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Invasive Earthworms in the Crown of the Continent System and Implications for Land Management

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INVASIVE EARTHWORMS IN THE CROWN OF THE CONTINENT SYSTEM AND IMPLICATIONS FOR LAND MANAGEMENT

By

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ABSTRACT

The United States contains invasive earthworms originating from Europe and Asia; the majority are European lumbricids. Direct introduction occurs primarily through human activity and, once established, earthworm populations are difficult to address. When exotic earthworms engage in bioturbation, they negatively alter subterranean food webs and nutrient cycling by disrupting soil layering systems. The most prominent form of physical alteration is the change and removal of the topmost organic layer. This disruption is associated with altered nitrogen and carbon cycling, as well as altered forest floor plant communities.

The Crown of the Continent ecosystem is located in southwestern Alberta, southeastern British Columbia and northwestern Montana. This unique transboundary system is home to distinct biodiversity and is less altered by humans than many other ecosystems. The presence of exotic earthworms introduces new challenges for land managers and local soil systems. Current US policy offers an ineffective “innocent until proven guilty” attitude towards introduced species. Preventing spread and mitigating the effects of exotic earthworms is needed to preserve soil quality. Non-native earthworms and earthworm products could be banned and/or restricted by land managers to prevent further spread. Supplemental action, such as invasive species education programs, can enhance preventative practices.

INTRODUCTION

PURPOSE

The purpose of this project is to investigate the presence and significance of exotic earthworms in the Crown of the Continent ecoregion. It explores the implications of their presence and informs land managers how to address exotic earthworms effectively.

RESEARCH QUESTIONS

a) What is the destructive potential of exotic earthworms in the Crown of the Continent?
b) What are the implications for land managers in the Crown?
c) What actions can land managers pursue to prevent further spread and mitigate the negative effects of exotic earthworms?
d) What wider impacts can be inferred?

BACKGROUND

The United States contains invasive earthworms originating from Europe and Asia. Two of the most common means of introduction are soil translocation and the direct release of live bait used for recreational fishing (Bohlen et al., 2004). Sometimes called "invisible invasives," earthworms are challenging to address because they can withstand undesirable environmental conditions and will quickly spread across new habitats through human action. They engage in soil systems primarily through bioturbation, or the mixing of soil materials by plants or animals. However, when invasive earthworms perform bioturbation in their new soil systems, they can negatively alter subterranean food webs and nutrient cycling.

The Crown of the Continent ecosystem, or COC, is a transboundary ecological system comprised of northwestern Montana, southeastern British Columbia, and southwestern Alberta. This system is unique because it is less altered by humans than many regional ecosystems; it is a meeting point of the Rocky Mountains and the Great Plains, which provides stunning biodiversity (Crown Managers Partnership, 2020). This ecosystem is currently facing two major challenges: increased human activity and high sensitivity to climate change. However, with the presence of exotic earthworms confirmed within the Crown, this system and its land managers face new challenges to the Crown's soil systems.

AN INTRODUCTION TO EARTHWORMS

EARTHWORM ANATOMY AND TAXONOMY

Earthworms are invertebrates of phylum Annelida, class Oligochaeta, and order Opisthophora, which consists of terrestrial segmented worms. They are soft-bodied invertebrates with a simple tube body structure: one exterior tube and one interior tube. One of their most notable interior features is the crop and gizzard system. Figure 1 displays an internal anatomy similar to that of a bird: the crop receives ingested materials and the gizzard grinds food as it passes into the digestive tract. In the study of ecology, they are best known for their influence on soil structure and the breaking down of organic materials (Coleman et al., 2004).

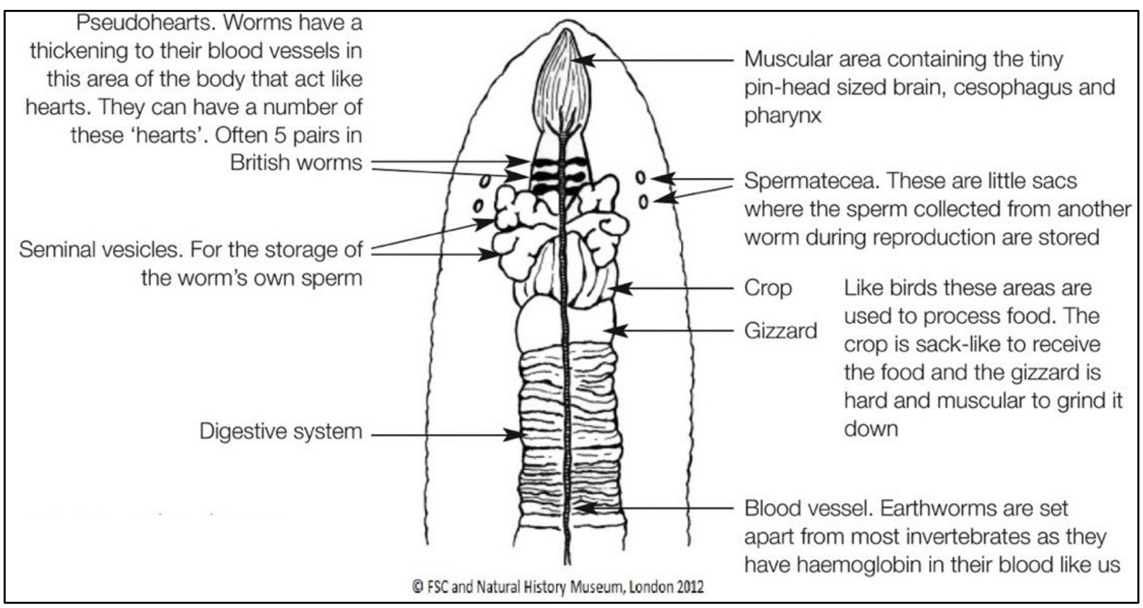

Figure 1. The simplified internal anatomy of earthworms (Source: Earthworm Society of Britain, 2020)

PRESENCE IN NORTH AMERICA

The distribution of native earthworms in North America is believed to be heavily influenced by the Wisconsin Glaciation of the late Pleistocene Epoch (Tiunov et al., 2006). Very few native earthworms can be found in the areas previously covered by the Wisconsin Glaciation's ice sheets, as displayed in Figure 2. Species currently found within the areas of the major ice sheets are believed to have colonized the area post-glaciation. There are five native families of earthworms in North America: Lutodrilidae, Sparganophilidae, Komarekionidae, Lumbricidae, and Megascolecidae (Hendrix, 1995). Table 1 lists these families and their locations across the continent. As noted later in this literature review, the majority of native earthworms in North America can be found in the more temperate regions of the United States, especially in eastern deciduous forests.

Figure 2: The ice sheets of the Wisconsin Glaciation (Source: Encyclopædia Britannica, 2022).

Table 1. A brief overview of earthworms native to North America (Source: Hendrix, 1995)

TAXONOMIC FAMILY	DOCUMENTED RANGE	SPECIES OBSERVED IN THE CROWN OF THE CONTINENT	LOCATION IN THE CROWN OF THE CONTINENT
Lutodrilidae	Louisiana, United States	none	
Sparganophilidae	Across United States (except Southwest region) Ontario, Canada	none	
Komarekionidae	Eastern United States	none	
Lumbricidae	Neararctic Eastern United States, as far west as Kansas Lake Ontario, United States	*Bimastos beddardi*	Lake County, 1917 (Reynolds, 2016)
Megascolecidae	American Midwest American Southeast American Southwest Mexico	none	

EXOTIC EARTHWORMS

NON-NATIVE SPECIES VERSUS INVASIVE SPECIES

The terms “exotic” or “non-native” refer to species not naturally occurring in the area in which it is found; the term “invasive” refers to an exotic species that causes ecological disturbance to the area in which it is introduced (Hendrix et al., 2008). For the duration of this paper, the terms “exotic” and “non-native” will be used interchangeably. The answer to why some geographic areas are more highly invaded than others can only be partially answered due to lack of adequate research. Invasion biology provides several answers: exotic earthworms are known to colonize and become established in areas of anthropogenic ecosystem disturbance. Whether a species becomes invasive depends on local climate, land use, and soil conditions.

EXOTIC EARTHWORM DISPERSAL

Anthropochory, or dispersal by humans, is considered the foremost method of exotic earthworm distribution in North America. Hydrochory, or dispersal by water, is considered to be another effective method of dispersal. Zoochory, or dispersal by animals, and anemochory, or dispersal by wind, are not considered major methods of dispersal (Terhivuo and Saura, 2006). The earliest form of non-native earthworm anthropochory in North America is believed to be by European settlers, who deposited soils from both ship ballast and plant materials transported to the Americas (Tiunov et al., 2006). Current forms of anthropochory include the disposal of fishing bait, vermicomposting, and intentional introduction by gardeners. Some of the most popular species used for fishing bait include *L. terrestris*, *L. rubellus*, *A. tuberculata*, and *A.*

turgida; these species can be found in domestic yards and gardens across North America (Cameron et al., 2007). *E. fetida, E. andrei,* and *D. veneta* are considered composting worms and can be found in both commercial facilities and in domestic bins (Suleiman et al., 2017). These earthworms are often cultured and raised in commercial facilities both domestically and abroad.

INVASION AND SPREAD

Though comparative studies of invasive versus non-invasive earthworms are lacking, exotic earthworm behavioral and morphological traits are known to act as mechanisms of invasion. However, prior invasion success is widely considered the clearest indicator of a species' ability to successfully invade a new area. Both endogenous traits, or traits inherent to a species, and exogenous traits, or traits inherent to an environment, can contribute to the overall invasiveness of some species (Hendrix et al., 2008). Predicting the invasiveness of exotic earthworms is a developing area of study; measurable factors, such as feeding, environmental tolerances, reproductive strategy, locomotion, and disturbance tolerance, are considered viable areas of such study.

Environmental plasticity – the ability of a species to adapt and survive in varying environmental conditions within its native habitat – is one probable factor in determining how invasive a species will be in a new habitat. A species becomes invasive when it is both widespread and locally dominant, and usually includes negative ecological impacts. The process of becoming invasive concludes when both establishment and local spread are followed by an increase in abundance (Colautti and MacIsaac, 2004). However, the details of invasion ecology are outside of the scope of this paper. Though spatial distribution of exotic earthworms within newly-invaded habitats can be patchy, these distributions correspond with environmental factors like temperature, soil texture, soil pH, and vegetation (Addison, 2009). Simulating exotic earthworm spread via modeling has rarely been pursued due to limited data, though modeling suitable habitat, introduction of adequate numbers, and local dominance can be used to help predict earthworm invasiveness.

Some earthworm species are known to survive in both frigid and arid areas for part of the year – in periods of unfavorable conditions, some deep-dwelling species of anecic earthworms will enter a state of cryptobiosis or will produce a protective cocoon from which they hatch when conditions are more favorable (Coleman et al., 2004). Some surface-dwelling epigeic species are hermaphroditic, containing both male and female reproductive structures, and others are parthenogenetic, able to develop viable ovum without fertilization. These qualities allow some species to reproduce individually, giving them the ability to spread into new areas without requiring another individual with which to mate and reproduce.

Of all exotic earthworm species considered invasive, the surface-dwelling *L. rubellus* is known to be one of the most destructive. This species can consume over 10 cm of intact forest floor in a single growing season, causing such rapid habitat alteration that vegetation rooted in this layer cannot adapt – consequently, plant mortality can be high. The less destructive *L. terrestris* gradually impacts forest floor thickness, which allows more time for organisms to adapt to such changes. Though it is commonly found deeper within soil layers, *L. terrestris* still consumes leaf litter, thereby reducing forest floor thickness and organic input to the forest floor's lower layers (Frelich et al., 2006).

CURRENT NON-NATIVE EARTHWORMS IN NORTH AMERICA

In a 2006 study within the Great Lakes region of the United States, climate, habitat, and human interaction all impacted invasions by European earthworms. Because many of the European species found in the Great Lakes are not frost-tolerant, it is likely that they hibernate deep within the soil (Tiunov et al., 2006). Exotic earthworm distribution and density can differ in native versus new habitats; these habitats contain differing soil conditions, such as pH, texture, moisture, and litter source. For instance, European evergreen forests with dry, sandy soil and acidic evergreen litter tend to contain less earthworm biomass than North American deciduous forests with wet loamy soils and thick, leafy leaf litter.

Though anthropogenic habitat alteration is associated with earthworm expansion, the Great Lakes study sites indicated that human activity remains the foremost determinant of earthworm dispersal. This study states that the main form of earthworm dispersal is the dumping of live fishing bait along bodies of water. The main species used for fishing bait are *L. terrestris* and *L. rubellus,* though it is not uncommon to find other species in fishing bait (Tiunov et al., 2006). In the United States, agricultural commerce is the main vector of earthworms into areas of high human activity; in more remote areas, off-road recreation and backcountry fishing are considered the main source of earthworm introduction. As of the 1990s, approximately 25 species of European Lumbricidae and 14 species of Asian Megascolecidae can be found in North America (Hendrix et al., 2008).

ATTITUDES SURROUNDING EARTHWORMS

The first person to show the effects of earthworms on soil processes was Charles Darwin. Subsequent research in terrestrial systems showed that earthworm activity was beneficial to agriculture: increased litter decomposition, enhanced water infiltration, improved soil aggregation, and increased nutrient transformation and uptake (Hendrix and Bohlen, 2002). Consequently, the prevailing attitude towards earthworms in North America is positive; few individuals are aware that some species are non-native and harmful to native forest systems (Ehrenpreis, 2014). However, awareness of exotic earthworms is increasing and the subject is considered a developing area of scientific research. In 2010, a global meta-analysis of conservation concerns listed "Vegetation change facilitated by earthworms in North American forests" as one of fifteen novel concerns relating to biodiversity and environmental quality (Sutherland et al., 2011).

Unsurprisingly, it can be difficult for land managers to address such non-charismatic "invisible" species due to limited information and limited public awareness (Cameron et al., 2013). Common management practices focus on prevention, as there is no functional method of controlling an established population of non-native earthworms. Prevention requires education, yet education does not always lead to the desired outcome. In 2009, the Alberta Worm Invasion Project was launched to increase the awareness of earthworm invasions in forests and to educate anglers on the disposal of worm bait in Alberta, Canada. This project included the use of magazine articles, posters in bait shops, television clips, and radio interviews. However, this study's main survey indicated no significant decrease in bait abandonment occurred; 46.7% of survey participants who were not initially exposed to this project's media indicated that they would not change their earthworm disposal habits after learning the harms of exotic earthworms (Cameron et al., 2013).

EXOTIC EARTHWORMS IN FOREST AND MOUNTAIN SOILS

PHYSICAL EFFECTS OF EXOTIC EARTHWORMS

A study in the forests of New York highlights some of the effects that earthworms can have upon deciduous forest soils. The presence of surface-dwelling *D. octaedra* and soil-dwelling species *L. rubellus* and *L. terrestris* resulted in the mixing of multiple organic sub-horizons over a thin A horizon and a well-developed E horizon. Figure 3 displays the basic layering of soil systems. This bioturbation facilitated by multiple non-native species caused the native New York forest soils to more closely resemble those of the Northern European hardwood forests – the same forests that are home to the aforementioned lumbricid species (Frelich et al., 2006). This kind of invasion is known to increase soil bulk density by displacing native soil invertebrates, decreasing forest floor thickness, and cementing soil through casting and burrowing.

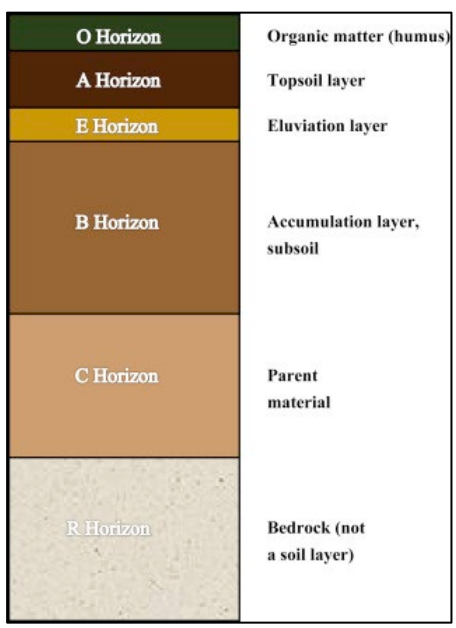

Figure 3: A visual of the major soil horizons (Source: Török and Dransfield, 2017, p. 346)

A 2020 study on the *Amynthas* species of earthworms, informally known as "Asian jumping worms," found that their presence is associated with increased soil aggregation across four forest types across the Upper Midwest: European buckthorn, sugar maple, white oak, and white pine (Bethke and Midgley, 2020). The relative abundance of larger soil aggregates close to 2 mm increased, whereas the abundance of smaller soil aggregates less than 500 µm decreased. This trend is likely due to the formation earthworm fecal pellets, which are simply aggregates of non-digestible materials – materials consisting mostly of inorganic soil particles. Increased soil aggregation via *Amynthas* activity is believed to decrease a soil's water-holding capacity, potentially affecting the growth of maple seedlings. These seedlings are known to have a shallow root system and, consequently, can only uptake water in the uppermost soil layers of soil wherein the majority of earthworm activity occurs.

CHEMICAL EFFECTS OF EXOTIC EARTHWORMS

A 2020 meta-analysis investigated the effects of invasive earthworms on soil chemistry. This study found that invasive earthworm bioturbation caused increased soil pH, as well as increased soil nitrogen fluxes and overall soil nitrogen loss (Ferlain et al., 2020). It concluded that these chemical shifts have the potential to alter plant, microbial, and invertebrate communities. In turn, changes in these communities have the potential to negatively alter the structures and functions of the native systems at large.

Earthworm presence is associated with reduced carbon-nitrogen ratios in forest soils; consequently, plant-available ammonium decreases and nitrification increases

(Szlavecz et al., 2006). A decrease in ammonium results in increased nitrate: an increase in nitrification results in a faster conversion of ammonia to nitrite and nitrite to nitrate. Of these three, nitrate leaches most easily and leaves the soil sink, as displayed in Figure 4. This relationship links increased nitrification to a decrease in overall nitrogen (Niboyet et al., 2011). The storage of organic carbon in soils often requires high levels of nitrogen, thereby linking nitrogen availability to soil's capacity to sequester and store carbon (Cotrufo et al., 2019). This relationship implies that exotic earthworms may negatively affect the native soil's carbon sequestration– a function that has gained special attention in the modern climate crisis.

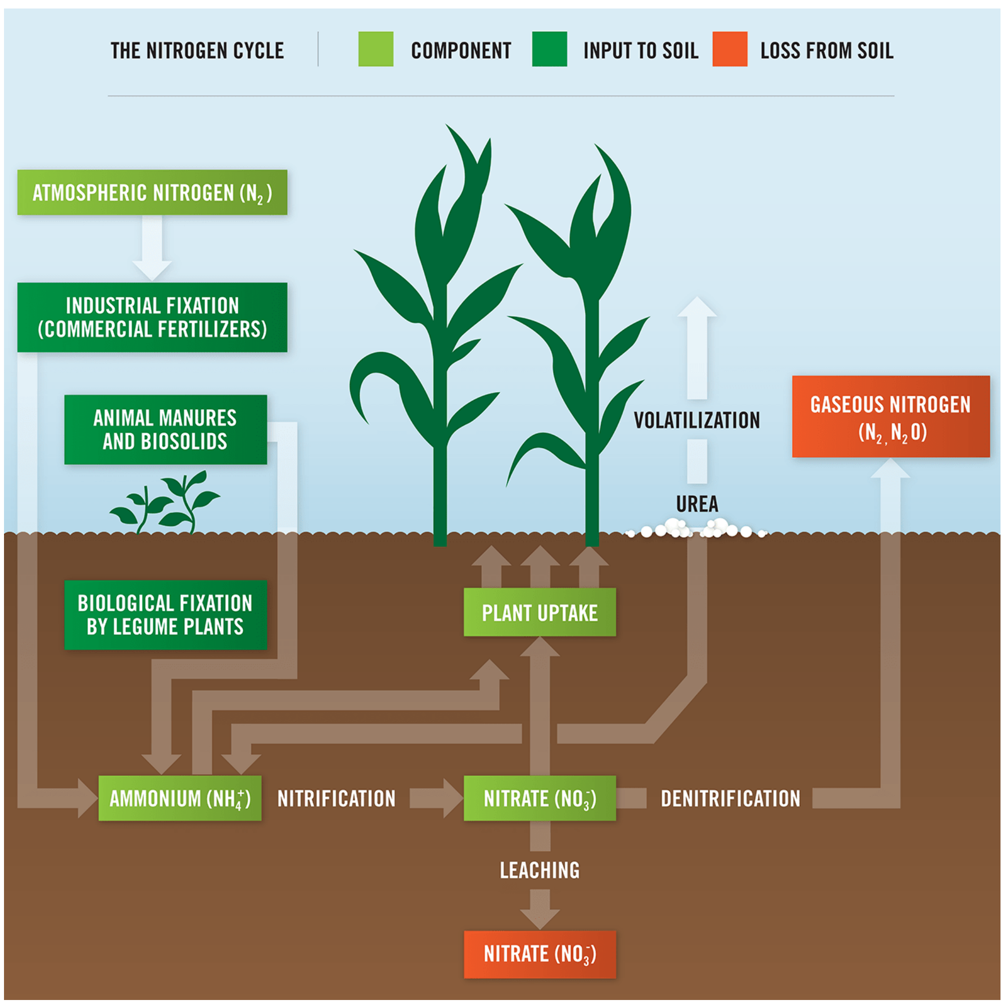

Figure 4. The nitrogen cycle in soils (Source: Koch Agronomic Services, 2021)

BIOLOGICAL EFFECTS OF EXOTIC EARTHWORMS

The impact of exotic earthworms upon native plant communities is considered both cumulative and substantial. In the mature sugar maple forests of Minnesota, it was found that invaded areas contained lower cover and density of both native tree seedlings and herbaceous plants, such as spikenard and Solomon's seal (Frelich et al., 2006). This study listed five different possible causes of this trend: removal of the organic-rich duff layer, increased deer-to-plant ratio, disruption of mycorrhizae, earthworm consumption of seeds, and changes in soil chemistry. Of these five possibilities, the removal of duff layer – the organic-rich layer between a soil's surface and its mineral soil – is the most viable and substantial cause of direct impact.

In such temperate forests, leafy detritus provides key nutrient input for the underlying soil and serves as both a seedbed and a rooting zone for plants. Through the consumption and removal of the topmost duff layer, non-native earthworms directly remove a major source of soil organic matter. This activity can disrupt both tree seedlings and herbaceous plants, which can significantly alter forest floor structure. When understory plant species accustomed to a thick forest floor are suddenly without this key organic layer, thin-stemmed plants accustomed to a thin forest floor and direct contact with mineral soil can outnumber duff-dependent herbaceous plants (Frelich et al., 2006). These duff-dependent herbaceous plants are not adept colonizers and are slow to re-establish without nearby source populations, hence sparse assemblages of low-diversity understory plants can dominate forest floors for decades and even centuries following an earthworm invasion. This same Minnesota study suggests that earthworm species type and the order in which multiple species invade a soil system can impact forest understory diversity following an earthworm invasion.

There are few detailed studies on earthworm interactions with soil microbes – primarily fungi and bacteria. They display contradictory findings across several forest types and earthworm species. However, the presence of exotic earthworms is known to decrease fungal species density, diversity, and richness. These few studies have found that, in low-carbon soils, earthworms are associated with an increase in microbial respiration and biomass. (McLean et al., 2006). It is hypothesized that, when exotic earthworms are introduced to a soil system, the microbial community responds by changing to a less diverse, more active assemblage of microbes – an adaptation that directly decreases microbe biodiversity.

As for soil invertebrates, exotic earthworms can facilitate a few positive short-term impacts. These impacts include increased abundance of soil invertebrates, increased soil heterogeneity, and the introduction of earthworms as a potential food source to small vertebrates or large invertebrates (Migge-Kleian et al., 2006). However, native invertebrates can bear negative effects in the long term – burdens that outweigh the few positive impacts that non-native earthworms can bring. Both lab and field studies indicate that bioturbation via earthworm activity leads to decreased abundance of soil fauna. Resource competition, altered understory vegetation, disturbance of organic horizons, and the physical disturbance of soil are all believed to contribute to this decline. Additional evidence suggests that vertebrate fauna, such as salamanders, can decline in number due to reduced abundance of soil fauna and disturbance of soil microclimates.

THE CROWN OF THE CONTINENT

AN OVERVIEW OF THE CROWN

The Crown of the Continent ecosystem, abbreviated COC and CCE, is a transboundary ecological system comprised of northwestern Montana, southeastern British Columbia, and southwestern Alberta. Figure 5 displays a heterogenous landscape comprised of a 43,700 km^2 network of mountains, valleys, rivers, and lakes. The center of this system includes Waterton-Glacier International Peace Park, which has been designated by the United Nations as both a World Heritage Site and an International Biosphere Reserve (Hauer et al., 2007). This park contains Triple Divide Peak, whose precipitation flows into the Mississippi, Columbia, and Saskatchewan river systems. The United States side, which contains approximately 60% of the Crown, contains five federally protected wilderness areas and Glacier National Park; the Canadian side, which contains approximately 40% of the Crown, contains Waterton Lakes National Park plus an adjacent provincial park (Prato and Fagre, 2007).

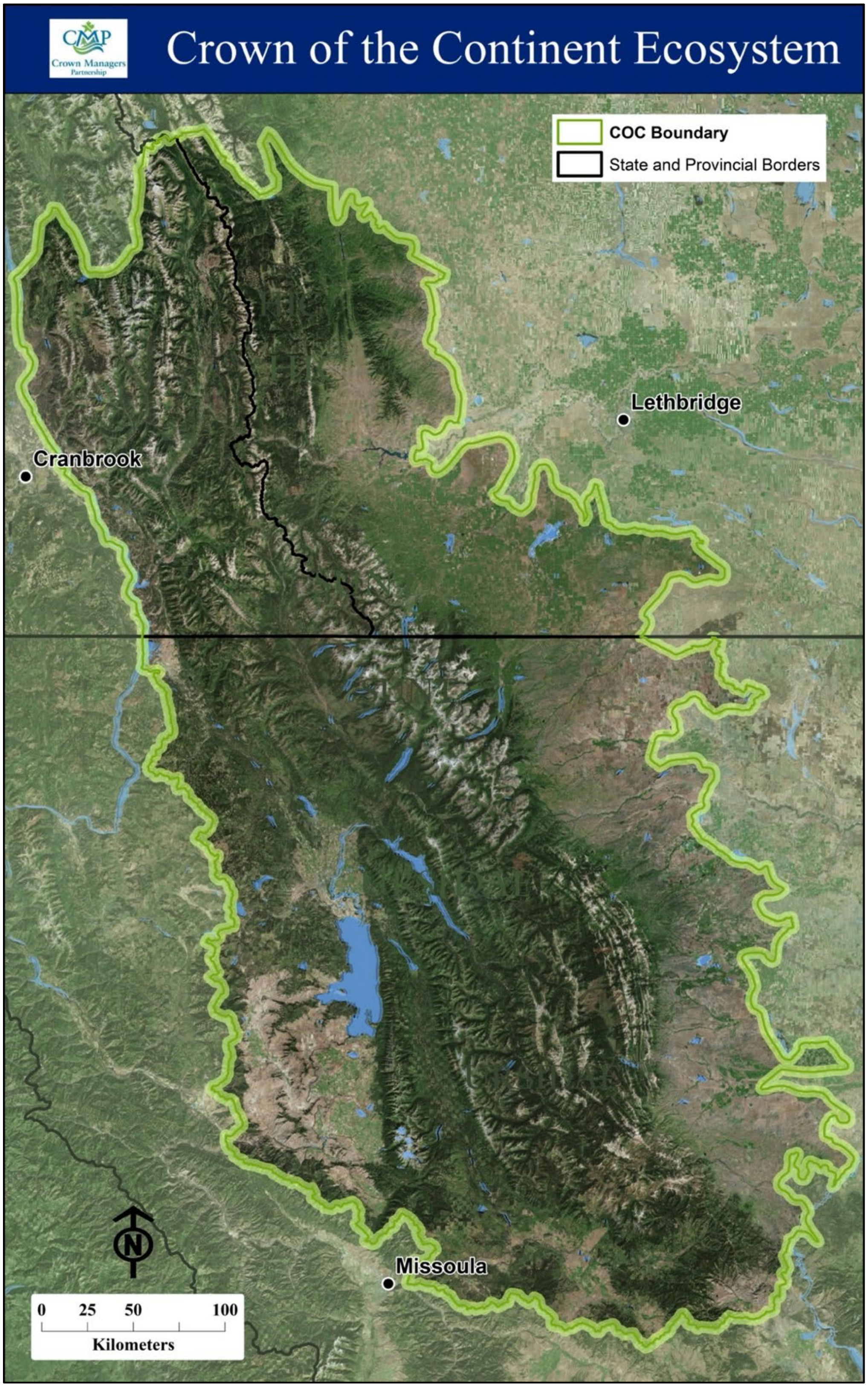

Figure 5. Crown of the Continent Ecosystem Landscape (Source: ScienceBase, 2017)

This system is the meeting point of the Pacific Northwest, Rocky Mountains, the Great Plains, which provides the conditions for biodiversity found nowhere else in North America (Crown Managers Partnership, 2020). This system is special because it is less by humans than most of North America. Vast swathes of connected land corridors reaching as far north as the Yukon region of northern Canada provide large terrestrial mammals, such as grizzly bears, a wide range in which to travel and reproduce. The Crown's aquatic habitats are renowned for their cold, clear, and clean waters – the slightest environmental change is known to cause massive ecological disruption (Prato and Fagre, 2007). Its plant communities include lush valley grasslands, herbaceous shrubs within coniferous forests, carpets of alpine wildflowers, and, more recently, nuisance exotic weeds.

LAND MANAGEMENT WITHIN THE CROWN

Knowing the differences between private land and public land ownership key to understanding land management within the Crown. As of 2007, 17% of the COC's lands are privately owned, while the remainder is mostly public land (Prato and Fagre, 2007). Most of the Crown's flatland is privately owned agricultural land; with recent population growth, some rural land owners have developed or sold their property. However, some private landowners have contributed their land to conservation efforts, such as The Nature Conservancy and Nature Conservancy Canada.

The US Department of the Interior and the US Forest Service manage millions of hectares of forests, reservoirs, and wildlife refuges. The Crown is home to several recognized Indigenous groups: the Blackfeet Tribe, the Confederated Salish and

Kootenai Tribes, the Kainai First Nation, the Piikani First Nation, and the Ktunaxa Nation. Montana's state parks and Canada's provincial parks provide large areas for outdoor recreation and wildlife management. Waterton-Glacier International Peace Park is comprised of two parks: the United States' Glacier National Park and Canada's Waterton Lakes National Park. This transboundary area is used for both recreation and preservation, except for a few parcels of private land contained within Glacier National Park.

One of the foremost areas of focus for these land managers is transboundary cooperation. As displayed in Figure 6, the Crown contains a plethora of jurisdictions on both sides of the border. Such fragmentation creates the challenges of cumulative effects and incremental decision making – informally known as the "tyranny of small decisions" – which threaten consistent, sustainable management of such a distinct landscape. Therefore, cooperation between management entities must be pursued in order to achieve effective ecological co-management. A 2003 study in which local land managers were interviewed regarding transboundary cooperation identified its four major benefits (Pedynowski, 2003, p. 1268):

1. Long-term continuity
2. Commitment of jurisdictional resources to collaborative projects
3. Essential sharing of data
4. Acceptance of the results obtained from collaborative studies

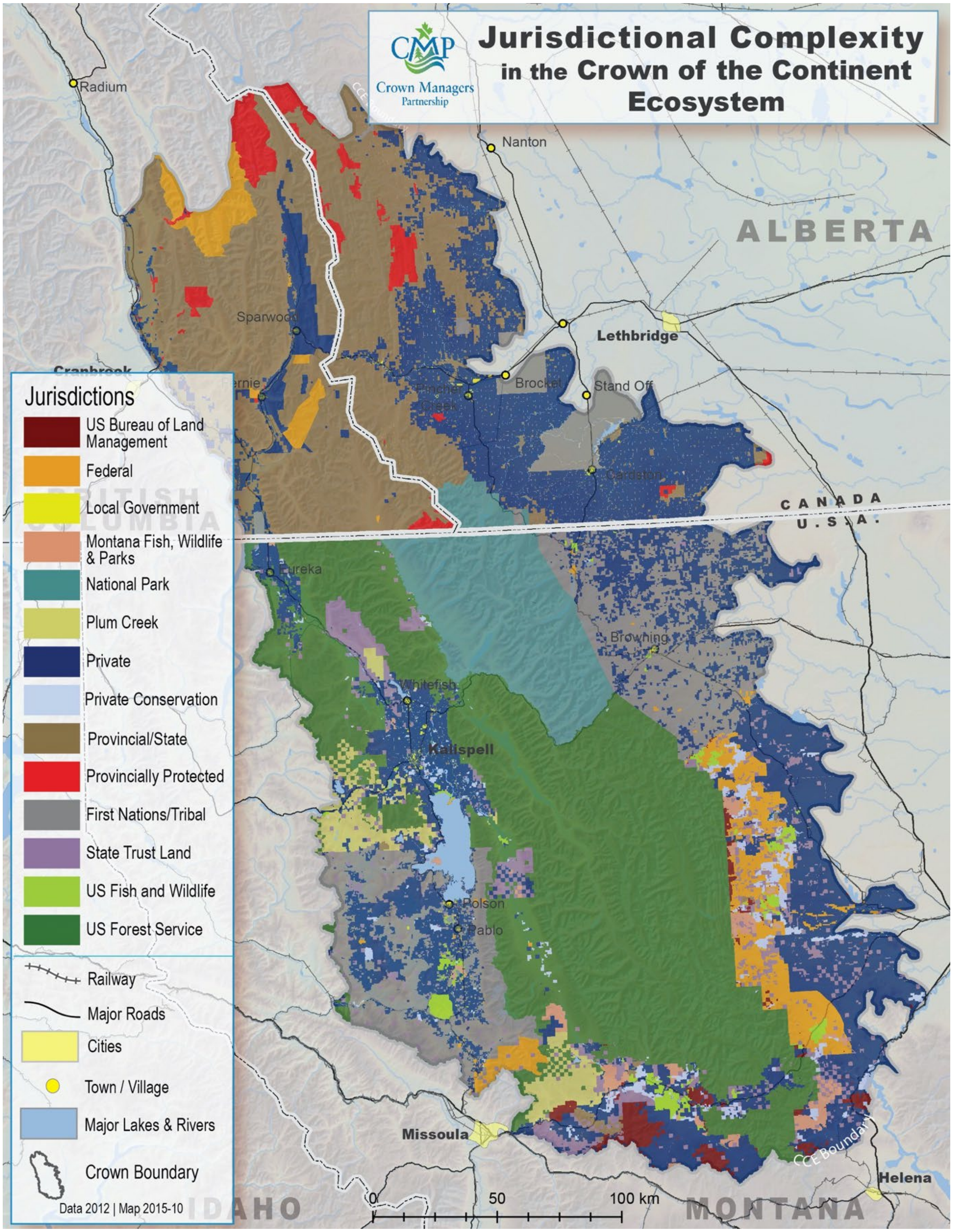

Figure 6. Jurisdictional Complexity in the Crown of the Continent Ecosystem (Source: ScienceBase, 2016)

CURRENT PREDOMINANT THREATS

Human presence is widely considered the largest threat to the Crown of the Continent's landscape. Its picturesque lands, bounty of natural resources, and increased economic growth have attracted new residents, while these same factors encourage old residents to stay. The Rocky Mountain West experienced a population increase of 25% in the 1990s, while its economic base saw a shift from resource extraction to recreation and tourism (Prato and Fagre, 2007). Anthropogenic changes in land cover and land use both impair the Crown's ability to provide ecosystem services, such as water purification and nutrient cycling.

Landscape change via physical development of land into roads and residential or commercial properties remains the most prominent form of human disturbance. Population and economic growth are the primary drivers of such physical development, which can increase the spread of non-native species and can directly cause negative environmental impacts. Environmental degradation is known to depress economic conditions, lower personal incomes, and impair human health. Analyzing the impacts of future development in the Crown is challenging because comprehensive ecosystem modeling is demanding due to the ecosystem's complexity; much uncertainty remains regarding future policy and a large amount of data must be generated in order to complete such an assessment (Prato and Fagre, 2007).

The Crown of the Continent is particularly sensitive to climate change, as mountainous regions are already subject to wide-ranging climate variability and tend to experience acute impacts of climate change. In the Crown, global climate change can be seen in glacier recession, reduced snowpack persistence, and intensifying forest fires (Prato and Fagre, 2007). From 1910 to 1980, the Glacier National Park area experienced a 1.6°C/2.88°F increase of average annual summer temperature – an increase nearly three times the global average of 0.6°C (Prato and Fagre, 2007).

Non-native species are considered one of the greatest threats to native biodiversity in the Crown of the Continent. Though their adverse effects upon native biodiversity is a developing body of knowledge, it is known that they disrupt key ecological processes, such as predation and competition. The most prominent non-native species are plants, such as knapweed and leafy spurge; the spread of these plants is associated with human activity, especially those involving motorized vehicles (Prato and Fagre, 2007). Managing exotic vegetation utilizes strategies such as biocontrols, manual removal, herbicide use, and revegetation. Animal invasives, such as the brook trout and the brown trout, and pathological invasives, such as white pine blister rust, sometimes utilize similar methods of management.

ALPINE CONDITIONS: SOIL AND WATER

The Crown of the Continent is considered an alpine region, with picturesque high peaks and small niches tucked within its crevices. These mountainous regions are poorly understood because weather-recording stations are difficult to maintain in such isolated areas with mountain weather (Prato and Fagre, 2009). However, it has been established that, in the Crown, summer climate conditions are characterized by long days of intense solar radiation, high winds, and warm temperatures. Winter climate conditions are characterized by low temperatures and short days of low solar radiation, as well as snowfall sometimes exceeding the precipitation input of summer storms. In high elevations, this snowfall is the main source of precipitation and water input. Slopes facing the west and southwest tend to hold little snow, whereas snow on the opposite slopes tends to accumulate.

As with the climate of the entire region, the geologic conditions of the Crown are defined by mountains and ice. The Pleistocene Glaciation is one of the foremost events influencing the Crown's current soils and glacial till can be found throughout the region. The Crown's presence within the mid-latitudes of the globe means distinct seasonal shifts, with short summers and long winters influencing soil development; its alpine soils tend to be poorly developed and immature, with some areas absent of soil and consisting only of bare rock. The most fertile and well-developed soils can be found at the bottom of deep valleys, where silt and sand have accumulated for millions of years (Prato and Fagre, 2007).

EXOTIC EARTHWORMS IN THE CROWN OF THE CONTINENT

RECORDS OF NATIVE AND NON-NATIVE EARTHWORMS IN THE CROWN

A 2009 study of the exotic earthworms in Canadian forest ecosystems provides more localized information on the presence of earthworms in the Northern Rockies and its surrounding regions. The earliest formal records of non-native earthworms in Canadian forests begin in 1980s. Reports in the late 1990s and early 2000s from the northern temperate forests of the United States sparked concerns of similar impacts: altered nutrient cycling, changes in forest floor composition, and decreased microbial biomass (Addison, 2009). Only eight species of earthworms are native to Canada, including *B. beddardi,* and the majority of these exhibit limited distribution across the country, as listed in Table 1. Conversely, nineteen species of exotic earthworms can be found across the country – the majority of which are European lumbricids and can be found in the forests scattered across Canada's vast landscape. Table 2 lists the exotic Lumbricidae species found in northwestern Montana – several of which are known to cause ecological harms of varying degrees.

Table 1. An overview of earthworms native to North America (Source: Hendrix, 1995)

TAXONOMIC FAMILY	DOCUMENTED RANGE	SPECIES OBSERVED IN THE CROWN OF THE CONTINENT	LOCATION IN THE CROWN OF THE CONTINENT
Lutodrilidae	Louisiana, United States	none	
Sparganophilidae	Across United States (except Southwest region) Ontario, Canada	none	
Komarekionidae	Eastern United States	none	
Lumbricidae	Neararctic Eastern United States, as far west as Kansas Lake Ontario, United States	*Bimastos beddardi*	Lake County, 1917 (Reynolds, 2016)
Megascolecidae	American Midwest American Southeast American Southwest Mexico	none	

Table 2: Lumbricidae species found within seven counties in northwestern Montana (Source: Reynolds, 2016).

SPECIES	ORIGIN	LOCATION IN MONTANA
Aporrectodea longa	Europe	Powell Co.
Aporrectoea rosea	Europe	Lake, Lewis and Clark, Powell, Teton Cos.
Aporrectodea trapezoids	Europe	Flathead, Lake, Lewis and Clark, Powell, Teton Cos.
Aporrectodea tuberculata	Europe	Flathead, Glacier, Lake, Powell, Teton Cos.
Aporrectodea turgida	Europe	Lake, Powell Cos.
Bimastos beddardi	North America (native)	Lake Co.
Dendrobaena octaedra	Europe	Lake, Powell Cos.
Dendrodrilus rubidus	Europe	Flathead, Glacier, Lake Cos.
Eisenia foetida	Europe	Lake, Lewis and Clark Cos.
Eiseniella tetraedra	Europe	Flathead, Lake Cos.
Lumbricus rubellus	Europe	Flathead, Glacier, Lake, Powell, Teton Cos.
Lumbricus terrestris	Europe	Lake, Lewis and Clark Cos.
Octolasion tyrtaeum	Europe	Flathead, Glacier Cos.

Studies of the aspen and lodgepole pine forests of the Kananaskis Valley, located on the eastern slope of the Rockies outside of the Crown's northern boundary, yielded results similar to those of the exotic earthworm studies in the United States. The Kananaskis study is rare because the site was studied over more than twelve years and, because no exotic earthworms were found prior to 1985, a significant portion of studies after 1985 focused on environmental conditions both before and after recorded earthworm presence (Addison, 2009).

RISK ASSESSMENT: PRESENT SPECIES AND KNOWN RISKS

Because the connections between below and above ground ecological processes are poorly understood, performing any kind of risk assessment for exotic earthworms is distinctly difficult. For instance, the species listed in Table 3 are all exotics currently found in North America, yet simply understanding adverse effects upon soil does not qualify as an adequate risk assessment. Research on invasive terrestrial invertebrates focuses primarily on pest insects, while research on invasion biology of soil invertebrates focuses primarily on species of economic importance (Hendrix and Bohlen, 2002). The invasion of soil fauna is so fundamentally different from other terrestrial invertebrates that it is sometimes considered more similar to plant invasion than animal invasion. Differences in data are so distinct that patterns of exotic flatworm invasion are considered ideal models of comparison to those of exotic earthworm invasion.

Table 3: Species of exotic earthworm found in North America and their known adverse effects (Source: Montana Field Guide).

SPECIES OF EXOTIC EARTHWORM	**KNOWN EFFECTS UPON SOIL**
Dendrobaena octaedra	Decreased C/N ratios and concentrations Bioturbation of organic and mineral layers
Lumbricus rubellus	Acute forest floor consumption and thin humus layer Decreased litter layer thickness
Lumbricus terrestris	Forest floor consumption and thin humus layer Decreased litter layer thickness Decreased C/N ratios and concentrations Bioturbation of organic and mineral layers
Octolasion tyrtaeum	Decreased C/N ratios and concentrations, especially soil carbon

However, risk assessment of earthworm invasion and level of perceived risk should focus on three areas (Hendrix and Bohlen, 2002, pg. 8):

1. Potential impacts on environmental quality and soil processes (i.e., increased carbon turnover in soils)
2. Potential impacts on desirable and beneficial species of animals, plants, and microbes (i.e., rare plant species and native earthworm populations)
3. Potential for earthworms as vectors of pathogens (i.e., plant or animal diseases)

Determining which species is considered a successful invader in a single system is equally difficult, and the success of one species does not predict the success of a related species. Previous success at invasion, propagule pressure, habitat matching, and disease vector potential are considered criteria for determining how successful an introduced species will be (Hendrix and Bohlen, 2002). Previous success at invasion in similar habitats is considered the clearest indicator of a non-native earthworm's ability to become established in another location. Propagule pressure, in simple terms, refers to the probability of establishment of a new species once a sufficient population size has been introduced and how often these introduction events occur. Habitat matching refers to how similar a new habitat is to an introduced species' native habitat; the closer the new habitat matches the habitat of origin, the higher the probability of establishment. However, this is not always true for the species displaying environmental plasticity. Disease vector potential considers the incidence of earthworm-borne disease, along with both known and suspected pathogens. Figure 7 displays additional biological and ecological data to consider when performing a risk assessment for an introduced species in a new area, including the amphimictic reproduction strategy: capable of freely breeding and procuring viable offspring.

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

Figure 7: Additional biological and ecological data to consider while performing earthworm risk assessments (Reproduced from Callaham et al., 2006).

No single aforementioned attribute is a clear indicator of invasion potential – yet, when identifying species of concern, land managers and decisionmakers should consider all four in the greatest possible detail. Figure 8 displays similar characteristics to consider when making such determinations. Quarantining materials is intended to provide time to determine if a species poses any risk or if an ecosystem is considered sensitive to the species. Currently, no data bank or central source containing such information exists; it has been recognized that such a resource would be of immeasurable value in determining invasion potential (Hendrix and Bohlen, 2002).

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

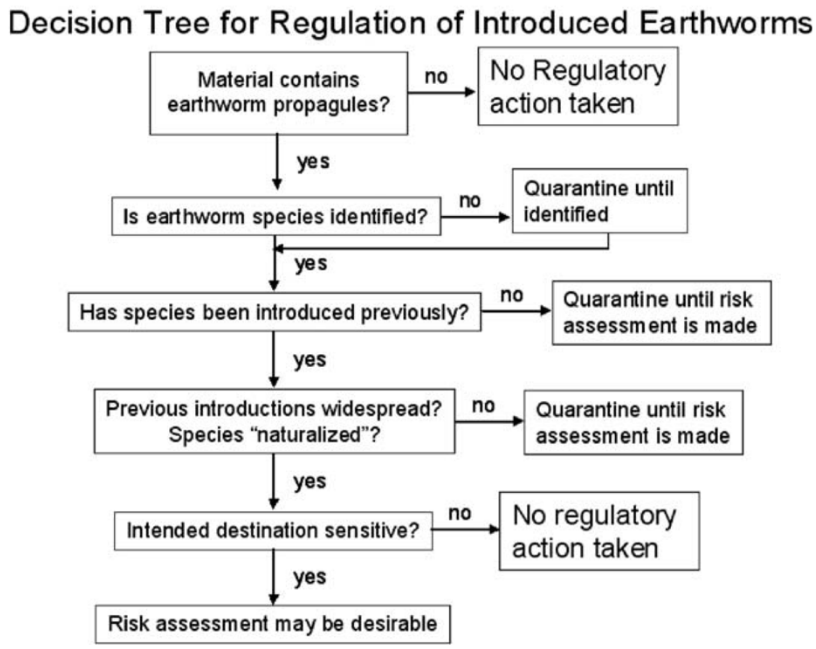

Figure 8: A decision tree for the regulation of earthworms and earthworm-containing materials **(**Reproduced from Callaham et al., 2006)

RISK ASSESSMENT: BIOLOGICAL, PHYSICAL, AND CHEMICAL RISKS

Earthworm presence can affect the foliage of both the balsam poplar, *P. balsamifera,* and the trembling aspen, *P. tremuloide.* These trees can be found in the Crown of the Continent's boreal forests – the same forests found across the Canadian provinces and in some of the northernmost forests of the United States. A combination of observational and experimental studies indicated that earthworm presence is associated with increased sapling leaf herbivory by insects. *P. balsamifera* displayed decreased concentrations of chemical defense compounds in earthworm-invaded sites. It is hypothesized that the increased nitrogen availability in mineral soil associated with earthworm activity causes trees to invest more of their energy into growth and less into defense (Thakur et al., 2021).

Non-native Asian earthworms can be found in Ontario, New Brunswick, and Québec; it is anticipated that both the climate and soils in these areas are conducive to further expansion into adjacent provinces. Though they have greater potential for colonization than European earthworms, local distribution of Asian earthworms can be patchy in Canadian forests. They are relatively new invaders, but they have been associated with forest floor depletion, altered soil structure, and nutrient mineralization – all of which make forest systems vulnerable to nutrient losses (Moore et al., 2018). Exotic Asian earthworm expansion and their long-term effects upon North American forests are both considered developing areas of study.

The greatest chemical risk of non-native earthworms in the Crown of the Continent and its surrounding regions is altered carbon flux. Earthworm activity can sequester carbon through the formation of castings, yet can mobilize carbon through detritus consumption and deposition into deeper layers of soil. These opposing trends have only been observed within the last 20 years and continued research is needed to unravel this contradiction. However, considering 17% of the world's total soil carbon is contained in Canadian soils and the boreal forests of the northern Crown contain a high accumulation of organic material, changes in soil carbon cycling within these forests can have immense consequences (Addison, 2009).

A 2007 study investigated the effects of *L. terrestris, O. tyrtaeum,* and *Db. octaedra* in the aspen forests of southern Alberta's Kananaskis Valley. The density of *L. terrestris* was associated with both a thin litter layer and a thin humus layer; the density of *Db. octaedra* was associated with a thick litter layer. The presence of both species was associated with decreased carbon and nitrogen concentrations and ratios, similar to results from similar studies in North American deciduous forests. These observations indicate that both species' activities thinned the organic layer and increased the humus layer's mineral content through the bioturbation of the organic and mineral layers (Eisenhauer et al., 2007). Additionally, the activities of *Db. octaedra* altered nitrogen cycling by decreasing its concentrations, and, therefore, its immediate availability to plants and microbes. Surprisingly, the change in soil nitrogen caused by *Db. octaedra* led to a disproportionate change in soil carbon by *O. tyrtaeum*, causing decreased C/N ratios. As discussed previously, such a change has the potential to further alter both above and below ground systems by affecting C:N through increased nitrogen turnover. This study confirmed that the incorporation of both carbon and nitrogen deeper into the soil depletes their soil sinks by making both nutrients more bioavailable – therefore, more water soluble and more prone to loss by leaching.

CURRENT AND FUTURE INVASION RISK FACTORS

Human activity is widely considered the largest risk factor of exotic earthworm invasion: timber harvest operations, disposal of live fishing bait, and infrastructure development are all considered major vectors of spread (Gundale et al., 2005). A study of the Sylvania Wilderness Area of Ottawa National Forest in Michigan's Upper Peninsula investigated the susceptibility of hardwood forests to exotic earthworm invasion. This study found that non-wilderness areas contained higher exotic earthworm densities than wilderness areas, with *D. octaedra* as the only exotic earthworm found in the Sylvania Wilderness Area. It is believed that land history and proximity to roads were the primary influencers of exotic earthworm presence: the non-wilderness sampling sites were all adjacent to roads and were all second growth forests, whereas the Sylvania sites were more isolated from nearby roads and were all old growth forests. Studies in Kentucky and Puerto Rico confirm that land disturbance is correlated with the establishment of exotic earthworms: the more disturbed the site, the higher the chance of exotic earthworms establishing a successful population (Callaham et al., 2006). However, the results of the Michigan study did not indicate that recreational fishing and timber harvest increase the probability of invasion in non-wilderness areas without a recent history of these activities.

One potential risk factor of earthworm invasion in forests appears to be forest type. A 2005 study found that total earthworm biomass in deciduous sugar maple stands was four times greater than that of boreal aspen and fir forests. Impacts upon coniferous forests are unclear, but it is expected that *D. octaedra* can easily colonize Canadian forests with environmental conditions similar to those of its native Russia – environments with both acidic organic input and cold winters (Addison, 2009). Temperature appears to be another potential factor of earthworm invasion in Canadian forests, but cold winter temperatures cannot entirely protect a forest from earthworm invasion – especially with temperature rise due to global climate change.

As for community resistance, a host of studies indicate that native and non-native earthworms can coexist in the short-term. These same studies indicate that physical and chemical factors of an environment are better indicators of community resistance to earthworm invasion than biological interactions. However, interactions between native and non-native earthworm species in Canada have not been studied thoroughly (Addison, 2009). The coexistence of exotic and native earthworms has been reported, though such interactions appear transient. The belief that exotic earthworms can displace or coexist with native species is a developing area of study – the degree of habitat disturbance and the impacts upon ecosystem services are possible factors in such interactions. However, physical disturbance and habitat fragmentation are believed to be prerequisites to exotic earthworm dominance in soils containing native earthworms. A proposed sequence of domination is as follows (Hendrix et al., 2008, p. 598):

a) habitat disturbance

b) decline or extirpation of native species

c) introduction of exotic species

d) colonization of empty habitat by exotic species

RECCOMENDATIONS FOR RESEARCH PRIORITIES

INVASIVE EARTHWORMS AND THE CROWN

The prevailing attitude towards earthworms is positive because bioturbation is widely considered beneficial to soil systems; few individuals are aware that earthworms can be invasive and are harmful to forest systems (Ehrenpreis, 2014). In Montana, exotic earthworms are not considered a priority, and, therefore, hardly receive any attention by land management entities. They are certainly not as visible as zebra mussels and cheat grass, nor are their effects as direct. However, soil health is of undeniable importance for terrestrial systems, especially the forest systems found in the West. Soil health impacts ecosystem productivity, water storage, and climate change mitigation, to name a few ecosystem services (Lal, 2016).

If soil health in the Crown of the Continent is to be maintained and the negative effects of non-native earthworms are to be avoided, land managers must consider such threats to soil integrity in their future practices. If the spread of exotic earthworms is to be prevented and the aforementioned effects avoided, swift and effective action is necessary. Fortunately, the majority of modern exotic earthworm management options and control approaches include the ban of earthworm products. Unfortunately, exotic earthworm management should not be pursued with conventional approaches to nuisance organisms due to limited knowledge of how exotic earthworms directly impact the Crown.

Adaptive ecosystem management accounts for such uncertainty by allowing participants and stakeholders to maximize continuous learning about system responses to management decisions. It uses concepts of the scientific method, such as data collection, experimentation, and hypothesis testing, to yield information that can be used to guide decision making (Prato and Fagre, 2007). Collaboration between stakeholders, such as scientists and land managers, is crucial to maximizing success, properly implementing plans, and analyzing action. If stakeholders are to implement effective action to combat exotic earthworms, flexible approaches like adaptive ecosystem management can and should be pursued.

THE VALUE OF MONITORING

Systematic sampling and monitoring should be the first step in guiding exotic earthworm management. The Crown of the Continent would benefit greatly from the long-term monitoring and sampling of exotic earthworms because current exotic earthworm data for the area is patchy and incomplete. Comprehensive data collection and reporting would provide a knowledge base from which Crown-specific action can be made. Including sampling sites of varying land uses and different jurisdictions can create a wholistic view of how extensive this invasion might be. Systematic sampling techniques and specimen identification can easily be pursued through post-secondary academic institutions, such as research universities and tribal colleges. Specific sampling details can be decided by the individuals involved based on their resources and even partnerships with land management entities. However, maintaining sampling consistency across entities and efforts is a key consideration so comparison can be possible for future research. Monitoring through regular sampling also presents a valuable tool in future research into rates of earthworm expansion, especially the magnitude and scope of expansion within newly-invaded areas. Once sampling and monitoring have occurred, they can be combined with policy and practice to prevent further invasion.

RECOMMENDATIONS FOR MANAGEMENT ACTIONS

POTENTIAL MANAGEMENT STRATEGIES

Studies across North America indicate that, because several non-native taxa of earthworms are already established in new habitats and often exhibit patchy distribution, complete containment and eradication is simply not possible. Mitigating spread and negative effects requires knowledge of a species' population and spread dynamics. For instance, European lumbricid species are known to disperse slowly at 4 – 30 m per year and human transport is considered their main form of spread; pheretimoid invasion is not as well understood, but are believed to spread similarly to lumbricids (McCay et al., 2020).

Preventing introductions is considered the most cost-effective method of addressing non-native species, but fails to address how to manage a non-native species once it has been introduced. Unfortunately, once a species is introduced and eradication is not possible, the only options for control are slowing spread, controlling the population, and adapting. To address introduced species, the Ecological Society of America recommends the following (Hueffmeier, 2012, p. 15):

1. Reduce number of pathways
2. Institute risk screening
3. Monitor for early invasions
4. Provide authority and funding for eradication and control programs
5. Fund slow-the-spread programs
6. Establish a center for invasive species management

Early detection and rapid response, or EDRR, is considered the next best option or even an action complimentary to prevention; it is a loosely-defined concept whose related practices are intended to address non-native species. Early detection involves coordinated preliminary action and target analysis, which can include physical surveying and performing impact assessments. Once the species in question has been identified, reported, and has undergone risk assessment, rapid response can then occur. Rapid response involves efforts to contain, control, or eradicate within the introductory stages of an invasion, which, depending on context, can take anywhere from few weeks to a few years. It includes appropriate planning, use of information and technology, and training to respond effectively in the timeliest manner possible (Reaser et al., 2020).

Exotic earthworm regulation should be determined by ecosystem susceptibility to invasion and the species' specific ecological characteristics. However, prevention is widely considered the most effective way to combat further spread. In the United States, the regulation of soil-borne nuisance organisms, such as fire ants (*Solenopsis* spp.) and the root knot nematode (*Meloidogyne* spp.), is used to control spread and limit introduction (Callaham et al., 2006). When a nuisance organism is detected in materials transported into an uninfected area, the materials are usually quarantined. Items originating from infested areas must be certified pest-free and cleaned of all materials capable of spreading the nuisance organism. Similar measures can be used to limit or regulate the transport of exotic earthworms into and within the United States. Deciding how to regulate and isolate materials can be achieved using a process similar to that displayed in Figure 8.

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

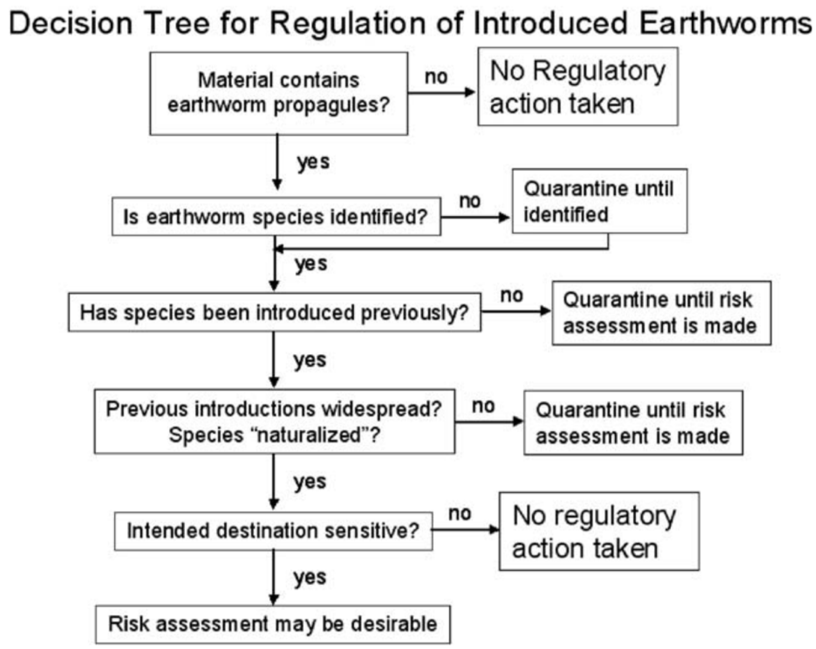

Figure 8: A decision tree for the regulation of earthworms and earthworm-containing materials **(**Reproduced from Callaham et al., 2006)

RESTRICTED USE OF EARTHWORMS AND EARTHWORM MATERIALS

Selective use of earthworms and earthworm materials can be developed using processes similar to those already present in Canada, which includes the importation of only *L. terrestris* from the Netherlands and the use of pathogen-free packaging. Ideally, the four major factors of invasion success – propagule pressure, habitat matching, previous invasion success, and potential for disease – should be heavily considered when deciding which non-native earthworms can be imported. For selective importation and use, a list of approved species would need to be developed by both experts and policy makers. These same entities would be ideal in the creation of procedures to address earthworm materials, such as vermicompost (Hendrix and Bohlen, 2002).

Such an approach would greatly minimize ecological damage, but would not ensure complete protection from both future invasives and established invasives. Unfortunately, such practices could be considered unnecessary – yet each case of introduction should be thoroughly examined. For instance, habitat matching for the African *Eudrilus eugeniae* has led to successful culturing for fish bait in both the United States and Canada. Though no records of their existence outside of the controlled environments in the North American continent currently exist, this species has been found in Puerto Rico (Callaham et al., 2006).

COMPLETE BAN OF EARTHWORM DISTRIBUTION AND SALE

A complete ban on earthworm sale and use would drastically reduce ecological impacts and new invasions, but would be difficult to enforce fully. Across the United States and Canada, live earthworms can be found locally at small bait stores and large chain sporting goods stores like Cabela's; online avenues include both Amazon and smaller online stores, such as Uncle Jim's Worm Farm. An earthworm ban would require users, such as gardeners, anglers, and vermicompost operations – to rely on established earthworm populations – populations that are challenging to study (Hale, 2008).

Any policy constituting a full ban on earthworms, whether cultivated in North America or beyond, may contain an exception for earthworms used for research. Making the sale and transport of earthworms illegal across jurisdictions is a possibility; because earthworms are not widely considered a clear and present danger to biodiversity, such a possibility is not probable. However, in New York, pheretimoid worms are recognized as problematic and are considered invasive by the New York Department of Environmental

Conservation. They are listed as a "prohibited invasive species" and are not allowed to be transported or distributed within the state (Johnson et al., 2021).

CITIZEN SCIENCE TO AID EARTHWORM RESEARCH

Public participation via citizen science allows individuals to contribute to large-scale biodiversity monitoring and data collection. Smartphone apps, such as iNaturalist and Project BudBurst, allow scientists and researchers to address the challenge of determining the scope of exotic organism presence. These apps provide the unique opportunity for accurate documentation over a large geographic area to actively occur in places that may not have established research or education programs. Though such tools are no replacement for systematic sampling and documentation, they do provide a way of recording local observations and potentially useful data.

Citizen science also benefits participants by offering opportunities for education in ecology and involvement in scientific research. Programs are often supported and enhanced by curricular materials, such as those for middle and high school students participating in the Earthworms Across Kansas program of the early 2010s. Alternatively, the Earthworm Society of Britain regularly offers earthworm surveying, collecting, and identification sessions; once records are verified, they are entered into databases for future research (Chang et al., 2021).

However, early detection via citizen science requires individuals who can accurately identify exotic earthworms. Therefore, early detection is sometimes limited to small clusters of experts and research facilities with the equipment needed to correctly identify specimens. The quantity and quality of submissions depends on communication between experts and participants. This issue has been addressed through highly organized efforts, and these efforts have proven successful in both the United Kingdom and in the United States. In the US, Extension Master Gardeners use both hotlines and regular surveying to help identify exotic species. In the UK, Open Air Laboratories encourages citizen science efforts to use reporting tools to gather data on both soils and earthworms (McCay et al., 2020).

Examples of effective citizen science can be found across the United States. The Great Lakes Worm Watch was one of the first programs to use citizen science as a detection tool for non-native European earthworms in the Great Lakes region (Chang et al., 2021). Citizen science in the urban areas of Madison, Wisconsin confirmed the presence of non-native pheretimoid species and resulted in the first record of *Metaphire hilgendorfi*, another non-native species from Asia (Chang et al., 2021). New York's Cornell University and local use of the *i*Mapinvasives app have both aided in monitoring pheretimoid jumping worms (Chang et al., 2021). Citizen science efforts across both the Eastern Seaboard and the Great Lakes states can be seen in Figure 9, which includes records from published records, The Great Lakes Worm Watch, iMapInvasives, and iNaturalist (McCay et al., 2020).

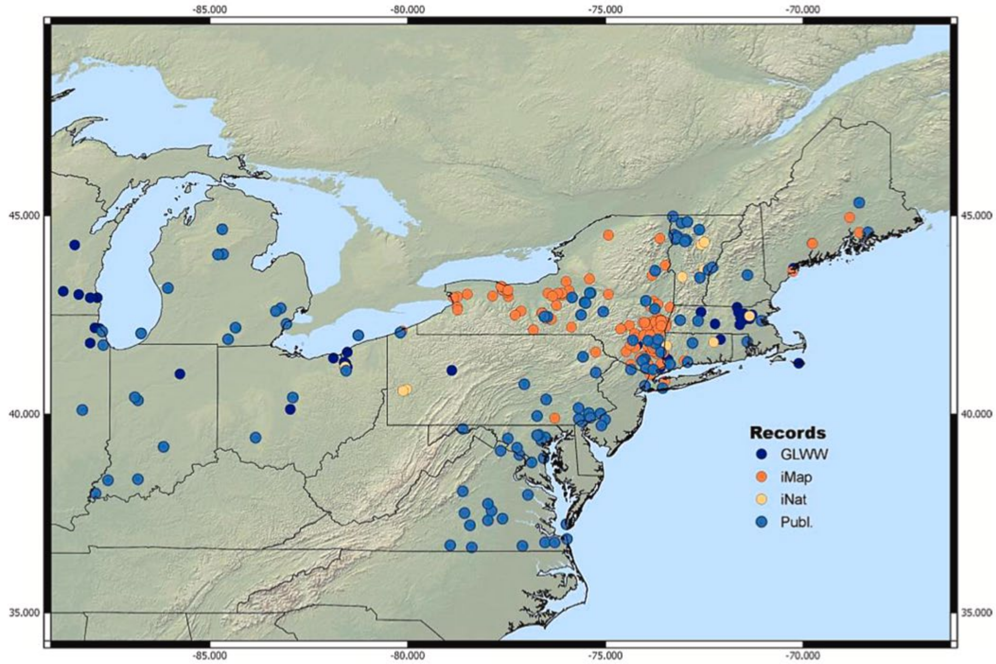

Fig. 2. Locations of records of pheretimoid earthworms in the Northern United States and Canada based on published records (Publ.) and reports from citizen-science efforts (iMapInvasives.org [iMap], iNaturalist.org [iNat], and Great Lakes Worm Watch [GLWW]). Citizen-science data were accessed 30 May 2020. Note that these species have a broader distribution than represented here and that the reported locations were strongly dependent on spatially patchy monitoring and research efforts.

Figure 9: Public records of exotic pheretimoid earthworms in the Northeastern US and Canada with data gathered via citizen science (Reproduced from McCay et al., 2020).

UNREALISTIC CONTROL PRACTICES AND UNINTENDED CONSEQUENCES

In areas of North America with an established population of exotic earthworms, management practices should focus on the control or elimination of the population. Currently, pest management strategies and environmental modification are considered potential methods of elimination or control (Chang et al., 2021). However, both present the unintended consequences of greater ecosystem harm. Manual removal of surface-dwelling exotic earthworms is only effective in the short-term over small areas in domestic settings, such as home gardens and plant nurseries (McCay et al., 2020).

Integrated pest management for exotic earthworms is rare and what little research exists focuses primarily on the management of golf courses. As for predation, the Asian pheretimiod earthworms can fall prey to the introduced turbellarian flatworms (*Bipalium* spp.) and native centipedes. However, neither of these forms of predation have been studied thoroughly and the aforementioned flatworms are known to prey upon non-target species, such as lumbricids (Chang et al., 2021). Physical habitat modification via fire removes the leaf litter food source and can kill cocoons or juveniles. The use of fire on controlled plots has proven effective in the decline of lumbricid and pheretimoid cocoons, but adults were able to survive fire by burrowing into the soil.

Large-scale soil treatment appears unrealistic due to unintended consequences upon non-target organisms. In North America, there are no chemical pesticides intended for use on earthworms (Boyle et al., 2019). Organic expellents, such as teaseed meal and onion extract, are known to irritate the exterior mucus membrane and force earthworms to the soil surface. However, the earthworms must then be removed manually and the expellant must be reapplied to ensure long-term results. Soil acidification offers another potential solution, but pH tolerance varies by earthworm species: altering soil pH would likely result in negative long-term effects for both the soil system and the greater ecosystem. The systemic application of biochar, a charcoal-like substance produced through pyrolosis, is known to cause earthworm mortality, but does not appear to yield long-term impacts (McCay et al., 2019).

Introduced biocontrols, such as parasitic nematodes, have the potential to spread into surrounding areas where other soil invertebrates may be negatively affected (Boyle et al., 2019). There are currently no studies that focus on how microbes can act as biocontrols for different earthworm species. Some fungi can act as insecticides for both live earthworms and earthworm cocoons. A study of 16 fungi, which included

Penicillium sp., *Fusarium* sp., *Aspergillus* sp., and *Trichoderma* sp., proved effective on *Eisenia fetida*. However, this research was not focused on biocontrols, but vermicomposting. In a series of unpublished data, the bacterium *Staphylococcus* sp. and *Bacillius* sp., along with the fungi *Beauvaria bassiana*, proved effective at killing earthworms in a controlled laboratory setting (McCay et al., 2020).

NO ACTION

Through the Federal Plant Pest Act and APHIS (Animal and Plant Health Inspection Service), the United States harbors an "innocent until proven guilty" attitude to potentially invasive species that have not yet undergone adequate risk assessment. Consequently, if an import of plants, soils, or animals does not carry pathogens, it is allowed to be distributed within the United States – and the distribution of non-native earthworms is a direct result. Without foreign pathogens and their risk, non-native earthworms are effectively not considered invasive by the United States federal government. This lack of action is believed to have caused continuous distribution and invasion of both new and established populations of exotic earthworms (Hendrix and Bohlen, 2002).

EFFECTIVE POLICY AND ACTION: MINNESOTA

The Minnesota Worm Watch Program provides an example of how effective education and outreach can lead to increased public awareness. To help limit the spread of exotic earthworms to remote areas, the University of Minnesota launched this program in partnership with the state's Department of Natural Resources and the Minnesota Native Plant Society. Public education on the ecological consequences of introduced earthworms consisted of Internet-based educational materials and the distribution of 1500 educational posters to visitor centers and bait shops, as displayed in Figure 10. The main message of the campaign – do not dump unused bait in remote areas – was well received and public reception to the campaign was positive (Callaham et al., 2006).

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

Figure 10: A promotional poster used in a Minnesota-based public education program (Reproduced from Callaham et al., 2006).

COST-BENEFIT ANALYSIS OF POTENTIAL ACTION

Table 5 lists a simple cost-benefit analysis of the major actions listed in this section. The only action that does not require upfront costs of time, money, or resources is “No Action,” but the risks of newly introduced earthworm species and newly introduced pathogens could result in great long-term costs. Of these actions, a complete ban and limited use are widely considered the most effective forms of preventing the spread of exotic earthworms. Both require time, money, and resources, yet present the benefit of decreased ecological damage due to exotic earthworms. EDRR and citizen science can be used to supplement such action, but do not provide effective action by themselves.

Table 5: A cost-benefit assessment of actions intended to combat the spread of exotic earthworms.

ACTION	COST	BENEFIT
Complete Ban	Time, money, and resources Negative impact upon vermicomposting operations and sporting goods stores/bait shops	Considered best way to decrease exotic earthworm introduction and spread Decreased ecological damage
Restricted or Limited Use	Time, money, and resources Negative impact upon vermicomposting operations and sporting goods stores/bait shops Does not eliminate the chance of introducing other species potentially contained within earthworm products	Targets species that cause the most specific ecological damage Decreased ecological damage
No Action	Risk of new introductions Risk of pathogen introduction	No change in current operations according to APHIS protocol No upfront costs of time, money, and resources
Predation and Biocontrols	Time, money, and resources Risk of unintended ecological consequences, especially for non-target organisms	Decreased number of target species
Physical Modification	Time, money, and resources Risk of unintended ecological consequences, especially for non-target organisms	Decreased number of target species
Large Scale Soil Treatment	Time, money, and resources Risk of unintended ecological consequences, especially for non-target organisms	Decreased number of target species
Early Detection and Rapid Response	Time, money, and resources Time-sensitive	Flexible, specific ecological planning Intended to produce swift, effective action Uses preventative measures (i.e., complete ban, restricted use)
Citizen Science	Time, money, and resources	Opportunity for widespread sampling Large scale biodiversity monitoring Public participation in ecological research

POTENTIAL STARTING POINT: INTERNAL EDUCATION AND PRACTICE

The education of state, provincial, and tribal entities regarding the harms of non-native earthworms provides a starting point for internal action. Operations and practices focusing on soil quality can pursue appropriate change according to their resources. Using public communication methods similar to those used in the Minnesota Worm Watch program and educating field researchers on the specific harms of exotic earthworms can provide a “top-down” and “bottom-up” approach to achieving a desired outcome. Targeting the foremost vector of introduction – recreational fishing – can be as simple as distributing literature and requesting that any live bait be disposed of at invasive mussel boat checking stations found near Flathead Lake. The use of soil transplants, especially in plant restoration projects, is another vector of exotic earthworm introduction that can potential be addressed by agricultural product regulators. This potential form of new introduction can be addressed by heating soils to an appropriate temperature in order to kill any propagules and remaining adult specimens.

SPECIFIC SOLUTIONS FOR THE CROWN OF THE CONTINENT

REALISTIC ACTION: LIMITING EARTHWORM PRESENCE AND SPREAD

Limiting earthworm presence and preventing further spread may be achieved with the following actions:

- Use preliminary data and information gathering to determine which non-native earthworm species pose the greatest threat to the Crown's soils
    - Preliminary studies can be performed by post-secondary institutions (i.e., the University of Montana, Montana State University, University of Lethbridge, University of Calgary, community colleges, and tribal colleges) and/or government entities (i.e., the Animal and Plant Health Inspection Service, the Montana Natural heritage Program, the Montana Departments of Natural Resources, Agriculture, and Fish, Wildlife, and Parks)
- Ideally, perform systematic sampling for exotic earthworms across the Crown with the intention of using the data collected as a baseline for future monitoring and mitigation
    - Remain consistent in sampling techniques and include a variety of sampling sites that encompasses the major land use types across the Crown
- Based on the data collected from both preliminary and field studies, form a series of potential policies and practices that can be used across jurisdictions

    - The policies and practices should be based on sound evidence, but can benefit from being flexible enough to address exotic earthworms with a variety of resources
    - Selective use and/or a complete ban of non-native earthworms and related products is considered the simplest, most effective manner of controlling spread
- Continue regular monitoring through sampling to continue collecting valuable data on exotic earthworm patterns of invasion
    - Such data can be used to guide future research and policy
    - Collaboration between entities, such as the Montana Invasive Species Council, the Montana Department of Fish, Wildlife and Parks, and the Montana Department of Agriculture, can and should be pursued
- Introduce regulation for vermicompost operations and agriculture products in order to reduce introductions via live earthworms or earthworm propagules
    - Key stakeholders, such as vermicompost operators, bait shops, and gardening groups, should be informed of the risks of exotic earthworm introduction
- Introduce public education that targets recreational fishing, utilizing strategies similar to those in the Minnesota Worm Watch program

Some tips and pointers for land managers, stakeholders, agriculture product regulators, and policy makers to consider include, but are not limited to, the following:

- Use citizen science to aid in data collection

- A total ban on the transport and use of earthworms and earthworm products does not guarantee full protection from future introductions
- The collaborative efforts of scientists, experts, and policy makers should be used to the greatest degree possible
- The goal of any action surrounding exotic earthworm mitigation should focus primarily on soil quality
- Utilize public education in simple forms, such as distributing literature at boat check stations and encouraging disposal of live bait at stations
- Any formal action limiting the transport and use of earthworms should consider exceptions for research

CONCLUSION

ANSWERING ORIGINAL RESEARCH QUESTIONS

The physical impacts of non-native earthworms primarily include intense bioturbation and the disruption of soil layering systems. Alteration and removal of the topmost organic layer can easily be considered the most prominent form of physical alteration. The primary chemical impacts include the disruption of nutrient cycling within soils. Alterations of carbon and nitrogen cycling can both be tied to disruption of the topmost organic layer. The biological impacts of non-native earthworms include the disruption primarily plant communities, especially those found on the forest floor.

Human activity remains the foremost cause of exotic earthworm spread, and continued inaction regarding the spread of exotic earthworms can lead to compromised soil quality. If soil health in the Crown is to be preserved, swift and effective action to combat the spread of earthworms must be pursued. Preventing spread can mitigate negative effects by stopping new introductions, especially for areas that do not currently contain populations of exotic earthworms. Land managers and agricultural product regulators can pursue actions and policies that result in the ban and/or restricted use of non-native earthworms and/or earthworm products. Supplemental actions, such as citizen science and public education, can bolster efforts to understand risks and prevent further spread.

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