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ORIGINAL PAPER

Policy and management responses to earthworm invasions in North America

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Abstract The introduction, establishment and spread of non-native earthworm species in North America have been ongoing for centuries. These introductions have occurred across the continent and in some ecosystems have resulted in considerable modifications to ecosystem processes and functions associated with above- and belowground foodwebs. However, many areas of North America have either never been colonized by introduced earthworms, or have soils that are still inhabited exclusively by native earthworm fauna. Although several modes of transport and subsequent proliferation of non-native earthworms have been identified, little effort has been made to interrupt the flow of new species into new areas. Examples of major avenues for introduction of earthworms are the fish-bait, horticulture, and vermicomposting industries. In this paper we examine land management practices that influence the establishment of introduced species in several ecosystem types, and identify situations where land management may be useful in limiting the spread of introduced earthworm species. Finally, we discuss methods to regulate the importation of earthworms and earthworm-containing media so that introduction of new exotic species can be minimized or avoided. Although our focus in this paper is necessarily North American, many of the management and policy options presented here could be applicable to the problem of earthworm invasions in other parts of the world.

Keywords Biological invasion · Quarantine · Biogeography · Earthworms · Lumbricidae · Megascolecidae · Glossoscolecidae · Introduced species · Exotics

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Patterns of earthworm invasion in North America

The present-day biogeographical distributions of earthworms in North America are the product of two dramatic events in relatively recent geologic time. The first of these events was the Wisconsinan Glaciation ending about 12,000 years BP, and the second was the rapid colonization of the continent by humans of European origin beginning about 400 years BP.

The principal effect of the Wisconsinan glaciation was to influence the distribution of the native North American earthworm fauna, with total extirpation of earthworms from soils directly affected by ice sheets and permafrost. Since the recession of the glacial ice sheets, climatic factors have been the primary drivers in the distribution of native earthworm fauna, with major refugia for native earthworms developing in wet and humid regions of the continent such as the Pacific northwest, the southeastern US, and parts of southern California and Mexico (Gates 1966; James 1990, 1995; Fender and McKey-Fender 1990; Fragoso et al. 1995). Recolonization of formerly glaciated soils by native species has been slow, and the southern boundary of the glacial ice sheets still provides an approximation of the northern extent of native earthworm distributions (Fig. 1).

More recent, but no less profound than the effects of glaciation, have been the effects of human colonization on the biogeographical distributions of earthworms in North America. The human mediated changes in earthworm biogeography are the focus of this paper. There have been three general manifestations of these effects. First, and perhaps the most important factor affecting current distributions of exotic earthworm species, is the historic transport of exotic earthworms via human activities associated with European settlement and the continued spread of introduced species by the use of earthworms as a commodity, as in the fish-bait and vermicomposting industries (Edwards and Bohlen 1996; Edwards and Arancon 2004). Second, international commerce involving horticultural materials has been identified as a source of propagules for new earthworm species (Gates 1982; Hendrix and Bohlen 2002). Finally, soil disturbances associated with agricultural development, logging or other perturbations appear to be associated with

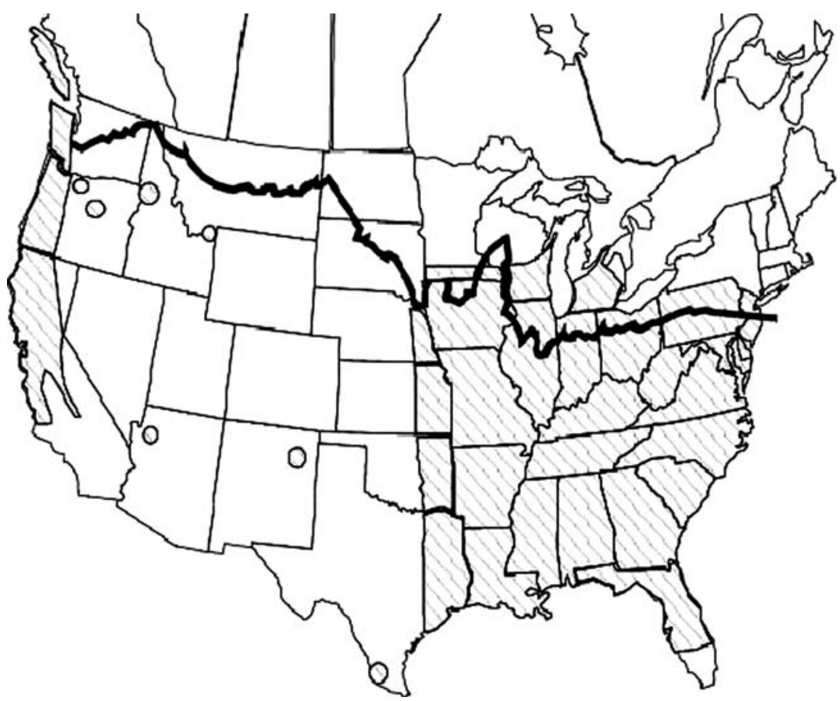

Fig. 1 The southern extent of the Wisconsinan Glaciation (bold line), and approximate present day distributions of native earthworm species in North America (hatched area). Redrawn from Hendrix and Bohlen 2002

successful establishment of introduced earthworms in some areas (e.g. Kalisz and Dotson 1989; González et al. 1996; Zou and González 2001; Callaham et al. 2003) due to changes in soil physical and chemical properties, net primary productivity, and plant litter chemistry (Fig. 2). Taken together, these three factors provide criteria by which we can make informed predictions about the likelihood that a site will become inhabited by non-native species (i.e., distance from roads, agricultural fields, waters frequented by fishermen, or human habitations are good predictive variables). One important geographical distinction in the patterns of earthworm invasion and establishment involves the presence or absence of a native earthworm community (see Fig. 1). Whereas establishment of exotic earthworm species often appears to be less successful in soils where native earthworm populations and/or native vegetation is intact (Kalisz and Dotson 1989; Callaham et al. 2003; Zou and González 1997; Sanchez et al. 2003; Hendrix et al., this issue), it is clear that soils without a native earthworm fauna are susceptible to invasion and

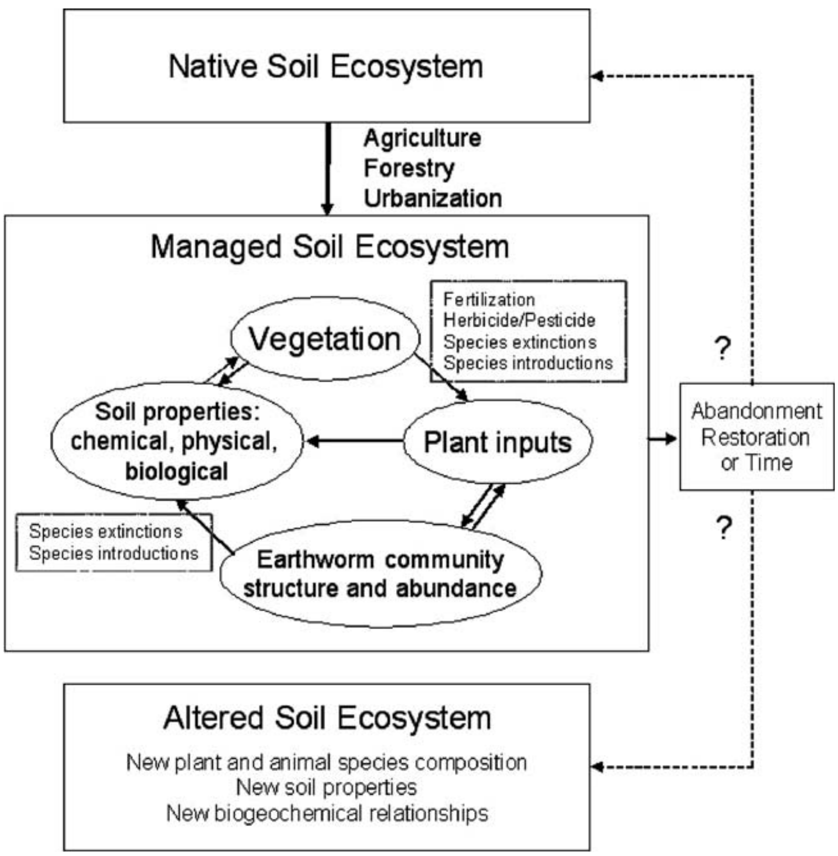

Fig. 2 Conceptual model depicting hypothesized linkages between land use, vegetation change, earthworm community change, and changes to soil properties (based on González et al. 1996). These interactions are seen to have two eventual outcomes in the event of land abandonment and restoration through natural succession or other means. The first is a return to the native state with a full complement of native species of plants and animals (in this case soil invertebrates, including earthworms), and the second is transition to an altered state consisting of a mixture of native species and exotic species with uncertain biogeochemical properties. Evidence suggests that introduced earthworms contribute to the movement of soil ecosystems toward altered states that are not likely to revert to the native condition. Indeed, introduced earthworms can be the primary drivers of such changes even in the absence of large disturbances, as has been observed in soils previously devoid of native earthworms (see text for examples)

introduced earthworms are able to establish even in pristine, undisturbed areas (Dymond et al. 1997; Bohlen et al. 2004; Hale et al. 2005; Frelich et al., this issue).

Ecological effects of introduced earthworms

The question of whether policy and procedures are needed to manage the introduction of new species of earthworms may be best answered by an analysis of the ecological and economic risks associated with such introductions. Earthworms are widely considered to be ''good'' for soil by the general public, and are usually suggested to be beneficial for soil fertility and other soil characteristics. Indeed, earthworms have frequently been purposely introduced to soils with the objective of soil improvement in agricultural settings (Baker 2004), and in soil reclamation projects (e.g., Butt et al. 1999; Curry and Boyle 1995; Baker et al., this issue). Nevertheless, in spite of the beneficial effects usually associated with earthworms, it has also long been proposed that earthworms are undesirable in certain situations. For example, Walton (1928) tested several chemical treatments for control of unwanted earthworms on golf courses where the castings of earthworms interfered with smooth play on the putting greens. Later, Stebbings (1962) suggested that interactions between native and introduced species could be leading to the competitive exclusion of native earthworm assemblages. However, only recently have there been thorough assessments of the effects that introduced earthworms can have on ecological properties and processes in natural systems (Fig. 2). The most dramatic of these effects was observed in areas that had previously been devoid of any earthworm fauna (i.e. areas north of Pleistocene glacial margins; Frelich et al., and Tiunov et al., this issue).

In the aspen and pine forests of Alberta, Canada, where the European earthworm *Dendrobaena octaedra* was accidentally introduced, the influence of this earthworm on the forest floor was dramatic in terms of microbial characteristics, changes in the community of other invertebrates, changes in nutrient cycling, and even effects on soil horizonation (Scheu and Parkinson 1994; McLean and Parkinson 2000a, b). Further, introduced European earthworms play an important role in litter decomposition in aspen forests in the Rocky Mountains of Colorado, USA (González et al. 2003). Similarly, in undisturbed sugar maple forest soils of New York, recent work has shown that introduced European earthworms of several species had effects on forest floor structure, distribution of microbial biomass, soil C storage, phosphorus cycling and fine root distributions (Bohlen et al. 2004; Groffman et al. 2004; Suárez et al. 2004; Fisk et al. 2004).

In the north temperate forests of Minnesota, invasions of European earthworms resulted in dramatic changes to soil structure; these changes were associated with declines in soil nutrient availability, as well as declines in diversity and abundance of tree seedlings and herbaceous plants (Hale et al. 2005). Also in Minnesota, one study linked the local extirpation of populations of a rare fern, *Bostrychium mormo*, with the presence of the introduced earthworms *Lumbricus rubellus* and *Dendrobaena octaedra* (Gundale 2002). In this study, the dramatic changes in forest floor structure associated with the mixing activity of the epigeic and epi-endogeic earthworms was implicated in the destruction of appropriate habitat for the fern.

The effects of earthworm introductions into ecosystems where a native earthworm assemblage is already present are less well known, but some work detailing differences between the ecological roles of native and introduced earthworms has been reported. In tropical forests of Puerto Rico, the introduced species *Pontoscolex corethrurus* increased rates of litter decomposition and CO_2 efflux from the forest floor relative to rates observed in the presence of native species alone (Liu and Zou 2002). Also in Puerto Rican soils, native and introduced earthworm species had differential effects on soil processes such as nitrogen mineralization and microbial respiration (González et al. 1999; Lachnicht et al. 2002). In the North American tallgrass prairies of Kansas, non-native earthworms were dormant during the summer growing season, whereas native species remained active, suggesting that the influences on soil processes of the different species are different depending on season, and may have important implications for nutrient cycling in the system (Callaham et al. 2001). Other examples of ecological impacts of introduced earthworms on native assemblages are discussed by Hendrix et al., this issue.

Control of earthworm invasions

Policy context

Increasingly, environmental policy has been developed in a context of formal risk analysis. Development of ''rational policy'' is possible when a problem is well defined, complete information regarding risk is available, a range of policy alternatives has been assessed, and the goals of the policy are agreed upon (Fiorino 1995). That is, in such circumstances, a theoretical benign autocrat could weigh the pros and cons of a given situation and create uncontroversial and effective policy. Situations where the ''rational policy'' model is applicable are rare.

In the case of developing strategies to mitigate problems associated with invasive earthworms, none of the aforementioned conditions for a simple rational policy approach are adequately met. First, the problem is multifaceted and eludes simple definition—that is, the problem can be stated as one concerning biodiversity decline, harm to critical ecological services, loss of aesthetic value (e.g., loss of native species), and impairment of recreational opportunity (e.g., earthworms damaging putting greens, or limiting the use of non-native earthworms for fishing bait). Secondly, although research on this topic has become more intensive in recent years, the conclusions are not definitive and the risks associated with earthworm invasion are not thoroughly understood or quantified for all species and all potentially impacted ecosystems. Thirdly, policy alternatives have yet to be fully developed and their efficacy is untested. Development of policy alternatives awaits the outcome of a number of different research programs which should evaluate the effectiveness of eradication, control, and management of invasions. Finally, the goals of policy formulation for invasive earthworms are not broadly agreed upon. Although there is a virtual consensus among ecologists on the risks associated with unchecked proliferation of invaders, public awareness of these problems is more limited (Colton and Alpert 1998) and this severely limits the political will to act. This problem is exacerbated when considering earthworms as potential pests since the general perception is that earthworms are 'good'. Furthermore, policies limiting the sale or distribution of non-native earthworms (or earthworm-containing materials) have the potential to result in negative economic impacts for people involved in these trades, and as such, should be expected to meet with strong opposition. Crafting and implementing effective policy in this circumstance depends upon promoting a more balanced and scientifically informed view of the effects of non-native earthworms on ecosystems.

Cost-benefit analysis has been promoted as a useful economic tool to serve as the analytical basis for policy (Patton and Sawicki 1993). Conceptually, assessing both the negative and positive impacts associated with decisions is straightforward. However, cost-benefit evaluation is analytically complex. Commonly, the approach is based upon incremental costs, that is, the cost associated with moving to a new (usually more stringent) level of control. In the case of policy regarding earthworm invasions, there are currently no specific controls, so an assessment of marginal cost of going from no regulation to regulation is difficult to assess. Moreover, as is the case in most policy development associated with ecological risks, a subset of the objectives has a moral basis. That is, although there are clear economic benefits associated with conserving species threatened by invasive earthworms, not all of the motivation for limiting invasive earthworm damage is based upon utility. Conservation is also based upon a sense of responsible stewardship. Addressing policy alternatives to halt biodiversity decline may therefore not be a tractable problem for economic cost-benefit analysis to arbitrate (Roughgarden 1995). Nevertheless, a quantitative and explicitly monetary assessment of policy decisions regarding earthworm invasion may still prove to be useful. Additionally, when performing such an assessment, it is critical to consider that benefits of conservation accrue over the long term, whereas costs associated with regulation and management are both immediate and ongoing. Depending upon the discount rate used in evaluating cost and benefit accruals stemming from conservation policy, investing in conservation can seem unattractive to decision-makers (Krautkraemer 1995). Therefore, creative incentive schemes may be needed to make the benefits arising from seemingly esoteric policy (such as regulation and management for invasive earthworms) appear more attractive. Incentives are also crucial to make the benefits credible to those organizations and individuals who bear the costs of implementing the policy.

Control by stages of invasion

In developing effective approaches to minimizing the risks associated with invasions it is useful to recognize a variety of stages associated with the phenomenon of invasion. These include introduction, establishment, expansion, and saturation by an invader (Shigesada and Kawasaki 1997). Each of these stages will require a different policy approach to be most effective.

Arguably, the lowest cost associated with containing a major invasion is prevention, that is, regulation of materials deemed to harbor a potential invader. However, since not all introduced species will mount a large-scale invasion (Williamson 1996) it would clearly be onerous and prohibitively expensive to quarantine or restrict all such importations. Therefore, a mechanism for assessing risk associated with particular introductions has considerable value. Most of these predictive tools are qualitative and based upon expert assessment (Reichard and Hamilton 1997), though some are quantitative (Kolar and Lodge 2002). Below we recommend an assessment approach suitable for peregrine earthworms.

Approaches that attempt eradication or control at the stage of establishment can be potentially cost-effective. For instance, if one considers the probable costs associated with containing the gypsy moth in Medford, Massachusetts in the 1860s, relative to the current and ongoing costs of controlling this insect invader, the cost-benefits of early intervention seem obvious. Once again, however, knowing which introduced and naturalizing species to target for eradication is made problematic by our limited ability to predict which subset of introduced species will launch major ecosystem-modifying invasions (Williamson 1996). In the case of earthworms a systematic evaluation of which earthworm species may have the greatest impact, and which ecosystems are likely to be most impacted, will allow informed development of effective eradication and control strategies.

Finally, when an invader is expanding rapidly or has reached a saturation point in the invaded systems, eradication is usually not the most feasible alternative. In this case, control of the species through land management practices or other large-scale remediation of the damage caused by the species is most likely to be effective.

Below, we evaluate regulation and control strategies for earthworm invaders. This includes discussion on regulating the importation or movement of soils containing earthworm propagules and discussion on the role of the management of site disturbances in influencing the impact and spread of introduced earthworms.

Regulation of earthworm-containing materials

Regulation of other soil dwelling organisms

Regulation of soil-borne organisms has been standard practice in the USA and Canada for many years, in an attempt to limit introductions or to control spread of agricultural or other plant pests. Examples within the USA include the root knot nematode (*Meloidogyne* spp.), soybean cyst nematode (*Heterodera glycines*), and the imported fire ants (*Solenopsis invicta* and *Solenopsis richteri*). There is a full list of regulated organisms for Canada as well (see http://www.inspection.gc.ca/english/plaveg/protect/dir/d-00-04e.shtml). All of these organisms are subject to some form of quarantine when propagules of the organism are detected in materials flowing into an uninfected region. For example, in the case of fire ants in the southern USA, soil may be transported from areas that have been infested into areas not infested only when the destination is a laboratory that has been issued a special permit to receive such soils. In all other cases, soil or equipment originating from infested areas must be certified to be free of fire ants, farming implements or earthmoving equipment must be cleaned of all soil capable of transporting fire ant propagules (USDA 2004), and horticultural materials must be certified to be ant-free before shipment to non-infested regions can be made. Measures of this type could easily be adapted for use in the regulation or limitation of transport of earthworm propagules from place to place within North America.

Regulation of earthworms through policy

Given the long time-frame and wide geographical extent of earthworm introductions across North America and the globe, it may be tempting to subscribe to the opinion that it is too late for any regulatory action to have meaningful results. However, the most recent work to address this issue quantitatively (Gates 1982) indicates that the rate at which new species are introduced has increased with the increase in international trade in materials that may contain earthworms or earthworm cocoons. These observations were based on collections made at USDA agricultural inspection stations where materials from around the world were examined for presence or absence of earthworms. Furthermore, there still exist large areas of the North American continent that have yet to be invaded by exotic earthworms, and the potential ecological effects of invasion of these areas are not well known (Hendrix and Bohlen 2002).

For nations where no importation guidelines exist, regulatory actions for dealing with the potential introduction of new species of earthworms range from ''do nothing at all'' to ''do everything possible''. In practice, a resolution to ''do something effective and efficient'' is likely the most desirable outcome. Decisions about whether and how to regulate the introduction of earthworms must be based upon the best information available about the ecological characteristics of the earthworm species in question and the susceptibility of invasion for the ecosystem where the exotic earthworm will be introduced (Hendrix and Bohlen 2002). For example, there may be certain behavioral, physiological, or reproductive characteristics that cause certain earthworm species to be of particular concern in terms of ecological risk associated with introduction. Likewise, the locality into which species are introduced may have much to do with the success or failure of new species introductions. One example of the influence of habitat matching is the case of the African earthworm species *Eudrilus eugeniae* which is adapted to tropical lowlands. Although this species has been successfully cultured for sale in the fish-bait industry across the USA and Canada, there have been no published records of this earthworm existing anywhere in temperate North America outside the controlled environments found in gardens and culture beds (Gates 1970; Reynolds 1994a, b). However, this species has been reported from natural systems in the American tropics (Puerto Rico) where it may present serious ecological risks to native earthworm communities or ecosystem properties (Borges and Moreno 1994; G. González, personal observation). Thus, it is clear that regulation of material containing earthworms could be unnecessary and counterproductive in certain cases, but it is equally clear that each case should be examined carefully before the introduction of a new species is allowed; i.e., the possibility of widespread colonization should not be left to chance.

Here, we propose one potential decision-making tool with regard to handling of earthworm-containing media at inspection stations where the destination may be sensitive to the importation of new earthworm taxa (Fig. 3). Formalized decision-making processes such as the one proposed could be a helpful alternative to the *ad hoc* requests for guidance regarding earthworm importations sometimes sought by regulating agencies. This decision-making process allows for the quarantine of materials containing propagules of earthworms that have not been identified or widely introduced previously. These quarantines would provide time to determine the ecological risk posed by the introduction of a given earthworm species into particular systems. Suggested types of information needed to determine ecological risk associated with a quarantined earthworm species are listed in Table 1.

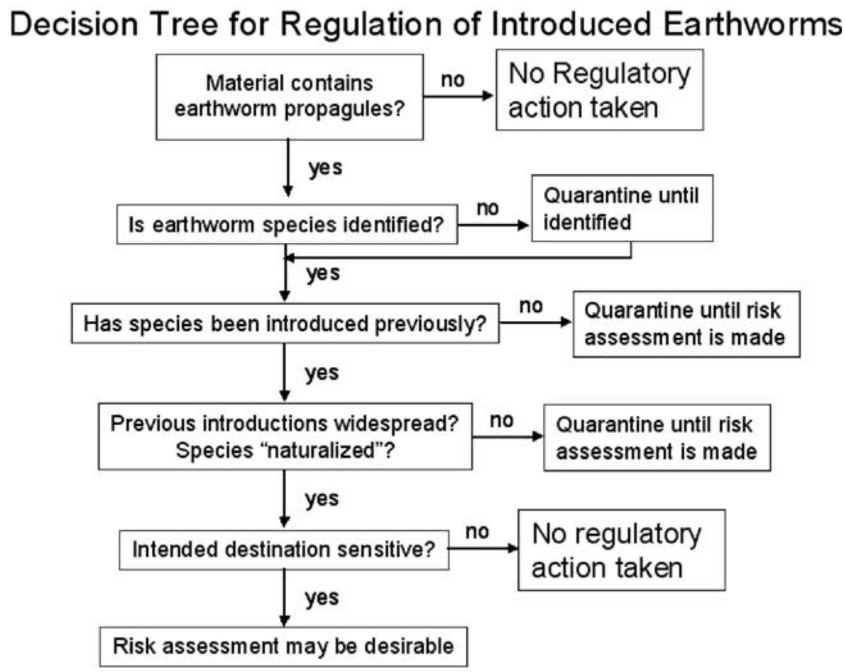

Fig. 3 A prototype decision tree for regulation of earthworms or earthworm-containing media. The initial box represents a source of earthworms or earthworm cocoons, with the ideal scenario being that potential sources (horticultural materials or other soil cargos) could be certified as ''worm-free'', resulting in no regulatory action

Whereas areas supporting both native vegetation and native earthworm communities may possess a certain level of resistance to exotic earthworm invasions (Hendrix et al., this issue), areas without a native earthworm fauna may be particularly susceptible to invasions whether the native vegetation is intact or not (Hale et al. 2005; Frelich et al., this issue). In these areas, the impact of human activity is related to the probability that such activities may transport invasive earthworm species. Given these general observations, when decisions are made about importation of earthworm-containing materials special attention should be directed toward areas where no earthworms (native or exotic) are currently present, where human activities with a high

Table 1 Suggested biological and ecological data to collect for complete risk assessment of new earthworm species potentially entering a new geographic area

Characteristic	Reason for test	Preferable result
Mode of reproduction	Determine if parthenogenic or amphimictic	Amphimictic
Number of embryos per cocoon	Numerous embryos per cocoon increases propagule pressure	One or few embryos per cocoon
Ecological ''strategy''	Determines type of food resource and soil stratum likely to be exploited by species	Depends on locality where introduced. If food resource or habitat of species is scarce, invasion less likely a problem
Temperature/moisture/pH tolerances	Determines habitats and ecosystems where invasion could occur.	Narrow tolerances limit areas where invasion could occur. Mismatch of temperature and moisture requirements to these conditions is desirable

probability of transporting earthworms occur, or where human disturbances have been limited (and native earthworms are present).

Influence of management practices on introduced earthworms

Once introduced, the success or failure of exotic earthworms to establish large populations appears to be influenced at least in part by the past management of the site. In areas where native earthworm populations are present this effect is generally related to the degree of disturbance the site has experienced: the less disturbed the site, the lower the likelihood of exotic earthworm establishment. This type of disturbance relationship has been documented in forested systems of temperate and tropical North America. Kalisz and Dotson (1989) and Dotson and Kalisz (1989) found differences in the frequency of exotic earthworms in soils of Kentucky to be dependent upon the continuity of forest vegetation and proximity to roads or other severe anthropogenic disturbance. In these studies the principal finding was that the fragmented forestlands of the Bluegrass physiographic region were largely dominated by exotic earthworm species, whereas the extensive non-fragmented forests of the Cumberland Plateau were dominated by native species except where severe disturbances had occurred. In tropical systems of Puerto Rico, Zou and González (1997) and González et al. (1999) found that conversion of native forest to pasture systems resulted in dramatic differences in the earthworm assemblages with nearly total dominance of the pasture systems by the pan-tropical exotic species *Pontoscolex corethrurus*. Although *P. corethrurus* was also present in forested systems, the earthworm species native to Puerto Rico were still dominant in the forest earthworm assemblages. However, the regeneration of secondary forest through natural succession in abandoned pastures was shown to promote the recovery of native earthworms, and the reduction of *P. corethrurus* density (Sanchez et al. 2003).

In another system where introduced earthworms coexist with native earthworms, the tallgrass prairie ecosystems of North America, disturbance is an important determinant of the earthworm community composition. The tallgrass prairie system is one that has been subject to chronic disturbance since its beginnings, and indeed the system appears to rely on disturbances such as grazing, fire, and drought to maintain its characteristic vegetation (Knapp and Seastedt 1986). In this case, disturbances vital to the maintenance of tallgrass vegetation were also associated with maintenance of native earthworm communities (James 1988). Further work in this system showed that relatively short-term departures from the natural disturbance regime (i.e., the absence of regular fire) resulted in a shift in dominance of the earthworm community to introduced species (Callaham and Blair 1999; Callaham et al. 2003).

Land management may be influential even in systems where no native earthworm species are present. Heneghan (2003) documented a synergistic relationship between an invasive shrub, and non-native earthworms in oak woodlands of the upper Midwest of the USA. Invasion of buckthorn shrub into oak woodlands in the Chicago area had strong effects on several ecosystem properties, including negative effects on understory vegetation (Heneghan et al. 2002). If the shrub was removed from an area soon after invasion, then these negative effects on native vegetation were short-lived. However, the presence of buckthorn was also associated with high biomass of invasive European earthworms and the additional effects of these earthworms on soil processes and soil structure caused negative effects on the understory plant community to persist for longer periods of time (Heneghan 2003). Thus, early control measures to limit the encroachment of the invasive shrub in these systems may also indirectly limit the size of non-native earthworm populations, and benefit restoration efforts in impacted areas.

Where non-native earthworms are not well established or are found in discrete populations, the use of chemical treatments to eradicate undesirable worms may be a successful strategy. This approach has long been used in the management of golf courses (e.g., Walton 1928; Schread 1952), and has also been successfully used in experimental manipulations of earthworm

Fig. 4 Reproduction of a poster placed in bait shops and other public locations in Minnesota directed at educating consumers about the problem of earthworm introductions. Reproduced courtesy of Minnesota Department of Natural Resources

communities (e.g., Parmelee et al. 1990). Although these treatments are known to be highly effective for earthworm control, it is clear that non-target effects of chemicals on the system should be carefully examined before large-scale use of such chemicals is recommended.

Given the diffuse nature of the spread of earthworms via a range of seemingly benign human activities (such as recreational fishing or planting of ornamental vegetation), public educational efforts will be a critical component of any comprehensive effort to control the spread of exotic earthworms. One example of this type of effort is the Minnesota Worm Watch Program initiated by scientists at the University of Minnesota. In a cooperative effort between the Minnesota Department of Natural Resources, Minnesota Worm Watch, and the Minnesota Native Plant Society, the program focuses on halting the spread of non-native earthworms into remote areas of Minnesota by educating the public about the ecological consequences of introducing earthworms. A variety of educational materials regarding earthworms is available on the internet (http://www.nrri.umn.edu/worms/default.htm). A poster and exotic earthworm fact sheet were distributed to more than 1500 bait shops, as well as hundreds of nature centers, park visitor centers, and other venues across the state (Fig. 4). Public response to these efforts has been generally favorable, and the basic message to avoid dumping unused bait in remote areas has been well received.

Conclusions

Although earthworm introductions have a long history in North America, there are still many areas on the continent where no exotic species occur. Efforts to prevent the introduction of exotic earthworms into these areas are most likely to be successful through some combination of regulatory policy, public education, and implementation of appropriate land management practices. We have suggested a decision-making strategy for regulation of earthworm-containing materials flowing into North America as well as movement of such materials from place to place within North America, but the data needed to efficiently implement this strategy are scarce. More research into the characteristics of earthworm species likely to become successful invaders of North American ecosystems is needed. Likewise, more research on land management effects on earthworm communities should result in better strategies for containment of non-native species and conservation of native species.

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