

Ecological Risk Assessment of Non-indigenous Earthworm Species

Prepared for U.S. Fish and Wildlife Service
International Affairs
Division of Scientific Authority

Final Draft
Submitted on March 4, 2003

Nick Proulx
Minnesota Department of Natural Resources
Division of Ecological Services
500 Lafayette Road, Box 25
Saint Paul, MN 55155

Purpose and Format of Assessment

The purpose of this assessment is to illustrate issues surrounding exotic earthworms within the United States, risks they pose to specific habitats, and recommendations.

This risk assessment does not follow the typical format, probability of establishment and consequences of establishment (ANS Task Force, 1996). The format will include a brief discussion describing exotic earthworms, current regulations pertaining to importation, environmental changes due to earthworms, potential risks for future actions, and recommendations.

The decision to deviate from the suggested risk assessment format culminated from three factors: exotic earthworms are widespread within in the United States, difficulty in earthworm identification, and another exotic earthworm risk assessment underway for the Animal and Plant Health Inspection Service (APHIS) at the United States Department of Agriculture (USDA).

At least 45 exotic earthworm species are already present in many portions of the United States (Reynolds, 1995). The majority of the introductions originate from Europe (25) and Asia (14) (Reynolds, 1995; Hendrix and Bohlen, 2002). The current populations of exotic earthworms are a concern, both in the United States and in the Upper Midwest, according to earthworm experts from Minnesota. The typical risk assessment format seemed of less value based on the fact that we know these exotic earthworms have established in the U.S. and there is and continues to be research regarding the consequences.

A number of earthworm species are difficult to identify (immature worms are nearly impossible) and the number of experts who can do so, is small (Reynolds, 1995; Cindy Hale, per. com. 2002). The difficulty in identifying earthworms have contributed to product contamination. Specific earthworm species are being advertised for retail sale, but often the advertised species are not what is being sent. For instance, when purchasing “nightcrawlers” for bait, Hale (per. com., 2002) found the common nightcrawler (*Lumbricus terrestris*) as well as the leafworm (*Lumbricus rubellus*), *Dendrobaena octeadra*, and *Amyntas spp.* Similar contamination rates occur in “composting” worms (Dr. Jill Clapperton per.com., 2003). Based on misidentification and contamination, regulation and education efforts need to accommodate *all* exotic earthworm species. Therefore, a species level risk assessment would have limited value to people heading those efforts.

The final reason for the format deviation is the exotic earthworm risk assessment concurrently being performed by Dr. Paul Hendrix (2002) for APHIS. That report will outline possible exotic earthworm risk assessment protocols and policy implications on earthworm imports into the U.S. In an effort not to replicate his work, but rather to build on it, the focus of this assessment will be on state and local exotic earthworm issues.

Background

Exotic Earthworms

For the purposes of this assessment the terms exotic, non-indigenous, and alien will be synonymous. According to the Executive Order 13112, an “Alien species means,

with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem.” (NBII, 2002). In regards to defining exotic earthworms in the United States, one must go back 10,000 to 15,000 years ago when the Wisconsin glacier covered portions of North America (Figure 1). The Post Quaternary Introduction Theory put forth by Reynolds et al (1974), states that native earthworms were extirpated by glaciation and any population reintroduced by methods other than the earthworms’ own ability to migrate is exotic. To support this theory, Reynolds (1994) took advantage of the Quaternary glaciation boundary in Indiana, where he was able to survey earthworm populations in both recently glaciated and unglaciated soils. In general, he found that earthworms, mainly of European origin (*Lumbricidae*), dominated areas recently glaciated and native earthworms dominated the unglaciated areas. Gates noted the same distribution years earlier during his quarantine and greenhouse survey work, where he identified earthworms in imports that contained soil (Gates, 1966; Gates, 1982; Kalisz, 1991). Years later, the theory was modified based on the knowledge earthworms do not fossilize well, so we don’t know the historic earthworm distribution and composition before the glaciers (Kalisz, 1991). Regardless of when or if native earthworms were present in recent glaciated areas, exotic ones have been introduced into the U.S.

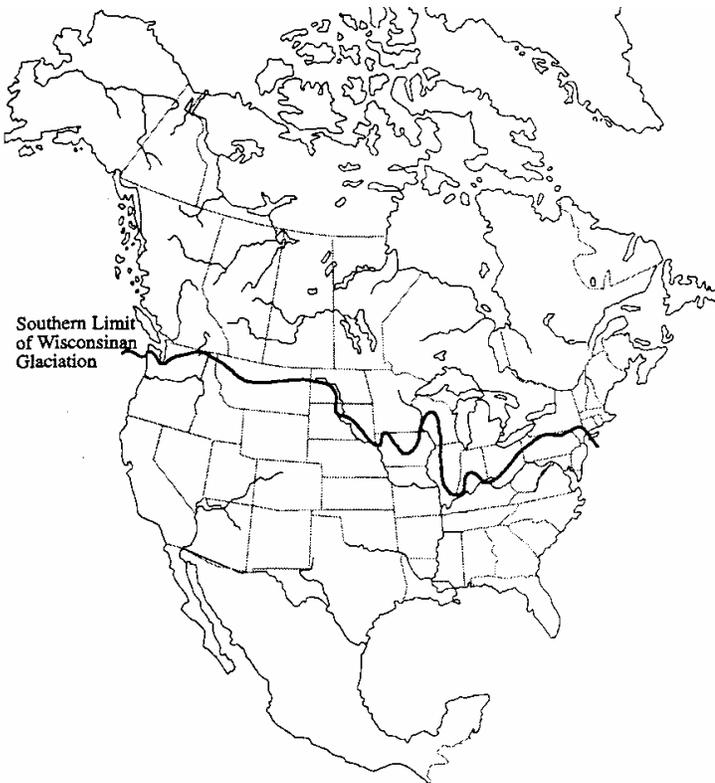


Figure 1. The southern limit of the Wisconsin glacial boundary (Reynolds, 1995); shown by solid black line.

Regulations

The United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (APHIS-PPQ) is the responsible agency for permitted earthworm importations into the U.S. To date only two species have been permitted for intentional importation, *Eisenia veneta* (*Eisenia hortensis*) and

Ecological Risk Assessment of Non-indigenous Earthworm Species

Lumbricus terrestris (common nightcrawler) from Canada (USDA, APHIS, PPQ 2002). There are restrictions on the earthworm diet before entry and no soil can accompany the shipment (defined areas of Canada are exempt). The purpose of the restriction is to reduce the risk of disease or other potential hitchhikers through contaminated soil and/or the contents of the earthworm's gut.

Once imported into the United States, APHIS does not regulate the interstate distribution of earthworms. At that point the State Departments of Agriculture are responsible for regulations. Regulations and enforcement vary from state to state. Efforts to regulate intra-state and inter-state sale of earthworms appears to be becoming more difficult. The quantity and variety of earthworm species available on the Internet (Table 1) and the convenience of Internet sales will hamper any regulatory effort.

Table 1. Results of a one-hour Internet search for earthworm vendors. Key words: worms and sale using Google search engine. Company names were excluded from this table.

State (Number of Vendors)	Advertised Uses	Earthworm Species (Trade Name)	Earthworm Species (Scientific Name – if given)
Alaska- (1)	Compost	Red wigglers	None
Arkansas- (1)	Compost and Bait	Red worms	None
California- (15)	Compost, Bait, and Pet Food	Red worms Red wigglers Worms Alabama jumpers Jumpers Nightcrawlers – Native, European and African	<i>Lumbricus rubellus</i> <i>Pheretima hawayana</i> <i>Eisenia fetida</i> <i>Eisenia foetida</i>
Connecticut- (1)	Compost and Bait	Red worms European nightcrawler	<i>Eisenia fetida</i> <i>Eisenia hortensis</i>
Florida-(5)	Compost, Bait, and Pet Food	Red worms Belgium, European and African nightcrawlers India blue Alabama jumpers Yellow-tail red	<i>Eisenia fetida</i> <i>Eisenia andrei</i> <i>Eisenia foetida</i> <i>Eisenia hortensis</i> <i>Perionyx excavatus</i> <i>Pheretima spp.</i> <i>Eurdrilus eugeniae</i>
Georgia-(2)	Compost and Bait	Tigerworms Swamp grown red wigglers	
Illinois-(1)	Bait	Nightcrawler	
Iowa-(1)	Compost	Red wigglers	
Louisiana-(1)	Pet food	Cold worm	
Massachusetts-(1)	Compost	Red wigglers	
Mississippi-(1)	Compost	California red worms	
New Jersey-(1)	Compost, Bait, and Pet food	Red worms European nightcrawler	<i>Eisenia fetida</i>
New Mexico-(1)	Compost	Red worms (manure worm)	<i>Eisenia foetida</i>
New York-(1)	Compost and Bait	Red wigglers European nightcrawlers	<i>Eisenia fetida</i> <i>Dendrobaena veneta</i>
Ohio-(1)	Compost and Bait	Red worms African nightcrawlers	
Oregon-(3)	Compost	Redworms Red wigglers	<i>Eisenia foetida</i>
Pennsylvania-(4)	Compost and Bait	Red worms Red wigglers African and North American nightcrawler Brandling worm	<i>Eurdrilus eugeniae</i> <i>Lumbricus rebellus</i> <i>Eisenia foetida</i> <i>Lumbricus terrestris</i>
South Carolina-(1)	Compost and Bait	European nightcrawler Belgium red worms`	
Texas-(4)	Compost and Bait	Red tigerworms Redworms European nightcrawler African worms	<i>Eisenia fetida</i>
Washington-(2)	Compost	Red worms	<i>Eisenia fetida</i>

Pathways

All exotic species need a viable pathway in order to be introduced outside their native range. Pathways are one factor in a list of several (number of individuals, travel time, and suitable habitat present upon arrival) that will determine the probability of a given exotic species arriving alive, establishing a reproducing population, integrating, and finally spreading (Venette and Carey, 1998). If one of the above factors is compromised, the probability of a given exotic species introduction failing will increase. Earthworms are no different, with the possible exception of certain species that exhibit parthenogenesis, the ability to self-reproduce, that trait would decrease the number of individuals needed to establish a reproducing population.

Earthworms migrate two ways: on their own, or by someone or something moving them (Reynolds, 1974; Gates, 1966). On their own, they are able to cover an average of 10 meters per year (Hoogerkamp et. al, 1983 and Hale et. al, 2002). If the last glacier receded between 12,000 – 25,000 years ago, earthworms would not be expected to occur more than 155 miles north of the furthest advancement of the permafrost layer, which are located varying distances south of the glacial line (Figure 1). The current distributions of earthworm species, especially exotics, are mainly due to something moving them (Figure 2).

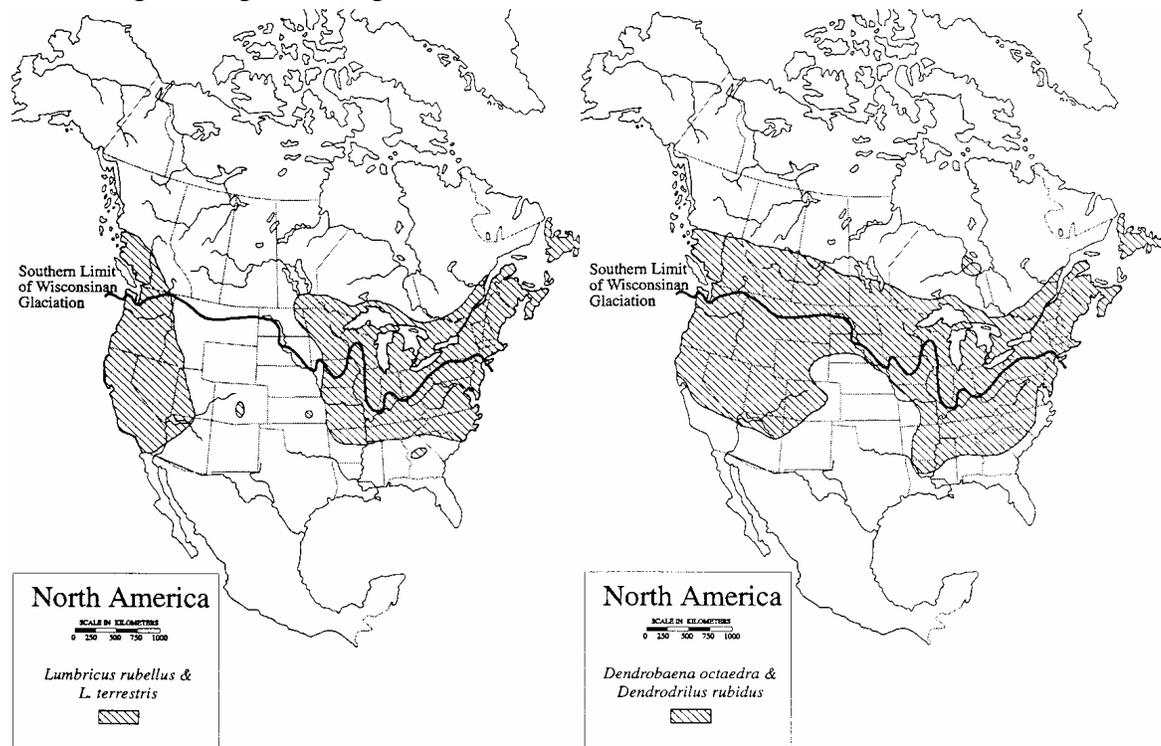


Figure 2. Examples of current distributions for four species of exotic earthworms in North America (Reynolds, 1995).

People have been introducing earthworms into North America for many years, some of the first importations of earthworms into the U.S. began around 1500A.D. when European settlers brought over plant material, some of which contained earthworms (Gates, 1974; Reynolds, 1994). The work done by G.E. Gates (1966) was instrumental in pointing out the magnitude in which exotic earthworms are currently entering the United States and, consequently, being moved between states.

He identified earthworms that were intercepted by the USDA and found that numerous species from around the world are being continually imported unintentionally. According to Hendrix (2002), this activity is still going on and is probably increasing.

Local pathways were assessed as part of this project. Earthworm experts and regulatory agency representatives from Minnesota were brought together to discuss earthworm issues (Appendix A). All suggested pathways were recorded and sorted by the group into one of three categories, based on the risk of earthworm entry and spread within and between states (Table 2). Pathways that were identified as high risk by the group and are well documented include the horticultural trade (plants transported with soil) (Gates, 1966; Fender, 1995; Hendrix, 2002) and the live bait industry (Langmaid, 1964; Gates, 1974; Gates, 1982; Tomlin, 1983; Alban and Berry, 1994; Fender, 1995; Hendrix, 2002).

Table 2. Potential pathways for earthworm spread and level of risk assigned by regional earthworm experts.

Pathway	Activity	Risk	Rational
Unintentional			
Live bait	fishing	High	Large number, over large area
Nursery stock	potted plants	High	Large number, over large area
Landscaping	topsoil, sod	High	Large number, over large area
Community composting	mulch piles	High	Large number, concentrated area
Manure	fertilizer	High	Large number, over large area
Off-road vehicle	4-wheelers	High	Small number, over remote areas
Logging	skidders	High/Med.	Small number, remote areas
Heavy equipment	road construction	Medium	Large number, over small area
On-road vehicle	truck or car	Low	Small number, over small area
Horseback riding		Low	Small number, over small area – remote areas
Foot traffic	hiking, hunting	Low	Small number, over small area – remote areas
Animals	white-tailed deer	Low	Small number, over small area – remote areas
Intentional			
Composting	backyard	High	Large number, over large area
Commercial bait industry		High	Large number, over large area
Agriculture	augmentation	Low	Large number, in distributed areas
Bioremediation	sewage treatment	Low	Large number, not frequently used

Assessing Earthworm Activity

Ecological Value of Earthworm Activity

Earthworm activity can have positive and/or negative impact(s) depending on the earthworm species, soil type, land-use, microbes present, plant life, density of earthworms, geographical location, just to name a few variables (Hendrix, 2002; Hendrix and Bohlen, 2002).

Darwin (1881) was the first to observe and write about the earthworms' role in soil formation. Since that time, many studies have documented earthworm activities and the important part they play in soil dynamics, which has implications for the environment as a whole. The earthworm is commonly known for its ability to cycle

organic matter and nutrients back into the soil (Syers and Springett, 1984). The burrows and casts of earthworms can increase aeration, increase water infiltration, and stabilize soils (Butt et. al, 1994). Earthworms are a food source for microbes (Stout, 1983), birds, and mammals (Macdonald, 1983) and can even increase certain plant species productivity (Haimi et. al, 1992).

In agricultural settings, earthworms can contribute to the overall health of the crop and soil by decreasing the number of microbial pests and diseases (Linden, 1997; Doube and Brown, 1998), rehabilitate compacted soils (Larink and Schrader, 2000), and increase water infiltration and stabilize soils, depending on soil type, microbes present and plant cover (Bouche and Al-Addan, 1997). In land that is used for grazing, earthworms can increase production by aeration, increased infiltration, water conductivity, and reduce of the amount of stagnate water (Stockdill, 1982; Hoogerkamp et al., 1983).

Exotic Earthworms in Unglaciaded Portions of North America

Little is known regarding North American native earthworm abundance and distribution (James, 1995). Distributional studies done south of the Quaternary glaciation show native and exotic earthworms coexisting (Dotson and Kalisz, 1989). A study done in the Eastern Kentucky Appalachians, below the extent of recent glaciations showed, in general, intact native earthworm assemblages in undisturbed forest soils and exotic earthworms in disturbed forest soils (Dotson and Kalisz, 1989). The primary issue in unglaciaded areas of North America is the potential of exotic earthworms to out compete their native counterparts (when the habitat is altered) and ultimately reduce the diversity of native earthworm species (Stebbing, 1962; Kalisz and Dotson, 1989; James, 1991; Kalisz, 1991; Kalisz and Wood, 1995; James, 1995). Additional research is needed to further document exotic earthworm impacts in unglaciaded soils.

Exotic Earthworms in Recently Glaciaded Portions of North America

In the recently glaciaded portions of the United States, the most dramatic impacts of exotic earthworms are generally limited to northern deciduous forest habitats. To further define the area: "Part of it [forest] consists of mixed stands of a few coniferous species (mainly pine) and a few deciduous species (mainly yellow birch, sugar maple, and American beech); the rest is a macromosaic of pure deciduous forest in favorable habitats with good soils and pure coniferous forest in less favorable habitats with poor soils." (U.S. Forest Service, Ecosystem Provinces: Laurentian Mixed Forest, 2002). These habitats have developed during the last 10,000 years without earthworm activity and thus creating a unique ecology. Earthworms have been and continue to be introduced into these areas, and researchers are now documenting the impacts.

The concern with exotic earthworm invasions into these forest types is the rate at which leaf litter is cycled, and consequently, the change in soil characteristics (Neilsen and Hole, 1963; Alban and Berry, 1994). There have been many studies done to document the rate at which earthworms feed on leaf litter and alter soil. One of the early studies occurred in South Dakota, where Buntley and Papendick (1960) investigated changes in soil after exotic earthworms invaded and they found complete destruction of the organic soil layers. A few years later, Neilsen and Hole (1963)

weighed and measured leaf litter and organic soil layers in Wisconsin. They found that with exotic earthworm activity, the organic layer measured 1.6 cm and weighed 393 pounds per acre (estimation) and without earthworms the organic layer was 4.5 cm thick and weighed 3,530 pounds per acre (estimated). Hale et al (2002) in Minnesota, notes a thicker organic layer (10 cm) where exotic earthworms are not present and the complete removal of the organic layer after exotic earthworms have invaded. Another study looked at the consumption rate of the non-native common nightcrawler (*Lumbricus terrestris*) in a Michigan woodland floodplain, where Knollenberg et al. (1985) estimated 93.8 percent of the annual leaf fall was consumed within just four weeks. These consumption rates can reduce the forest floor down to the mineral soil, eliminating organic layers, and establishing a well developed “A” horizon, which is a mixture of organic and inorganic soils (Alban and Berry, 1994; Hale, 2002).

Change in the soil structure can have ecological effects beyond its physical characteristics, including altering or completely transforming habitat required by native plants and animals. One such effect, although not completely understood, is the alteration of the microbial and fungal community (Blair et al., 1995; Devliegher and Verstaete, 1997; McLean and Parkinson, 1998a, McLean and Parkinson, 1998b) and nutrient cycling dynamics (Nixon, 1995; Burtelow et al., 1998). Current research has begun by Groffman et al. (Institute of Ecosystem Studies and Cornell University) that will look at biogeochemistry changes in the soils of northeastern temperate forests after exotic earthworms invade. The changes in nutrient availability, mainly nitrogen and phosphorus, plant nutrient demands, and the production of fine root material among other things will be investigated.

Another ecological impact from earthworm activity is the change in northern deciduous forest vegetation. Plant species that depend on a thick layer of organic matter in order to survive, such as the goblin fern (*Botrychium mormo*) and other closely related plants, can be extirpated once earthworms invade (Casson et al., 2001; Gundale, 2002). Preliminary results from research being performed by Hale et al. (2002) shows a decrease in herbaceous plant species and seedling density in previously worm-free deciduous forests in Minnesota. Further research by Frelich (2002) and Frelich et al (2002), (University of Minnesota Center for Hardwood Ecology) is looking at native plant recovery after the invasion of earthworms coupled with grazing pressure by white-tailed deer. Frelich hypothesizes that white-tailed deer grazing inhibits native plant recovery after an earthworm invasion has decreased plant numbers. He also notes that exotic plant species, particularly ones from Europe, have evolved with earthworms and are better suited to survive in earthworm-worked soil and could ultimately dominate worm-invaded areas. Garlic mustard (*Alliaria petiolata*) invasions into hardwood forests appear to be a good example of this.

In human altered and simplified ecosystems such as urban and agricultural areas north of recent glaciation, earthworms are for the most part beneficial. There are exceptions to this and they include “green” areas within the urban setting (i.e. parks) where researchers have noted impacts similar to the ones mentioned above; altered soil characteristics (physical and chemical) and local extirpation of native plants dependant on a thick layer of organic matter (Nixon, 1995; Frelich, 2002). A lumpy

lawn caused by earthworm casting, particularly by the nightcrawler (*Lumbricus terrestris*), is another exception (Dr. Lee Frelich, per. com, 2002).

Risks

Environmental Considerations

The magnitude of risks associated with exotic earthworms depends on the geographic location, habitat, and earthworm species present. The environmental risks are highest when exotic earthworms are introduced to recently glaciated areas. Although environmental risks in unglaciated areas are of concern, current research suggests the impacts on soil processes are much less severe (Hendrix and Bohlen, 2002). There is evidence that native earthworm populations can coexist with exotic earthworms and in some instances may have an advantage if the site is not highly disturbed (James, 1991; Dotson and Kalisz, 1989; Callaham and Blair, 1999; Callaham et al, 2001).

Habitat is important when assessing environmental risk because it defines the scope of potential impacts. As discussed above, northern deciduous forest represents the habitat type presently identified as being at highest risk. The estimated area of northern deciduous forest, within recent glaciation, is approximately 147,300 square miles (USDA Forest Service – Ecosystem Provinces: Laurentian Mixed Forest, 2002) (Figure 2). This is an overestimation because additional environmental factors limit earthworm presence and/or their impacts. Factors such as water, wetlands, concrete, sandy soils, pH, etc are obvious. Other factors are not so obvious. For example earthworms' generally find oak (*Quercus spp.*) and beech litter (*Fagus spp.*) to be less palatable (Satchell, 1983; Knollenberg et al., 1985; Doube et al., 1997; Frelich et al. 2002) and site productivity can limit the extent of exotic earthworm impacts (Hale et al., 2002).

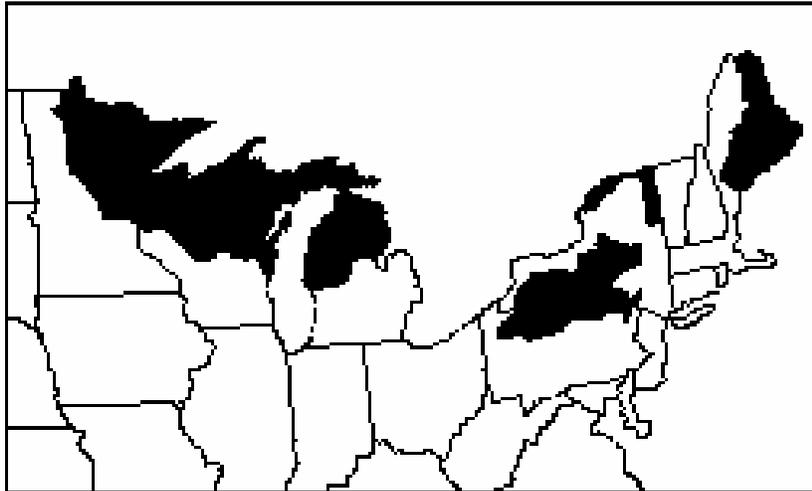


Figure 2. Laurentian Mixed Forest, source: USDA Forest Service.

The species of earthworms present can enhance or minimize impacts. Hale et al. (2002) noted that exotic earthworms invade unoccupied areas in a successional pattern. There are pioneering earthworms (epigeic species), which mix the upper

layer of soil, allowing deeper burrowing species (anecic) to follow, such as the nightcrawler (*Lumbricus terrestris*).

Summary of Environmental Risks

The impacts of exotic earthworms are more severe in recently glaciated deciduous forest ecosystems dominated by tree species other than oak or beech, which have a moderate overall productivity and contain earthworm species from the each of the feeding strategies (epigeic – surface, endogeic – mineral soil and anecic – deep).

Economic Considerations

Importing, rearing, and/or selling earthworms can provide significant profit. The bait and composting industries are multi-million dollar businesses (Tomlin, 1983; Associated Press, 2002) and are always on the lookout to expand markets or create new demand. An example would be the “nuclear worm” from Vietnam being imported for fishing bait (Murray, 2002) or the numerous companies willing to sell composting supplies including the start-up cultures (Table 1). Economic consequences of regulations to reduce ecological risk will depend on the extent of regulatory action and if sales and/or earthworm species are limited. Although, given the current abundance and distribution of exotic earthworms in the U.S., a complete ban on new earthworm imports may not negatively impact the industry (Hendrix and Bohlen, 2002).

Political/Sociological Considerations

Northern deciduous forests contain many lakes and provide recreational opportunities that are important to the local economy. Some of these activities use earthworms while others are potential dispersal mechanisms (Table 2). If recreational activities were curtailed significantly, political pressure will increase. Designation of off-road trails and slot limits for walleye on Mille Lacs Lake are two recent examples occurring in Minnesota that illustrates the need to, and difficulty in, balancing local economic concerns with environmental needs.

Additionally, there are environmental groups that are concerned about native woodland ecosystems. These groups can also increase political pressure if nothing is done to minimize harmful impacts caused by exotic earthworms.

Recommendations

At the Federal level, Hendrix (2002) and Hendrix and Bohlen (2002) outline possible regulatory scenarios to reduce the magnitude of both intentional and unintentional earthworm importations. Hendrix recommends using a “combination of selective imports and severe restrictions” as a way of balancing between economic and environmental concerns. This will also hold true at the state and/or local level. Local risk reduction efforts, regulatory and educational, should reflect the importance of pathways of introduction and the relatively limited area of concern. In order to address pathways, defining the area of concern is the first step. Utilizing glacial boundaries, terrestrial vegetation surveys, and known earthworm distributional information should give a rough estimate of “high-risk” areas and outline where future regulatory and educational efforts would be most useful. Narrowing the focus will increase local participation, decrease enforcement costs, and hopefully result in effective compliance.

Recommendation 1

- **Identify earthworm free areas within recently glaciated portions of the U.S.**

The risk reduction recommendations given below are only guidelines. Each state or management unit (e.g. National Forest, State Park) should determine, based on habitat and earthworm species composition, how best to pursue regulatory and educational efforts.

Pathway Risk Reductions for Intentional Introductions

Intentional exotic earthworm introductions could be best addressed with regulations. Regulations should be based on the likelihood of a given activity moving a large number of earthworms into earthworm-free areas. Ideally, future pathway risk reduction activities should decrease earthworm invasions into earthworm-free areas, without impacting heavily on economic and recreational activities. Regulatory limitations include misidentification of earthworm species and contamination of earthworm products.

Recommendations 2 and 3

- **Prohibit or implement sanitary measures within once glaciated portions of the U.S. that contain no earthworms, for activities that have a high risk of moving earthworms and/or their cocoons.**
- **When possible, regulate all earthworm species, rather than having species-specific regulations.**

Pathway Risk Reductions for Unintentional Introductions

Unintentional introductions of earthworm species continue, whether through the horticultural trade, construction, logging or any activity that can transport soil. Regulating unintentional earthworm introductions are problematic in terms of enforcement and unanticipated consequences to the economy. As a result, educational efforts are a useful and potentially powerful tool to reduce risks associated with unintentional pathways and to combat the belief that all earthworms are native and beneficial. Research continues to unveil new information that has increased our understanding of exotic earthworm impacts and this needs to be communicated to the public and resource managers.

Educational efforts should be focused in the geographic areas of concern and on high-risk activities. Possible avenues include, but not limited to state and federal parks (informational kiosks), regulatory booklets (fishing regulations, off-road trail maps, logging permits etc.), informational materials at bait stores, press releases, and Internet websites.

Recommendation 4

- **Provide exotic earthworm information to the public in a variety of educational materials and through multiple media outlets.**

Acknowledgements

This assessment is funded by a grant from the U.S. Fish and Wildlife Service, International Affairs Division of Scientific Authority. I also would like to thank participants of the regional earthworm risk assessment meetings (Appendix A), especially C. Hale, L. Frelich, D. Wright, J. Rendall, J. Casson and S. Balgie for taking the time to provide comments. Finally, to Dr. Paul Hendrix for allowing the use of his, at the time unpublished work, regarding exotic earthworm risk assessment.

Literature Cited

- Alban, D. H. and E. C. Berry. 1994. Effects of earthworm invasion on morphology, carbon, and nitrogen of a forest soil. *Applied Soil Ecology* 1:243-249.
- Aquatic Nuisance Species (ANS) Task Force. 1996. Generic non-indigenous aquatic organisms risk analysis review process.
- Associated Press – St. Cloud, MN. 2002. A Top Crop, Farmers value worms that can turn waste into nutrient rich soil. Mankato Free Press. February 11, 2002.
- Blair, J.M., R.W. Parmelee, and P. Lavelle. 1995. Influences of earthworms on biogeochemistry. pp.127-158. In: Hendrix, P.F. (ed.) *Earthworm ecology and biogeography in North America*, CRC Press, Boca Raton, FL.
- Bouche, M.B., and F. Al-Addan . 1997. Earthworms, water infiltration and soil stability: some new assessments. *Soil Biology and Biochemistry* 29: 3/4:441-452.
- Brown, G.G. 1995. How do earthworms affect microfloral and faunal community diversity? *Plant and Soil* 170: 209-231.
- 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.
- Butt K.R., J. Frederickson and R.M. Morris. 1994. Effect of earthworm density on the growth and reproduction of *Lumbricus terrestris* L. (Oligochaeta: Lumbricidae) in culture. *Pedobiologia* 38: 254-261.
- Buntley, G.J. and R.I. Papendick. 1960. *Soil Sci. Soc. Amer. Proc.*, 24 (2), 128.
- Callaham M.A. Jr. and Blair J.M. 1999. Influence of differing land management on the invasion of North American tallgrass prairie soils by European earthworms. *Pedobiologia* 43: 507-512.
- Callaham M.A. Jr., Blair J.M. and Hendrix P.F. 2001. Native North American and introduced European earthworms in tallgrass prairie: Behavioral patterns and influences on plant growth. *Biology and Fertility of Soil* 34: 49-56.

- Casson J., I. Shackelford, L. Parker and J. Schultz. 2001. Conservation approach for goblin fern, *Botrychium mormo* W.H. Wager. USDA Forest Service, Eastern Region. December 2001.
- Darwin, C. R. 1881. The Formation of Vegetable Mould through the Action of Worms with Observations on their Habits. Murray, London. 298.
- Devliegher W. and W. Verstraete. 1997. The effect of *Lumbricus terrestris* on soil in relation to plant growth: Effects of nutrient-enrichment processes (NEP) and gut-associated processes (GAP). *Soil Biology and Biochemistry* v. 29:3\4: 341-346.
- Dotson, D.B and P.J. Kalisz. 1989. Characteristics and ecological relationships of earthworm assemblages in undisturbed forest soils in the southern Appalachians of Kentucky, USA. *Pedobiologia* 33: 211-220.
- Doube, B.M., O. Schmidt, K. Killham, and R. Correll. 1997. Influence of mineral soil on the palatability of organic matter for Lumbricid earthworms: a simple food preference study. *Soil Biology and Biochemistry*. 29: 3/4: 569-575.
- Doube, B. M., and G. G. Brown. 1998. Life in a complex community: functional interactions between earthworms, organic matter, microorganisms, and plants. In: Edwards, C. A. (ed.). *Earthworm ecology*. 1998. CRC Press. Boca Raton, Florida.
- Fender, W.M. 1995. Native earthworms of the Pacific Northwest: An Ecological Overview. pp. 53-66. In: Hendrix, P.F. (ed.) *Earthworm ecology and biogeography in North America*, CRC Press, Boca Raton, FL.
- Frelich, L.E. 2002a. European earthworms, deer, and decline in Midwestern maple-oak forests. University of Minnesota Center for Hardwood Ecology, May 2002. Draft report.
- Frelich, L.E., C.H. Hale, and A. Holdsworth. 2002b. Report on 'Survey of European earthworms and native plant communities in hardwood forests of Minnesota'. Progress report on Minnesota DNR non-game grant awarded in 2000.
- Gates, G.E. 1966. Requiem – For Megadrile Utopias. A contribution toward the understanding of the earthworm fauna of North America. *Proceedings of the Biological Society of Washington*. Vol. 79, pp. 239-254.
- Gates, G.E. 1974. Contributions to North American earthworms (Annelida). On American earthworm genera. I. Eisenoides (Lumbricidae). *Bulletin of Tall Timbers Research Station*. 13: 1-17.
- Gates, G.E. 1982. Farewell to North American Megadriles. *Megadrilogia* 4:12-77.
- Groffman, P.M., P.J. Bohlen, T.J. Fahey and M.C. Fisk. Project proposal. Invasion of North Temperate Forest Soils by Exotic Earthworm, Institute of Ecosystem

Studies, IES. Downloaded: 2001

<http://www.ecostudies.org/research/reports/grofreq2.html>.

Gundale M.J. 2002. The influence of exotic earthworms on the soil organic horizon and the rare fern *Botrychium mormo*. *Conservation Biology* (In press).

Hale C.M., L.E. Frelich and P.B. Reich. 2002. Impacts of invading European earthworms on understory plant communities in previously worm-free hardwood forests on Minnesota. (draft for publication).

Haimi J., V. Huhta and M. Boucelham. 1992. Growth increase of birch seedlings under the influence of earthworms – a laboratory study. *Soil Biol. Biochem.* V24, No. 12, pp. 1525-1528.

Hendrix P.F. 2002. Ecological risk assessment of importation of exotic earthworms into the United States. A report to the Animal and Plant Health Inspection Service United States Department of Agriculture. 1-28. (in press).

Hendrix P.F. and Bohlen P.J. 2002. Exotic earthworm invasions in North America: ecological and policy implications. *BioScience* 52: 9, p.801-811.

Hoogerkamp M., H. Rogaar and H.J.P. Eijsackers. 1983. Effect of earthworms on grassland on recently reclaimed polder soils in the Netherlands. pp. 85-103. In: Satchell, J.E. (ed.) *Earthworm Ecology from Darwin to Vermiculture*, Institute of Terrestrial Ecology, Cumbria, UK.

James, S.W. 1990. Oligochaeta: Megascolecidae and other earthworms from southern and midwestern North America. pp. 379-386. In: Dindal, D.L. (ed.) *Soil Biology guide*. John Wiley and Sons, New York.

James, S.W. 1991. Soil, nitrogen, phosphorus and organic matter processing by earthworms in tallgrass prairie. *Ecology* 72: 6: 2101-2109.

James, S.W. 1995. Systematics, biogeography and ecology of nearctic earthworms from eastern, central, southern and southwestern United States. pp. 29-52. In: Hendrix, P.F. (ed.) *Earthworm ecology and biogeography in North America*, CRC Press, Boca Raton, FL.

Kalisz, P.J. and D.B. Dotson. 1989. Land-use history and the occurrence of exotic earthworms in the mountains of eastern Kentucky. *The American Midland Naturalist*. 122: 288-297.

Kalisz, P.J. 1991. Native and Exotic Earthworms in Deciduous Forest Soils of Eastern North America. *Biological Pollution: The Control and Impact of Invasive Exotic Species*. Proceedings of a Symposium held at the University Place Conference Center, Indiana University-Purdue University at Indianapolis on October 25 and 26, 1991. 93-100.

- Kalisz, P. J. and H. B. Wood. 1995. Native and exotic earthworms in wildland ecosystems. pp. 29-52. In: Hendrix, P.F. (ed.) *Earthworm ecology and biogeography in North America*, CRC Press, Boca Raton, FL.
- Knollenberg, W. G., R. W. Merritt, and D. L. Lawson. 1985. Consumption of leaf litter by *Lumbricus terrestris* (Oligochaeta) on a Michigan Woodland Floodplain. *American Midland Naturalist* 113: 1-6.
- Langmaid, K. K. 1964. Some effects of earthworm invasion in virgin podzols. *Canadian Journal of Soil Science* 44: 34-37.
- Larink, O. and S.T. Schrader. 2000. Rehabilitation of degraded compacted soil by earthworms. *Advances in GeoEcology* 32: 284-294.
- Linden, D.R. 1997. Minnesota earthworms. *Biooptions* 8(2): 9-11. University of Minnesota.
- Macdonald, D.W. 1983. Predation on earthworms by terrestrial vertebrates. p. 393-409. In: Satchell, J.E. (ed.) *Earthworm Ecology from Darwin to Vermiculture*, Institute of Terrestrial Ecology, Cumbria, UK.
- McLean, M.A. and D. Parkinson. 1998a. Impacts of the epigeic earthworm *Dendrobaena octaedra* on oribatid mite community diversity and microarthropod abundances in pine forest floor: a mesocosm study. *Applied Soil Ecology*. 7: 125-136.
- McLean, M.A. and D. Parkinson. 1998b. Impacts of the epigeic earthworm *Dendrobaena octaedra* on microfungus community structure in pine forest floor: a mesocosm study. *Applied Soil Ecology*. 8: 61-75.
- Murray, M. 2002. Exotic new bait worms import worries. Gannett News Service, USA Today. Nation. August 19, 2002.
- The National Biological Information Infrastructure (NBII). 2002. Definitions of alien species, <http://www.invasivespecies.gov/laws/execorder.shtml>.
- Nielsen, G.A. and F.D. Hole. 1963. A study of the natural processes of incorporation of organic matter into soil in the University of Wisconsin Arboretum. *Wisconsin Academy of Sciences, Arts and Letters* 52: 213-227.
- Nixon, W. 1995. As the worm turns. *American forests* 101: 34-36.
- Reynolds, J.W., E.E.C. Clebsch, and W.M. Reynolds. 1974. Contributions to North American earthworms. The earthworms of Tennessee (Oligochaeta). I. Lumbricidae. *Bulletin of Tall Timbers Research Station*. 17: 1-133.
- Reynolds, J.W. 1994. The distribution of the earthworms (Oligochaeta) of Indiana: A case for the post quaternary introduction theory for Megadrile migration in North America. *Megadrilogica* v. 5, no. 3, pp 13-32.

Reynolds, J. W. 1995. Status of exotic earthworm systematics and biogeography in North America. pp. 1-28 In: Hendrix, Paul F. 1995. Earthworm ecology and biogeography. Lewis Publishers, Boca Raton, FL.

Satchell J.E. 1983. Earthworm ecology in forest soil. pp. 161-170. In: Satchell, J.E. (ed.) Earthworm Ecology from Darwin to Vermiculture, Institute of Terrestrial Ecology, Cumbria, UK.

Stebbins J.H. 1962. Endemic-exotic earthworm competition in the American Midwest. Nature v. 196 pp. 905-906.

Stockdill, S. 1982. Effects of introduced earthworms on the productivity of New Zealand pastures. Pedobiologia 24: 29-35.

Stout J.D. 1983. Organic matter turnover by earthworms. p. 35-47. In: Satchell, J.E. (ed.) Earthworm Ecology from Darwin to Vermiculture, Institute of Terrestrial Ecology, Cumbria, UK.

Syers, J.K. and J.A. Springett. 1984. Earthworms and soil fertility. Plant and Soil 76: 93-104.

Tomlin A.D. 1983. The earthworm bait market in North America. pp. 331-338. In: Satchell, J.E. (ed.) Earthworm Ecology from Darwin to Vermiculture, Institute of Terrestrial Ecology, Cumbria, UK.

United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine. Agricultural Permits, Earthworms. <http://www.aphis.usda.gov:80/ppq/permits/plantpest/earthworm.html>.

United States Department of Agriculture, Forest Service. Ecosystem Provinces. Downloaded November 2002, http://www.fs.fed.us/colorimagemap/html/ecoreg1_provinces.html.

Venette, R.C. and J.R. Carey. 1998. Invasion biology: Rethinking our response to alien species. California Agriculture, March – April vol. 52, number 2, pp. 13-17.

Appendix A – Participates of the regional exotic earthworm risk assessment team.

Name	Affiliation	Title
John Casson	U.S. Forest Service, Chippewa National Forest	Wildlife Biologist
Kevin Connors	U.S. Department of Agriculture – Animal and Plant Health Inspection Service	State Plant Health Director
Lee Frelich	Department of Forest Resources, University of Minnesota	Research Associate
Cindy Hale	Department of Forest Resources, University of Minnesota Natural Resources Research Institute	Ph.D. Candidate
Mike Hamm	Minnesota Department of Natural Resources	Conservation Officer
Meg Hanisch	Minnesota Department of Natural Resources	Public Affairs Specialist, Forestry
Andy Holdsworth	Department of Forest Resources, University of Minnesota	Ph.D. Candidate
Jack Lauer	Minnesota Department of Natural Resources	Fisheries Project Coordinator
Dennis Linden	U.S. Department of Agriculture – ARS University of Minnesota, Department of Soil, Water & Climate	Soil Scientist – Associate Professor
Carol Estes Mortensen	Leech Lake Reservation Division of Resources Management	Botanist
Steve Mortensen	Leech Lake Reservation Division of Resources Management	Wildlife Biologist
Ethan Perry	Minnesota Native Plant Society	Coordinator
Jay Rendall	Minnesota Department of Natural Resources	Exotic Species Program Coordinator
Nancy Sather	Minnesota Department of Natural Resources	MCBS Botanist
Joe Zachmann	Minnesota Department of Agriculture	Special Projects Advisor Source Water Protection Coordinator

Appendix B. A sub-sample of the exotic earthworm species found in Minnesota and a ranking of high, medium or low risk to the environment by the regional earthworm group (Appendix A).

Exotic earthworm species of concern	Rank of high, medium or low Risk
<i>Lumbricus terrestris</i>	High
<i>Lumbricus rubellus</i>	High
<i>Amyntas spp.(loveridgei)</i> (temperate spp)	High
<i>Eisenia foetida</i>	High
* <i>Aporrectodea trapezoids</i>	Medium
* <i>Aporrectodea tuberculata</i>	Medium
* <i>Aporrectodea rosea</i>	Medium
* <i>Aporrectodea caliginosa</i>	Medium
* <i>Octolasion tyrtaeum</i>	Medium
** <i>Dendrobaena octeadra</i>	Low-medium (more info)
** <i>Dendodrilus rubidus</i>	Low-medium (more info)
<i>Eisenia veneta</i>	Unknown

* Lump all the *Aporrectodea* and *Octolasion spp* together.

** Lump *Dendrobaena* and *Dendodrilus spp* together.