United States
Department of
Agriculture

**Forest Service
Pacific Northwest
Research Station**

United States
Department of the
Interior

**Bureau of Land
Management**

General Technical
Report
PNW-GTR-491
June 2000

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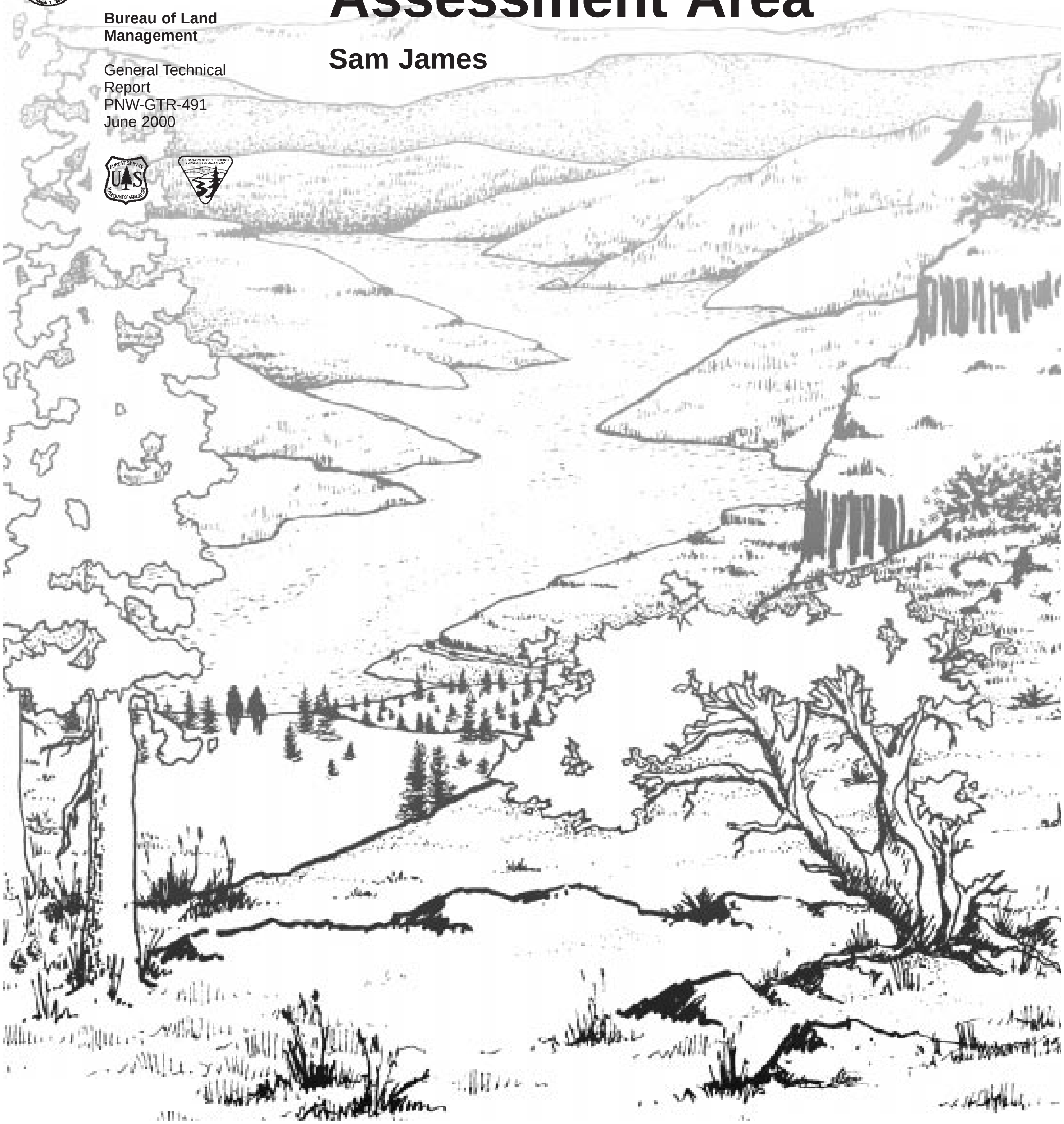
Sam James



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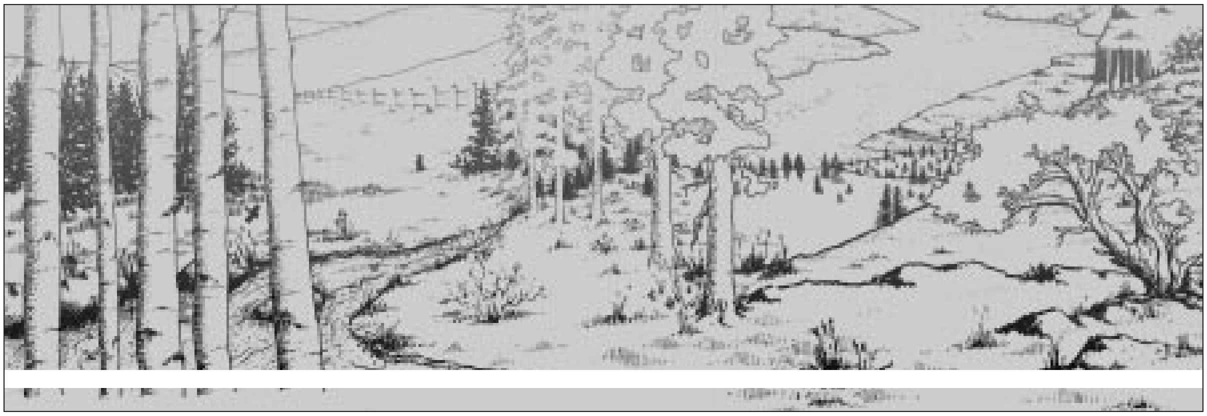

Earthworms (Annelida: Oligochaeta) of the Columbia River Basin Assessment Area

Sam James

Interior Columbia Basin Ecosystem Management Project: Scientific Assessment

Thomas M. Quigley, Editor

U.S. Department of Agriculture
Forest Service
Pacific Northwest Research Station
Portland, Oregon
General Technical Report PNW-GTR-491
June 2000

Preface

The Interior Columbia Basin Ecosystem Management Project was initiated by the USDA Forest Service and the USDI Bureau of Land Management to respond to several critical issues including, but not limited to, forest and rangeland health, anadromous fish concerns, terrestrial species viability concerns, and the recent decline in traditional commodity flows. The charter given to the project was to develop a scientifically sound, ecosystem-based strategy for managing the lands of the interior Columbia River basin administered by the USDA Forest Service and the USDI Bureau of Land Management. The Science Integration Team was organized to develop a framework for ecosystem management, an assessment of the socioeconomic biophysical systems in the basin, and an evaluation of alternative management strategies. This paper is one in a series of papers developed as background material for the framework, assessment, or evaluation of alternatives. It provides more detail than was possible to disclose directly in the primary documents.

The Science Integration Team, although organized functionally, worked hard at integrating the approaches, analyses, and conclusions. It is the collective effort of team members that provides depth and understanding to the work of the project. The Science Integration Team leadership included deputy team leaders Russel Graham and Sylvia Arbelbide; landscape ecology—Wendel Hann, Paul Hessburg, and Mark Jensen; aquatic—Jim Sedell, Kris Lee, Danny Lee, Jack Williams, Lynn Decker; economics—Richard Haynes, Amy Horne, and Nick Reyna; social science—Jim Burchfield, Steve McCool, and Jon Bumstead; terrestrial—Bruce Marcot, Kurt Nelson, John Lehmkuhl, Richard Holthausen, and Randy Hickenbottom; spatial analysis—Becky Gravenmier, John Steffenson, and Andy Wilson.

Thomas M. Quigley

Editor

United States Department of Agriculture

Forest Service

United States Department of the Interior

Bureau of Land Management

Interior Columbia Basin Ecosystem Management Project

Abstract

James, Sam. 2000. Earthworms (Annelida: Oligochaeta) of the Columbia River basin assessment area. Gen. Tech. Rep. PNW-GTR-491. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 13 p.

Earthworms are key components of many terrestrial ecosystems; however, little is known of their ecology, distribution, and taxonomy in the eastern interior Columbia River basin assessment area (hereafter referred to as the basin assessment area). This report summarizes the main issues about the ecology of earthworms and their impact on the physical and chemical status of the soil. The three main ecological types of earthworms found in the basin assessment area are epigeic, endogeic, and anecic. Each type has a different life history pattern, resource requirement, and ecological function. Effects of environmental and habitat variables in the basin assessment area on these three types are summarized. Key ecological functions of earthworms are presented in relation to the ecological types and habitats of earthworms in the basin assessment area. These key ecological functions include the effects of earthworms on soils, their role in nutrient cycling, and their relation to other fauna.

Distributions of earthworm species in the basin assessment area also are summarized. Although most of the known species from the area are exotics from Europe, at least three species are native to the region. Unpublished records indicate that there may be many more species that have either not yet been collected or for which descriptions have not yet been published. Both the possibility of discovering additional macrofaunal biodiversity and the precarious status of at least one known species argue for additional research on earthworms in the basin assessment area.

Effects of land use and management practices on earthworms are explored by examining research on similar human influences in other ecosystems as no research on these issues has been done in the Western United States. Suggestions for land use and future research priorities are provided.

Keywords: Earthworm, Oligochaeta, Columbia River basin, soil biota, land management.

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Introduction

Earthworms (Annelida: Oligochaeta) are an important but much neglected component of ecosystems. It has been said that we know more about the 2 kilograms of bird tissue flying over each hectare than about the 200 kilograms of earthworms working the soil of each hectare (Bouche 1977; numbers apply to temperate Western Europe). Understanding the key role of earthworms in many biogeochemical cycles and in soil development requires an understanding of the impacts of land uses and other human-caused influences on earthworms. This is particularly true in relation to restoration of damaged systems and to preventive maintenance to avoid damage.

Along with the effects of earthworms on soil development, decomposition, and nutrient dynamics are other important considerations: earthworms are eaten by small mammals and birds; invasion of soil in the basin assessment area by exotic earthworm species has occurred in many locations and is probably ongoing; invasions occurring in locations previously free of earthworms likely will alter nutrient cycling patterns, soil food webs, and potentially the diets of small vertebrates; reduction in ranges of native species is due to destruction of habitat, displacement by exotic species, or by a combination of the two; and currently, not enough is known about the native species to determine whether they are threatened or endangered.

The intent of this report is to supply sufficient information about earthworm ecology in the eastern portion of the interior Columbia River basin (hereafter referred to as the basin assessment area) to those who make management decisions and determine research priorities. This paper provides a brief review of earthworm ecology, highlights their key ecological functions, and presents distributional and ecological data for both native and exotic earthworms in the basin assessment area. Management implications and directions for future research also are discussed.

General Earthworm Ecology

Earthworms are segmented worms of the phylum Annelida, class Oligochaeta. About 4,300 species are known, and many more may await description, including some in the basin assessment area. They differ in certain fundamental characteristics of body plan and reproductive organ layout from their close relatives in the aquatic Oligochaeta. One basic requirement of earthworms, closely tied to their aquatic ancestry, is moist soil in order to remain active, because gas exchange is conducted through a water film on the integument (Edwards and Bohlen 1996), and burrowing is easier in moist soil. Earthworms influence the soil environment, and that influence differs with the ecological niches of different species. More detail follows about environmental influences and constraints on earthworm populations, the effects of earthworm activity on their ecosystems, and the ecological differences among earthworms.

Environmental influences on earthworms— Three environmental factors, moisture, temperature, and pH, plus food resource quantity and quality, are the most important influences on earthworm populations. Soil moisture affects earthworm abundance, activity patterns, and geographic distribution. Soil temperature influences seasonal activity, limiting earthworms during warm and cold periods. Soil pH often is cited as a limiting factor on earthworm distributions, as the best studied group, European Lumbricidae, generally does not inhabit soils with pH below 4.0. Quality and quantity of food resource also influence earthworm abundance.

Soil climate determines the periods of earthworm activity. Within a habitat type, variations in soil climatic factors occur (because of slope, aspect, soil particle size distribution, and drainage characteristics), that result in variation in earthworm activity period and earthworm abundance. A forested habitat probably has a relatively buffered soil climate compared to the more exposed grasslands and agricultural land. Grassland temperature and moisture regimes are probably more extreme and could accentuate the effects of slope, soil properties, and other site characteristics. An agricultural cycle having long periods of bare ground could further intensify the impact of weather on earthworms.

Although the well-known Lumbricidae typically do not inhabit soils with pH below about 4.0, other taxa tolerate lower pH values, including some Pacific coast native species (pH 3.1 to 5.0; McKey-Fender and others 1994), thereby indicating that soil acidity might be less limiting for certain earthworm species than for others.

Organic matter enters soil food webs from litter fall or from root deposition. Surface litter may be fed on directly or after prior ingestion and defecation by other detritivores. Dependence on these sources of organic matter, which are discussed later, differs by species. Quality of organic matter differs greatly among plant sources and can affect earthworm populations. Organic matter may render the soil strongly acid, could be rich in digestibility-reducing compounds, or could have a high carbon-to-nitrogen ratio. These qualities tend to reduce earthworm populations.

Lack of organic matter is generally a significant limiting factor for earthworms. The fact that most agricultural soils are depleted of organic matter likely accounts for lower abundance of earthworms in agricultural land or recently abandoned cropland.

Effects of earthworms on soils and organic matter—Much is known about the effects of earthworms on soil characteristics and nutrient availability (see Edwards and Bohlen 1996, Lee 1985). Soil structure is altered by the creation of macropores and macroaggregates. Soil profiles may be mixed vertically. Forest floor litter layers can be entirely consumed by earthworms. These structural alterations affect the environments and resource bases of other soil fauna, alter the relative abundances of bacteria and fungi in favor of bacteria, and change the patterns of water and gas movement into and within soils. Nutrient mineralization is enhanced by earthworm activity, either by digestion, assimilation, excretion, and tissue breakdown, or indirectly through accelerated bacterial attack on organic matter. All earthworm excreta have higher levels of available macronutrients and cations than the material ingested (see Lee 1985). Urine is a source of available nitrogen. Also body tissues readily decompose after death. In addition to mineralization, chemical effects resulting from passage of soil organic matter through earthworms increase availability of some soil mineral nutrients. Because of the impact and generality of these phenomena, earthworms often are considered “keystone” members of soil and litter decomposer communities. To understand the effects of earthworms on their environments, three ecological types of earthworms and how they affect soils differently must be considered.

Ecological diversity among earthworms: definitions and functional roles—Three main ecological categories of earthworm are widely recognized: epigeic, anecic, and endogeic (Bouche 1977). Epigeic worms are typically small, darkly pigmented, and reside in leaf litter layers under the bark of decaying logs or in other concentrations of organic material. They have high rates of reproduction and short lifespans. Anecics inhabit a permanent or semipermanent deep vertical burrow and emerge at night to consume relatively fresh plant detritus on the surface. These are the largest and longest lived earthworms. Endogeics live in the mineral soil and consume organic matter within the soil or at the soil-litter interface. They are larger, less pigmented to unpigmented, have longer lifespans, and have lower reproductive rates than epigeic worms. All three types also consume mineral soil to varying degrees, with the endogeics being the greatest processors of mineral soil.

Lavelle (1983) further divided the endogeic category into polyhumic, mesohumic, and oligohumic types. Polyhumic endogeics work on richer sources of organic matter in the early stages of decomposition closer to the soil surface or at the soil-litter interface. *Lumbricus rubellus* and possibly *Aporrectodea trapezoides* are examples of this type of earthworm, which is characterized by moderate dorsal pigmentation and modest development of intestinal surface area. Intestinal structures that increase gut surface area are most highly developed in the oligohumic endogeics found deeper in the soil and feeding on more decomposed organic matter. Intestinal surface area is least developed in epigeics and anecics. Mesohumic endogeics have little or no pigmentation, intermediate secondary development of intestinal surface area, and poorly developed escape behavior. Feeding is on well-decomposed organic matter.

The diverse life patterns of the different ecological types of earthworms cause different functional roles or effects on the ecosystem of each species. The preceding general overview of the effects of earthworms on soils and soil processes should be understood in the contexts of the different ecological types of earthworms. The next level of refinement of understanding would be species-specific knowledge of functional roles of earthworms; this information, however, is not known for any of the native species in the basin assessment area, thus ecological type is the extent of our discussion.

Epigeic earthworms, which are generally forest dwellers, likely serve the following functions:

- Organic matter comminution—Reducing the size of organic matter particles during passage through the worm makes organic matter more accessible to digestive action by other decomposers.
- Nutrient cycling—Earthworms digest organics and thus mineralize some of the nutrients bound in them.
- Soil structure modification—Burrowing and defecating create soil structures significant (though the details are unknown) to other soil biota. The soil structures created are hydrologically significant, and soil water-stable aggregation is promoted.
- Transfer of organic matter to the soil—Consumption of surface litter results in defecation in the mineral soil, particularly if worms retreat into the mineral soil to avoid unfavorable climatic conditions in the litter.
- Food for other animals—Predators of earthworms include small mammals, feral pigs, beetle larvae, centipedes, some flies, and birds.

Anecic earthworms transfer relatively fresh plant litter from the surface to deep levels of the soil, thereby creating deep vertical burrows, which enhance water infiltration. Other earthworm types can contribute to these processes but generally do not. Anecics also provide food resources to endogeic worms by depositing fecal organic matter (or casts) into the soil where endogeics can reach it.

Functional roles of endogeic earthworm are similar to those mentioned for the epigeic species, with the following modifications:

- Soil profile development or transfer of materials within the soil—Defecation within the mineral soil will not always be at the same level as consumption. Deposition of casts may occur on the soil surface, in which case mineral soil is being brought up to the surface, and upper soil horizon material may be being deposited in the deeper strata.
- Soil carbon protection—Endogeic earthworms produce fecal pellets, which are water-stable aggregates, and within which soil carbon is partially protected from oxidation. Although the initial evolution of a cast includes a phase in which microbial respiration of soil carbon is enhanced, the long-term effect of the incorporation of organic matter into casts is to slow the oxidation of soil carbon (Lavelle and Martin 1992). In this way, earthworms contribute to the soil carbon sink.

With some basic knowledge of earthworm ecology, we can now consider the status of earthworms in ecosystems of the basin assessment area, specifically their distribution and ecology. We also will discuss management priorities.

Native and Exotic Earthworms of the Basin Assessment Area

The state of present knowledge—Presently, little is known about earthworms in the basin assessment area. Although much of the region is

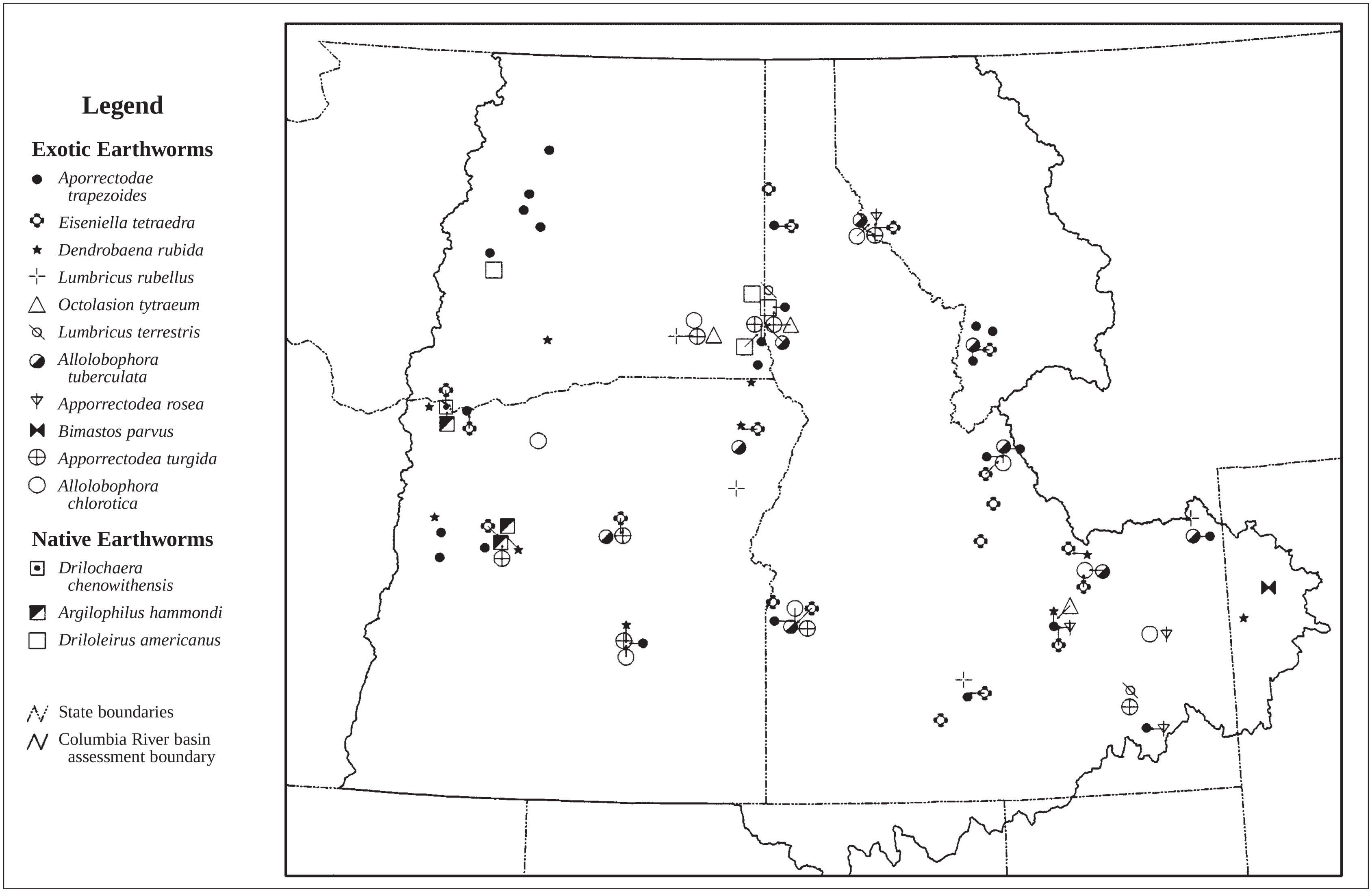

Figure 1—Collection points for native and exotic earthworms in the Columbia River basin. Two sources for some of the collection point information are Fender (1985) and Gates (1967).

too arid to support earthworms, many habitats do have earthworms, both native and exotic. Lack of knowledge of native earthworm fauna, some of which may be endangered by habitat loss, is a cause for concern. Undescribed species are likely present in the region. Nothing is known of how native species contribute to ecosystem processes in the basin assessment area, or of how they interact with other species, such as earthworm predators. On the other hand, many exotic species occur in the basin assessment area, possibly altering previously worm-free soils and nutrient cycling pathways, competing with native species, and generally modifying any processes linked to soil physical or chemical properties.

The known distributions of earthworms in the basin assessment area are shown in figure 1 (Fender 1985, Gates 1967). Many of the distribution marks are tightly clustered because several species were found at one site; hence a cluster is generally one site, not several neighboring ones. Published data on earthworms of the basin assessment area thus are based on a limited number of collection locations. Only a small portion of the earthworm-inhabitable basin assessment area has been surveyed.

Fender[1] indicates that five native genera are represented in the basin assessment area: *Driloleirus*, *Drilochaera*, *Argilophilus*, *Arctiostrotus*, and *Macnabodrilus*; however, only three species have been described. *Driloleirus americanus* is known from eastern Washington and western Idaho. *Driloleirus americanus* may be anecic, based on its deep burrowing habits and largely organic diet. *Drilochaera chenowithensis* is known from only one site along the Columbia River at Chenowith Creek, west of The Dalles, Oregon (McKey-Fender 1970). *Argilophilus hammondi* has been found at the Chenowith Creek site and well to the south in the Ochoco National Forest on the slopes of Grant Butte in Crook County, in an open ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forest with sedges and grasses in the understory, and at an elevation of about 1600 meters (McKey-Fender 1970). These native genera have other species on the west side of the Cascade Range. *Argilophilus* ranges well to the south into California to the latitude of Riverside, California (Wood and James 1993).

The factors that influence native species populations are unknown. Only by assuming that they are comparable to those of other earthworms can it be said that soil moisture, soil temperature, organic matter quantity and quality, and soil pH are probably the most important factors (Lee 1985). We have, however, already narrowed the consideration to specific habitat types; and those probably fall within the limits of tolerance of most temperate zone endogeic earthworms.

Because much research has been done on the ecology of European earthworm species, more is known about the exotics than about the native species of the basin assessment area. The European species *Dendrobaena rubida* and the eastern North American *Bimastos parvus* are epigeic. *Eiseniella tetraedra* (also native to Europe) has epigeic physical and life history characteristics, but it is semiaquatic. *Bimastos parvus* was found in Engelmann spruce-subalpine fir (*Picea engelmannii* Parry ex Engelm.-*Abies lasiocarpus* Hook. Nutt.) cover under logs and stones, whereas *Dendrobaena rubida* was found in a riparian area within agricultural land (Gates 1967).

Lumbricus terrestris (common name: nightcrawler) is a European anecic species. It was recorded from two artificial environments, a lawn at the University of Idaho and in a roadside picnic area near Pocatello, Idaho (Gates 1967).

The native species *Drilochaera chenowithensis* and *Argilophilus hammondi* are probably endogeic, based on the physical characteristics given in McKey-Fender (1970). European endogeic species recorded thus far are *Aporrectodea trapezoides*, *A. tuberculata*, *Eisenia rosea*,

[1] Personal communication. 1996. Fender, W.M. Soil Biology Associates, 835 Ashwood Avenue, McMinnville, OR 97128-6801.

Lumbricus rubellus, and *Octolasion tyrtaeum*. All these species are widely distributed in North America because of human activity.

Habitat factors important to earthworms in the basin assessment area—Both the potential roles of earthworms in basin assessment area ecosystems and the possible impact of management decisions on earthworms can be roughly predicted by considering the habitat requirements of the main ecological types of earthworms in relation to the climates and vegetation cover types of the basin assessment area. In addition to simple edaphic parameters and soil properties, the age and species composition of specific vegetation types are important.

Soil pH level often is cited as a limiting factor to the establishment of earthworms in boreal forests or other acid soils. If any of the higher elevation forests have this characteristic, earthworms may be restricted from those sites. The species present in the basin assessment area are mostly exotics with proven abilities to handle wide variations in soil conditions, such as *Aporrectodea trapezoides*. The known native species tolerant of acid soil are from the west slope of the Cascade Range. Within the basin assessment area, *Argilophilus hammondi* was collected from two ponderosa pine sites of pH 5.5 and 6.0, values tolerable to almost any earthworm.

Epigeic earthworms require plant remains in early stages of decomposition and typically live in accumulations of organic material such as forest litter layers. Some species such as *Dendrobaena rubida* and *Bimastos parvus* are frequently found in down woody material. To harbor epigeic species, a forest stand must either grow under conditions that permit development of a litter layer or be old enough to produce down woody debris, or both. Leaf litter depth must be sufficient to provide moisture retention in the lower layers of the litter between rains so the worms can feed on the litter. Three to six centimeters of litter and humified organic matter is a safe minimum. Because these worms are so active, they can find deep litter accumulations and woody debris, provided the moisture regime is favorable.

Down wood of 10 centimeters diameter will have sufficient bark and decomposing cambial layers to support these worms. The stage of decay and species of tree, however, are important. Logs in contact with the ground and reaching the state at which the bark is loose but not yet falling off are most likely to harbor these worms. In eastern forests, log-dwelling species seem less likely to be encountered in down oak and conifer logs, and more often are found in species such as maple, birch, aspen, tulip poplar (*Liriodendron tulipfera* L.), and cherry. It is unknown whether any native epigeic species are in the basin assessment area and, if so, whether any of them utilize logs.

Anecic species can live in forested or grassland-shrubland areas provided they can escape deep into the soil when soil climate is outside their activity range. The only other known requirement is sufficient quality and quantity of litter production to sustain earthworm growth and reproduction. Because this factor is strongly controlled by water availability, litter quality is more likely to be an issue than litter quantity.

Endogeic species seem to have the broadest habitat ranges. In the basin assessment area, endogeic species occurred in a wide range of habitats, including forests, savannah, grassland-shrubland (including exotic grass pasture and seral stages following cessation of agriculture), and cultivated land. The primary factors accounting for the distribution of exotic species in the basin assessment area are a combination of accidental introduction by humans and the availability of sufficient moisture where these accidental introductions have occurred. In the basin assessment area, native endogeics are probably confined to higher elevations and riparian areas. They may be absent from some inhabitable areas because of historical geological and climatic conditions of different regions within the basin assessment area.

Biogeography—The eastern portion of the basin assessment area contains diverse land forms, soils, and vegetation types, some of which harbor earthworms. Distributions of native and exotic earthworms in the basin assessment area depend on many historical factors in addition to the general soil climatic requirements of earthworms. Large-scale climate changes, vulcanism, and substrate evolution could affect the presence or absence of native species in regions where current conditions are favorable. Human activity has had a tremendous impact, both by destroying habitat and by inadvertently introducing exotic species.

Presently, there is insufficient published information to allow us to identify areas of high diversity or endemism or to outline regions where past climate or geological influences are responsible for earthworm absence from habitable conditions. On the local scale, earthworms in temperate zones generally show low within-site diversity, with three to six species per site. In topologically complex land areas, many species have limited distributions, which leads to high diversity among sites. For example, New Zealand has about 200 species of earthworms, but seldom are more than four found in any one spot (Lee 1959). Fender (see footnote 1) estimates the Pacific coast earthworm fauna to contain 80 to 100 species, including many undescribed basin assessment area species. Given the size and topographic diversity of the basin assessment area, a conservative estimate of the eventual number of earthworm species there might be about 20.

Forest Service and Bureau of Land Management lands, particularly the former, are likely to harbor most surviving native earthworm species populations in the basin assessment area. Interior ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) forests and other non-xeric habitats probably support the native species. Forest Service and Bureau of Land Management lands near fishable streams or human settlements also may harbor exotic species. The Steens Range, bitterbrush areas, juniper stands, and sagebrush are thought to lack earthworms (see footnote 1). Fender suggests that native species tend to favor fine-textured soils, whereas European Lumbricidae species can more easily invade coarse-textured soils. This could possibly be related to the prevalence of human activity along watercourses with their alluvial coarse soils.

Among land areas outside of Forest Service and Bureau of Land Management land areas, riparian zones, privately owned grazing land, and timber land are most likely to contain native and exotic earthworms; agricultural land, particularly dryland farms, is less likely to contain either. Earthworms have been recorded from sites within cover types shown in basin assessment area current vegetation cover type maps (Eyre 1980, Hann and others 1997, Shiflet 1994),[2] and where available, collection data from Gates (1967) and McKey-Fender (1970): SAF 206 (Englemann Spruce-Subalpine Fir), SAF 210 (Interior Douglas-Fir), SAF 213 (Grand Fir), SAF 218 (Lodgepole Pine), SAF 237 (Interior Ponderosa Pine); SRM 107 (Western Juniper, Big Sagebrush, Bluebunch Wheatgrass), SRM 109 (Ponderosa Pine-Shrubland), SRM 110 (Ponderosa Pine-Grassland), SRM 304 (Idaho Fescue-Bluebunch Wheatgrass), SRM 607 (Wheatgrass-Needlegrass); CRB 001 (Agricultural land), CRB 002 (Mixed grass-agriculture-shrubland), and CRB 004 (Subalpine herbaceous). The following additional vegetation cover types from Gates (1967) and McKey-Fender (1970) likely could be inhabited by earthworms: CRB 003 (Seral shrubland-regeneration), SAF 217 (Aspen), SAF 235 (Cottonwood-Willow), SRM 103 (Green Fescue), SRM 306 (Idaho Fescue-Slender Wheatgrass), and SRM 402 (Mountain Big Sagebrush).

Sensitivity to disturbance and population trends are unknown for all the native species. Collection data from Fender (see footnote 1) and McKey-

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[2] Columbia River basin succession model, (CRBSUM) current vegetation cover types map. 1996. On file with: USDA Forest Service; USDI Bureau of Land Management, Interior Columbia Basin Ecosystem Management Project, 112 East Poplar Street, Walla Walla, WA 99362. Also available on line: www.basinemp.gov/spatial/.

Fender (1970, 1994), however, suggest that virtually any disturbance that alters vegetation or allows the entry of exotic species can possibly reduce or eliminate native species populations. Because their observations are not based on experimental manipulations, it would be difficult to define what conditions would threaten or endanger native species. We also do not know the degree to which habitat disturbance and ecological competition contribute to the replacement process. More information on this issue is presented in the next section.

The exotic species from Europe have achieved their current global temperate zone distribution because of their broad adaptability to different habitats and their resilience following disturbance. Populations likely are expanding in numbers and geographic extent as movements of individual species (basically a diffusion process) and accidental transport by humans enlarge the occupied territory.

Management Issues

Biodiversity concerns: preservation of native species and alterations to the ecosystem caused by exotics—The basin assessment area is inhabited by at least three native earthworm species belonging to three genera. All three should be of special concern. The giant earthworm, *Driloleirus americanus*, was considered for inclusion in Wells and others (1983) because its habitat was threatened and its range was small. Current information suggests that it may be a narrow endemic using a threatened habitat (shrubland sites with good soil). The collection data give little detailed information about habitat type. The three sites (near Pullman and Ellensberg, Washington, and Moscow, Idaho [Fender and McKey-Fender 1990]) are located in what is now agricultural land, grassland, and shrubland (CRB 001, 002).

The other two native species, *Drilochaera chenowithensis* and *Argilophilus hammondi*, may be somewhat tolerant of habitat disturbance. Their type localities were on uncultivated canyon and surrounded by orchards (McKey-Fender 1970). They therefore may be considered more likely to survive but probably still should be given special attention. In particular, learning more about their ranges and ecological flexibility would enable land managers to determine whether or not special measures are necessary.

This leads to another area of concern to land managers: invasion by exotic species. Exotic earthworm species present in the basin assessment area are (thus far) all of European origin and are all members of the family Lumbricidae, with the exception of one species indigenous to America (*Bimastos parvus*). This invasion is a cause for concern for two reasons. First, these species may be able to outcompete native species. Replacement of native species by exotics has been observed in many parts of the world, including northern California (Eisen 1900), Illinois (Smith 1928), New Zealand (Lee 1961), and South Africa (Ljungstrom 1972). In general, native earthworms are vulnerable to habitat disturbance and invasion by exotic species (Kalisz and Dotson 1989). Large areas of intact habitat seem to be somewhat more resistant to native species loss, though the long-term outcome is not known.

The second reason for concern arises in regions where native earthworms do not occur. This absence may be for many reasons, such as glaciation, long dry periods, and isolation from potential colonists by intervening deserts. Soil and litter development in the absence of worms is different from that in soil inhabited by worms, particularly in forest ecosystems (for example, Langmaid 1964). There may be corresponding differences in the nutrient cycling dynamics, soil mesofauna, soil microfauna, and soil microflora of worm-free and worm-inhabited systems.

Sich concerns have led to the following questions: Do land managers wish to maintain worm-free areas in their natural state? Is it important to maintain native species, or for larger purposes of sustainable land use, is any worm good enough? Efforts to control the spread of exotic earthworms may be futile, and insufficient information exists about the relative ecological impact of native and exotic species to allow decisionmakers to make informed decisions about how to manage earthworm biodiversity.

Land uses, earthworms, and earthworm functions—The fundamental issue here is whether or not the ecological functions of and biodiversity concerns about earthworms are sufficiently important to shape management decisions. In some soil systems within the basin assessment area, earthworms function as keystone organisims; as such, they merit inclusion with other more conspicuous organisms. We now know that earthworm introductions alter previously worm-free soils and can potentially cause various effects on other groups of soil biota and on nutrient cycling processes. Vital data are lacking about biodiversity and about whether certain species may be endangered, either from habitat alteration or from the introduction of exotics. We do not have experimental evidence directed specifically at those basic management questions for which earthworm data could be relevant. For now, and as a stimulus for further inquiry, I have assembled some basic information on the impacts of grazing, prescribed fire, and logging on earthworms. These three land uses or management practices are widespread and economically important to the region.

Grazing—Effects of grazing on earthworms include at least three components. First, manure deposition on the soil surface reduces available leaf litterfall. Second, root death results from grazing, and thus rhizodeposition of detritus in the soil is increased (up to a point). Third, livestock can cause soil compaction, thereby making burrowing and feeding more difficult for earthworms.

Conversion of herbage to manure by cattle changes the quality and accessibility of detrital material for earthworms. What would have been litter is now partly predigested, may be toxic in the short term, is clumped rather than dispersed, and is highly attractive to several other invertebrates. James (1992) describes the response of several earthworm species to bison (*Bison bison*) dung pats in tallgrass prairie. Species with characteristics of polyhumic endogeics (including *Aporrectodea turgida*—present in the basin assessment area) were attracted to dung, whereas other endogeics were not. Other categories of worms were not represented in the system.

Hutchinson and King (1980) examine the effects of sheep stocking rates on soil invertebrate populations, and Seastedt (1985) and Seastedt and others (1986) consider the impact of clipping or mowing on soil arthropods. In general, these studies showed a peak of abundance at moderate plant defoliation levels. The results, however, are not as clear with earthworms: Seastedt and others (1988) are inconclusive, but Todd and others (1992) found increased abundance of some species with increased mowing frequency but no change (statistically insignificant declines of biomass) for other species. Consequently, it seems that any assessment of the impact of various grazing management scenarios will have to be case by case.

Soil compaction caused by animal activity (including humans) has variable effects on earthworm populations. Cuendet (1992) found contrasting effects of pedestrians on earthworms in two forest types; whereas Pizl (1992) found that the farm machinery in orchards negatively affects all earthworms. Different ecological categories of worms were affected to differing degrees in each case. More specifically, cattle trampling has a blanket negative effect that results in a decline in earthworm population but is less intense on large-bodied earthworms (Cluzeau and others 1992). In this study, trampling was intense, such as would be found by gateways or at water sources.

All three effects of grazing considered here show variable effects by earthworm species or habitat type or both. Endogeic species often suffered less than epigeics, and large species were also less heavily impacted. Without further knowledge about native earthworms and the presence or absence of earthworms in land subject to grazing in the basin assessment area, it is of little use to speculate further.

Prescribed fire— James (1988) describes the impact of fire in Kansas tallgrass prairie on native earthworm populations. The effect was positive because fire allows more rapid warming of the soil in spring, thereby stimulating growth of grasses. In contrast, European species declined with burning, probably because they were less able to tolerate the higher soil temperatures on burned plots. Fire, as a management tool, thus may be short-term neutral or positive on native endogeic species where fire is a natural and frequently recurring element of the ecosystem. If invasions by exotic species occur near their temperature tolerance limits under fire-suppression conditions, they may be pushed beyond the limits in the postfire environment. Anything that removes a litter layer and down logs could negatively impact epigeics. Additional information more relevant to forest fires can be found in Abbot (1984, 1985), though the work was done in jarrah forests of Australia.

Logging—The primary effects of tree removal on endogeic species seem to be in the soil climate area, with surface and soil organic matter pools probably sufficient to carry them through until second-growth plants become established. If selective cutting practices are adopted, this impact will be moderated. Dis-turbance caused from heavy equipment use may be the most deleterious (Schaefer and others 1990).

Epigeic species would be expected to suffer most from the loss of tree cover because this would make their preferred microhabitat less hospitable and ultimately less abundant, with the loss of annual leaf input. There may be a short-term increase from slash left on site, but it is difficult to say if the microclimate would remain suitable for earthworm activity.

The previously mentioned land uses and the management practices linked to them will affect earthworms. Considering that basin assessment area habitats likely to be inhabited by earthworms are generally those with enough precipitation to support some sort of economically driven land use, practical human activity, management decisions, and the fates of earthworm populations could be strongly related in the basin assessment area. Federal and private land decisionmakers in this diverse region may choose to incorporate earthworm ecology and biodiversity parameters in the information used in making management decisions.

Research and Monitoring Priorities

Complete rectification of the lack of information about earthworms in the basin assessment area is probably beyond the budgetary and scientific infrastructure resources (particularly the supply of experts) available. The most critical research need is an inventory of the species present, particularly the native species, and their geographical distribution. An inventory will simultaneously tell us much about the distribution of exotic species in the basin assessment area. The unprocessed collection information of Fender (see footnote 1) and McKey-Fender (1990) could be worked up, and survey efforts could be made to extend their work. Another high priority would be experimentally testing hypotheses of the mechanisms through which habitat disturbance, exotic species invasions, and other human-caused factors may affect native species. This should begin with those species potentially threatened both in the basin assessment area and globally, such as *Driloleirus americanus*. The next priorities would be to learn more about the population densities, habitat requirements, and general ecology of native species in the basin assessment area. An equally important priority for the exotic species would be research into their effects on litter decomposition, soil horizon development, and other soil invertebrates in regions otherwise free of earthworms.

Once the high-priority areas of research are covered, a basis for deciding the next direction for earthworm research in the basin assessment area could be determined. Native species existing as dense populations in particular vegetation types have a higher priority for process- and community-level investigation than species naturally occurring in low numbers. Integrated research with specialists on other basin assessment area biota is highly desired. Interactions with fungi, or earthworms as food resources for vertebrates, are some examples where high-priority organisms in forest ecology and wildlife conservation would be involved. Because little is known about the earthworms of the basin assessment area, research could begin on almost any one of the priorities.

Conclusion

Earthworms, called “the intestines of the earth” by Aristotle, are important to soil processes, other soil biota, and soil hydrology. Although large areas of the basin assessment area are too dry to support earthworms, they have been recorded in various habitats. Both exotic and native earthworm species exist in the basin assessment area. This report presents the basic ecological information necessary to begin evaluating the effects of land management practices and conservation policy on earthworm populations. In addition, the question of how to respond to the presence of invasive exotics has been raised. Findings presented in this paper provide a starting point, a source of hypotheses to be examined in future research efforts and discussions on ways to preserve our natural landscapes and their inhabitants.

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