compositional characteristics in old-growth and mature, managed hardwood forests of Minnesota, U.S.A. *Canadian Forestry Resource* 29: 1479-1489

Holdsworth, A. 2002. Field Experimental Proposal: The effects of reducing deer herbivory and earthworm density on understory plants in an old-growth maple-basswood-oak forest. In processing the experiments.

Hunter, M. L., Jr. 1999. *Maintaining biodiversity in forest ecosystems.* Cambridge University Press. Cambridge, UK ; New York, NY, USA. 698p

Lawrence, B., M. C., Fisk, T. J., Fahey, and E. R., Suaez. 2003. Infuluence of nonnative earthworms on mycorrhizal colonization of sugar maple (*Acer Saccharum*). *New Phytologist* 157: 145-153.

Reynolds, J.W. 1995. Status of exotic earthworm systematics and biogeography in North America. In P. F. Hendrix c1995. *Earthworm ecology and biogeography in North America,* pp. 1- 29. Boca Raton, FL., Lewis Publishers.

Reynolds, J. W., W. B., Krohn, and G. A., Jordan. 1977. Earthworm Populations as related to woodcock habitat usage in central Maine. *Proc. Woodcock symp.* 6: 135-146
Tomplin, A. D., M. J. Shipitalo, W.M. Edwards and R. Protz. 1995. Earthworm and their influence on soil structure and infiltration. In P. F. Hendrix c1995. *Earthworm ecology and biogeography in North America,* pp.159-184. Boca Raton, FL., Lewis Publishers.

University of Minnesota Duluth, Minnesota Earthworm Watch. 2002-2003 <*http://www.nrri.umn.edu/worms/withunderstory.html*>

University of Minnesota Extension Service, 2003. *Yard & Garden Line News* V. 5 n. 3 <http://www.extension.umn.edu/yardandgarden/YGLNews/YGLN-Mar0103.html#worms>

Xuyong L, Melany CF, Timothy JF, Patrick JB. 2002. Influence of earthworm invasion on soil microbial biomass and activity in a northern hardwood forest. *Soil Biology & Biochemistry* 34: 1929-1937