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Earthworms in the state of Paraná, Brazil: State of the art

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ABSTRACT: Paraná State has approximately 74 % of its territory destined for agricultural activities. Several agricultural management practices modify soil quality and biodiversity, including earthworm populations that can contribute to soil health. This study aimed to review the studies carried out in the state of Paraná, Brazil, focusing on earthworm populations (abundance, biomass, richness, proportion of native and exotic species) in different land-use systems. In total, 51 publications were compiled, including peer-reviewed papers, book chapters, dissertations and theses. We used studies that analyzed chemical and physical soil properties (n = 14) to perform a principal component analysis to explore the relationships between these properties and earthworm populations. In total, 90 earthworm species are known from Paraná, of which more than half (n = 46) may be new species that still must be formally described. Of the total, 24 are exotic and 66 are native species, though only 62 (16 %) of the 399 counties have earthworm records. Of the land-use categories sampled, the lowest abundance and biomass were recorded in annual crops under conventional tillage, and the highest populations were found in agroforestry systems. Higher earthworm abundance and species richness were related to higher chemical fertility (soil P and base contents), while biomass was related to higher silt and sand contents.

Keywords: Oligochaeta, species richness, ecosystem engineers, soil management, soil health.

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INTRODUCTION

Soils host as much as 40 % of all described species that perform essential services to human beings, but this biodiversity remains mostly unknown and little explored (FAO, 2020). Brazil may host as much as 10 % of the world's species (Lewinsohn and Prado, 2005), many of which are invertebrates that inhabit soils for at least part of their life cycles (Lewinsohn et al., 2005; Brown et al., 2015).

Earthworms are probably the most well-known among the soil macrofauna, i.e., invertebrates >2 mm in diameter and generally visible to the naked eye (Ruiz et al., 2008). These animals include litter transformers and ecosystem engineers (Lavelle, 1997). The former species live in the litter and/or the soil and contribute to litter decomposition, increased microbial activity and the release of nutrients to the soil, plants and other organisms (Lavelle, 1997), while the latter are organisms that are able to modify the soil as a habitat physically and the availability of resources for other organisms (Lavelle et al., 1997).

Moreover, earthworms are sensitive to changes in ecosystem properties and processes and are frequently used as bioindicators of environmental and soil quality (Paoletti, 1999; Brown and Domínguez, 2010). Hence, data on earthworms' abundance, biomass and species identity can be used to infer soil and land-use management practices adopted at a particular site. These include soil tillage, organic matter inputs (OM), and pesticides (Chan, 2001; Lavelle et al., 2001; Curry, 2004; Brown and Domínguez, 2010). Soils with greater vegetation cover and diversity, for example, tend to have higher OM contents and higher earthworm populations (Lavelle, 1997; Lavelle et al., 2001; Decaëns et al., 2004).

Paraná State, in Southern Brazil, has 399 counties and covers an area of 199 million square kilometers, of which 33 % is under annual cropping, 25 % in pastures, 29 % in natural forest and 6 % in forestry plantations (IAT, 2019). The last review on earthworms in the state, published 14 years ago (Sautter et al., 2007), reported 55 earthworm species (35 native and 20 exotic) collected in only 11 % (43) of the state's counties. Since then, the authors have undertaken intensive sampling efforts, and much new data has been made available.

In this study, we surveyed the published literature (papers, theses and dissertations) and updated information on the earthworm populations in Paraná. Since soil chemical, physical and biological properties are interrelated and can affect earthworm populations (Brown and Domínguez, 2010), we also collected information on soil and environmental attributes of the sampling sites to explore the relationships between earthworm populations and soil quality (Nadolny, 2017; Demetrio et al., 2020).

MATERIALS AND METHODS

Environmental context and geopolitical regions of Paraná

Paraná is divided into four main topographic regions according with the altitude: the Coastal Lowland, First Plateau, Second Plateau and Third Plateau (Figure 1). Furthermore, it includes ten geopolitical mesoregions: West (WE), Northwest (NW), Center West (CW), Center North (CN), North Pioneer (NP), Center East (CE), Metropolitan (MT), Center South (CS), Southeast (SE) and Southwest (SW) (IBGE, 2010). These regions were used to classify earthworm populations (see later). Finally, Paraná includes two major Köppen climates: Cfa (Coast, Southwest, West, North and a part of the Central region) and Cfb (Southern regions and part of the Central region). However, some regions, such as the Coast, Vale do Ribeira, and some counties in the Northwest region have distinct classifications depending on the source of the publication (Af, Cfa/Af and Cwa) (ITCG, 2008).

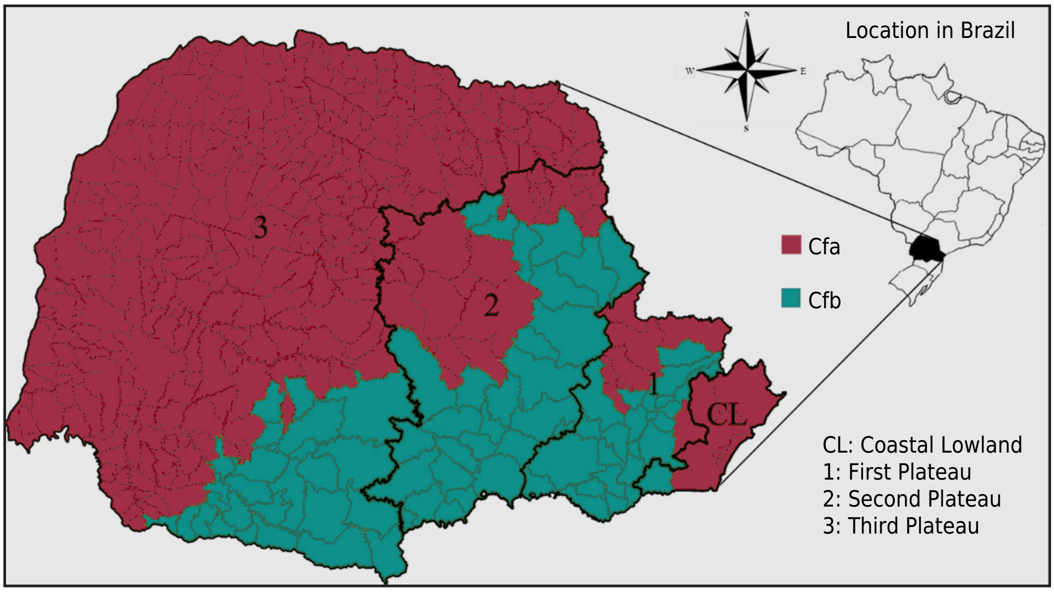

Figure 1. Climatic characterization (Cfa and Cfb) and topographic regions of the state of Paraná, Brazil: Coastal Lowland (CL), First (1), Second (2), and Third (3) Plateau. Adapted from Iapar (2019).

The agricultural history and practices adopted in the state were greatly influenced by European immigrants, who used the plow and tractor-pulled harrows as a technological model for soil preparation, called conventional tillage (CT) (Casão Junior et al., 2012). This system predominated until the 1990s when no-tillage (NT) became a major means of planting annual crops in the state, mainly due to the intense soil erosion caused by CT practices. Presently, around 80 % of the annual crops in the state are planted using NT (Fuentes-Llanillo et al., 2021). In the current review, we considered eight main land-use types, following the classification scheme of Nadolny et al. (2020): pastures (both native and exotic), native vegetation, agroforestry systems, integrated systems (agropastoral, agrosilvopastoral, silvopastoral), forestry plantations (including *Araucaria angustifolia*, *Eucalyptus* and *Pinus* spp.), perennial crops (e.g., coffee, citrus), grass lawns (mainly in urban setting), and annual crops, with three subcategories - under NT, CT and minimum tillage (MT).

Data collection and analysis

For data collection, online databases were consulted (Science Direct, SciELO, Web of Science and Google Scholar), using keywords in Portuguese and English (earthworm*, worm*, minhoca*, minhocuçu, Oligochaeta, oligoqueta*, soil quality, qualidade do solo) in conjunction with the study location (Paraná, Parana). Databases of theses and dissertations in Brazilian universities (*Base de Dados de Teses e Dissertações* – BDTA) and those located in Paraná State were also consulted. Books and/or book chapters and expanded abstracts in conferences, workshops and symposia relevant to the research theme were also reviewed. All references from 1969 up to 2021 were retrieved, and those including the selection criteria were maintained for a more detailed review. References before 1969 were obtained from the personal library of one of the authors, and were mainly of taxonomic nature, and only used to obtain information on species occurrence. The database with all the information collected was deposited in Zenodo, an open-access data repository (Dudas et al., 2023).

The following intensification gradient of these ten main LUS was applied to assess the impact of land-use intensification on the earthworm communities (listed in the order of lower to higher intensity level): NV<AF≤FP<IS<PA<GL<PC<NT<MT<CT, in which NV is Native Vegetation; AF is Agroforestry System; FP is Forest Plantation; IS is Integrated

System; PA is Pasture; GL is Grass Lawn; PC is Perennial Crops; NT is No-Tillage; MT is Minimum Tillage; and CT is Conventional Tillage, adapted from Nadolny et al. (2020). We considered as characterization of each LUS:

- Native vegetation: areas of native vegetation that maintain the natural characteristics of the environment, even with low anthropic disturbance (e.g., secondary forests) that, apparently, do not compromise the soil properties. Includes Seasonal semi-deciduous, Dense Ombrophilous and Mixed Ombrophilous forests and Natural Grassland (not grazed by cattle).
- Agroforestry system: a combination of trees and annual and/or perennial crops growing simultaneously in the same area.
- Forest plantation: areas with commercial tree plantations. Includes the exotic trees of *Eucalyptus* sp. and *Pinus* sp., as well as the native *Araucaria angustifolia*.
- Integrated system: areas with systems that include the combinations of either cropping, forestry and pasture (agrosilvopastoral, silvopastoral, agropastoral), except agroforestry.
- Pastures with native or planted grasses and animal grazing.
- Grass lawn: includes grass lawns of urban and rural gardens.
- Perennial crops: areas with perennial commercial cultures, such as *Coffea* sp., *Musa* sp. and *Euterpe* sp.
- No-tillage: areas with annual crops but no soil mobilization. Includes the no-tillage technique and the no-tillage system (considered Conservation Agriculture by FAO) (FEBRAPDP, 2017; Fuentes-Llanillo et al., 2022).
- Minimum tillage: areas with annual crops and minimal soil mobilization, i.e., shallow tillage (<0.10 m) or tillage only every three or four years.
- Conventional tillage: areas with annual crops and intense soil mobilization, i.e., disk or moldboard plow (deeper tillage) performed yearly.

Two main types of data were obtained regarding the earthworm populations at each sampling site:

1. Qualitative data on the occurrence and records of earthworm species in a particular locality from studies that collected earthworms using qualitative and quantitative sampling methods (see below). Qualitative methods included formalin extraction according to ISO 23611-1 (ISO, 2017), Pitfall traps [e.g., (Fernandes, 2009)], electrical extraction (Azevedo et al., 2010), and random sampling in the LUS to find the greatest number of earthworm species [e.g., (Bartz et al., 2014)]. The total number of species per site and per LUS were compiled and compared. Total richness values for each county and region in Paraná were also compiled. The proportion of native and exotic species in the different counties and in the different LUS was obtained from the analysis of species richness described in the surveys and using different sampling methods (TSBF, formalin, Pitfall traps, and qualitative sampling).
2. Quantitative data on earthworm abundance and biomass (expressed as ind m^{-2} and g m^{-2}, respectively), from studies exclusively applying the Tropical Soil Biology and Fertility (TSBF) hand-sorting method (Anderson and Ingram, 1993), or modifications thereof, also adopted by ISO 23611-1 for tropical regions (ISO, 2017). Mean values of these quantitative variables (abundance, biomass) were calculated for each main LUS class.

Using R software (R Core Team, 2020), a Principal Component Analysis (PCA) was performed using the quantitative data (TSBF, electrical or formalin extraction methods) available from studies that included soil chemical and physical analyses (pH, phosphorus – P, organic carbon – C, sum of bases – SB, % clay, % silt and % sand).

RESULTS

State of the art of studies on earthworm populations in state of Paraná

In total, 51 publications were found and analyzed, including peer reviewed papers, book chapters, dissertations and theses available in university databases and extended abstracts in scientific meetings, according to the keywords used in the search. Of these, all had abundance data, but only 14 had complete data on abundance, biomass, identification at the species level and soil chemical and physical properties. There were also reviews (Brown and James, 2007; Sautter et al., 2007) and descriptions of new species found in the state (Bartz et al., 2012; Feijoo and Brown, 2018).

The first native earthworm species reported from Paraná was *Andorrhinus duseni* (Michaelsen, 1918) a big earthworm collected in Curitiba in 1910. Large species like *A. duseni* are commonly called "minhocuçus" (earthworms longer than 0.25 m and wider than 5 mm) in Brazil. Nevertheless, the first quantitative study that evaluated earthworm populations in the state was carried out only in the late 1970s, through a collaborative project between the IAPAR (Agronomic Institute of Paraná, current IDR - Paraná Rural Development Institute) and GTZ (German Technical Cooperation Agency, current GIZ - German Corporation for International Cooperation). Two long-term soil tillage trials were evaluated: the first from 1977 to 1981 and the second from 1977 to 1982 (Derpsh et al., 1986; Voss, 1986). In these trials, the authors found a greater abundance of earthworms in NT than in CT, but Voss (1986) was the first one to identify the species collected, recording *Amynthas corticis* and *Amynthas gracilis* in Ponta Grossa. Both species are of Asian origin, exotic to Brazil (Brown et al., 2006).

Until 2002, few earthworm species were known from Paraná, with only 10 species listed, due to the low sampling effort in the state (Sautter et al., 2007). After extensive sampling from 2002 to 2019 and the identification of many of the specimens collected, the number of known species known from Paraná increased from 55 (Sautter et al., 2007) to 90 with this bibliographical review, of which 24 are exotic and 66 are native to Brazil (Table 1). Therefore, since the last reviews (Brown and James, 2007; Sautter et al., 2007), an additional 35 species were found, most of them native and many of them new to science, that are presently being described. Of the described species, 12 are known only from the state of Paraná (unique species, represented with a double asterisk in table 1), and of the total, eight are giant earthworms (*minhocuçus*, represented with an asterisk in table 1), that may have important impacts on soil properties and structure, which deserve further attention.

Regarding the exotic species, the "jumping" earthworms mainly of the genus *Amynthas*, but also of *Pheretima, Duplodicodrilus* and *Metaphire* in the Megascolecidae family were often dominant and widespread (found in 21 counties; table 1) in modified landscapes, being used as indicators of human-disturbed environments (Brown et al., 2006; Fernandes et al., 2010; Chang et al., 2021). Another widespread species (also found in 21 counties) was *Pontoscolex corethrurus* (Rhinodrilidae family), first described from Blumenau in neighboring Santa Catarina by the German naturalist Fritz Müller (1857). Römbke et al. (2009) found this species to be dominant in pastures and regenerating Atlantic forests in the Coastal region of Paraná. Finally, various *Dichogaster* spp., small endogeic and epi-endogeic species were also widespread (22 counties), and common particularly in the Western and Center North regions; see table 1), especially in NT systems (Bartz et al., 2013, 2014; Gorte, 2016; Santos et al., 2018). These exotic species occur throughout

Brazil in several regions and LUS (Brown et al., 2006), and are found in places with higher human impact, while native species are generally found in less disturbed environments (Brown, 2008).

Table 1. Earthworm species record, ecological category, sampling method, municipality, land-use system (LUS) and reference to the original publication, in the state of Paraná, Brazil

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Exotic/Peregrine					
Family Rhinodrilidae					
Pontoscolex corethrurus	Endogeic-mesohumic	Formalin, Qualitative, TSBF	Adrianópolis, Antonina, Arapongas, Cafeara, Cambé, Cianorte, Colombo, Curitiba, Entre Rios do Oeste, Faxinal, Foz do Iguaçu, Guaraqueçaba, Jaguapitã, Londrina, Marechal Cândido Rondon, Mauá da Serra, Morretes, Paranaguá, Rolândia, Santa Helena, São Jerônimo da Serra	AF, CT, FP, GL, NT, NV, PA, PC	(1), (2), (3), (5), (6), (7), (8), (9), (14), (17), (18), (19), (21), (25), (27), (29), (30), (31), (32)
Exotic					
Family Behanmiidae					
Dichogaster affinis	Endogeic polyhumic	Qualitative, TSBF	Arapoti, Entre Rios do Oeste, Itaipulândia, Jaguapitã, Londrina, Marechal Cândido Rondon, Rolândia, Santa Helena e Toledo	CT, NV, NT, PA, PC	(1), (2), (5), (6), (8), (17), (19), (25)
Dichogaster annae	Epigeic	Qualitative	Primeiro de Maio	GL	(8)
Dichogaster bolaui	Epi-endogeic	Formalin, Qualitative, TSBF	Arapoti, Castro, Entre Rios do Oeste, Itaipulândia, Jaguapitã, Londrina, Marechal Cândido Rondon, Rolândia, Santa Helena e Toledo	CT, NV, NT, PA	(1), (2), (5), (8), (17), (19), (25), (28)
Dichogaster gracilis	Endogeic	Qualitative, TSBF	Arapongas, Cafeara, Itaipulândia, Lapa, Londrina, Marechal Cândido Rondon, Mauá da Serra, Rolândia, Santa Helena, Toledo	CT, NT, NV, PA, PC	(2), (3), (5), (6), (7), (8), (13), (14), (17), (19)

Continue

Continuation

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Dichogaster saliens	Epigeic	Qualitative, TSBF	Arapongas, Cafeara, Entre Rios do Oeste, Itaipulândia, Jaguapitã, Jataizinho, Londrina, Marechal Cândido Rondon, Rolândia, Santa Helena e Toledo	CT, NT, NV, PA, PC	(1), (2), (3), (5), (6), (17), (8), (17), (19), (25)
Dichogaster sp.	N/D	Qualitative, TSBF	Antonina, Bela Vista do Paraíso, Campo Mourão, Carambeí, Cianorte, Cornélio Procópio, Entre Rios do Oeste, Jaguapitã, Londrina, Mercedes, Santa Helena, Toledo	AF, CT, NT, NV, PA, PC	(1), (5), (6), (7), (8), (17), (19), (22), (25)
Family Eudrilidae					
Eudrilus eugeniae	Epigeic	Qualitative	Londrina, Primeiro de Maio	vermiculture	(8)
Family Lubricidae					
Eisenia andrei	Epigeic	Qualitative	Londrina, São Jerônimo da Serra	vermiculture	(8)
Bimastos parvus	Endogeic polyhumic	Formalin	Castro	NT, PA	(28)
Aporrectodea rosea	Endogeic	Qualitative, TSBF	Curitiba	GL	(18)
*Lubricus rubellus***	N/D	Qualitative, TSBF	Curitiba	GL	(18)
Family Megascolecidae					
*Amynthas aeruginosus***	Endogeic polyhumic	Qualitative	Prudentópolis	N/D	(7), (8)
Amynthas corticis	Epi-endogeic	Qualitative, TSBF	Antonina, Campina Grande do Sul, Castro, Colombo, Curitiba, Lapa, Ponta Grossa	AF, FP, GL, NT, NV, PA	(10), (13), (18), (22), (28), (29), (30), (31), (34)
Amynthas gracilis	Epi-endogeic	Formalin, Qualitative, TSBF	Adrianópolis, Antonina, Arapoti, Campina Grande do Sul, Castro, Colombo, Curitiba, Entre Rios do Oeste, Lapa, Londrina, Marechal Cândido Rondon, Ponta Grossa, Rolândia, Toledo	AF, CT, GL, NT, NV, PA, PC	(1), (2), (3), (5), (7), (9), (10), (13), (17), (18), (21), (27), (28), (29), (30), (31), (34), (36)
Amynthas morrisi	Epi-endogeic	Formalin, Qualitative	Castro, Curitiba	NT, NV	(11), (28)

Continue

Continuation

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Amynthas sp.	N/D	Formalin, Qualitative, TSBF	Arapoti, Carambeí, Guarapuava, Guaraqueçaba, Jaguapitã, Londrina, Paranaguá, Primeiro de Maio, São Mateus do Sul, Tibagi	CT, NT, NV, PA	(7), (8), (17), (25), (26), (29), (33)
Methaphire californica	Epi-endogeic	Formalin, Qualitative, TSBF	Castro, Curitiba, Palmeira	FP, GL, NT, NV, PA	(11), (14), (18), (27), (28)
Duplodicodrilus schmardae	Epi-endogeic	Qualitative, TSBF	Colombo	FP, NV	(21), (23), (30), (31)
Pheretima darnleiensis	N/D	Qualitative	Curitiba	N/D	(11)
Family Ocnerodrilidae					
Eukerria eiseniana	Endogeic	TSBF	Cafeara, Jaguapitã	NT, PA	(7), (8), (25)
Eukerria emete	Endogeic	Qualitative	Londrina	NV	(8)
Eukerria n.sp.1	N/D	Qualitative	Centenário do Sul	NV	(8)
Eukerria saltensis	Endogeic	TSBF	Jaguapitã	PA	(8), (25)
Eukerria tucumana	N/D	Qualitative, TSBF	Curitiba	GL, NV	(18)
Nematogenia lacuum	N/D	Qualitative, TSBF	Marechal Cândido Rondon	NV	(19)
Ocnerodrilus occidentalis	N/D	Formalin, TSBF	Antonina, Guaraqueçaba, Jaguapitã	AF, CT, NV	(25), (29)
Ocnerodrilidae n.sp.2	N/D	Qualitative, TSBF	Entre Rios do Oeste, Santa Helena	NT	(5), (19)
Native families, genus and species					
Family Almidae					
Drilocrius n.sp.1	N/D	Qualitative	Jaguapitã	NV	(8)
Drilocrius n.sp.2	N/D	Qualitative	Bandeirantes	NV	(8)
Family Glossoscolecidae					
*Fimoscolex bartzi***	Endogeic	TSBF	Arapongas, Londrina, Rolândia	NT, PA	(6)
*Fimoscolex nivae***	Endogeic	Qualitative, TSBF	Colombo, Ponta Grossa	FP, NT, NV	(8), (16), (31)
Fimoscolex n.sp.1	Epigeic	Qualitative, TSBF	Entre Rios do Oeste, Marechal Cândido Rondon, Santa Helena	NT, NV	(5), (19)
Fimoscolex n.sp.2	Endogeic	Qualitative, TSBF	Entre Rios do Oeste, Itaipulândia	NT	(5), (19)
Fimoscolex n.sp.9	N/D	Qualitative, TSBF	Lapa	GL, NV	(13)
Fimoscolex n.sp.12	Endogeic	Qualitative, TSBF	Curitiba	GL, NV	(18)
Fimoscolex n.sp.13	Endogeic	Qualitative, TSBF	Curitiba	GL, NV	(18)
Fimoscolex n.sp.14	Endogeic	TSBF	Curitiba	NV	(18)
Fimoscolex n.sp.21	Endogeic	TSBF	Mauá da Serra, Palmeira	NV, NT	(14)
Fimoscolex n.sp.22	Endogeic	Qualitative, TSBF	Palmeira	NT	(14)
Fimoscolex n.sp.23	Endogeic	TSBF	Rolândia	NV	(2)

Continue

Continuation

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Fimoscolex n.sp.24	Endogeic	Qualitative TSBF	Palmeira	NT	(14)
Fimoscolex n.sp.26	N/D	Qualitative, TSBF	Campina Grande do Sul	NV	(10)
Fimoscolex n.sp.31	N/D	TSBF	Jaguapitã	CT, PA	(25)
Fimoscolex n.sp.34	N/D	Qualitative, TSBF	Lapa, Palmeira	NV, GL, NT	(13)
Fimoscolex sp.	Endogeic	Qualitative, TSBF	Londrina, Toledo, Mauá da Serra	NV, NT	(1), (5), (7), (8), (19) (14)
*Glossoscolex bergi**	Endo-anecic	Qualitative	Foz do Iguaçu	N/D	(35)
*Glossoscolex corderoi**	Endogeic	Qualitative	Campina Grande do Sul	GL	(8)
*Glossoscolex embrapaensis***	Endogeic	Qualitative, TSBF	Colombo	FP, NV	(16), (23), (31), (32)
Glossoscolex giocondoi	Endogeic	TSBF	Londrina	PA	(6)
Glossoscolex itaguajensis,***	Endogeic	Qualitative	Itaguajé	NV	(4), (8)
*Glossoscolex lutocolus***	Endogeic	Qualitative, TSBF	Centenário do Sul, Jaguapitã, Londrina, Lupionópolis	NV	(4), (8)
*Glossoscolex maschio***	Epi-endogeic	Qualitative	Colombo	NV	(16)
*Glossoscolex mariarum***	Endogeic	Qualitative	Lupionópolis	NV	(4),(8)
Glossoscolex matogrossensis	Endo-anecic	Qualitative	Foz do Iguaçu	N/D	(36)
*Glossoscolex primaensis***	Endogeic	Qualitative	Primeiro de Maio	NV	(4), (8)
*Glossoscolex palus***	Endogeic	Qualitative	Bandeirantes	NV	(4), (8)
*Glossoscolex sanpedroensis***	Endogeic	Qualitative	Lupionópolis	NV	(4), (8)
*Glossoscolex terraopimus***	Endogeic	Qualitative	Mauá da Serra, Ortigueira	NV	(4), (8)
*Glossoscolex uliginosus**	Endogeic	Qualitative	São Jerônimo da Serra	NV	(4), (8)
Glossoscolex n.sp.1	N/D	Qualitative, TSBF	Entre Rios do Oeste, Itaipulândia, Santa Helena, Toledo	NV	(5), (19)
Glossoscolex n.sp.2	N/D	Qualitative, TSBF	Marechal Cândido Rondon	NT, NV	(5), (19)
Glossoscolex n.sp.8	N/D	TSBF	Londrina	NT	(3)
Glossoscolex n.sp.13	N/D	Qualitative, TSBF	Lapa	GL, NV	(13)
Glossoscolex n.sp.14	N/D	Qualitative, TSBF	Lapa	GL, NV	(13)
Glossoscolex n.sp.22	Endogeic	Qualitative, TSBF	Faxinal, Palmeira	NV	(14)
Glossoscolex n.sp.23	Endogeic	Qualitative, TSBF	Palmeira	NV	(14)

Continue

Continuation

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Glossoscolex n.sp.24*	N/D	Qualitative, TSBF	Antonina, Campina Grande do Sul	NV	(8), (10)
Glossoscolex n.sp.25*	N/D	Qualitative, TSBF	Campina Grande do Sul	NV	(10)
Glossoscolex n.sp.26	N/D	Qualitative, TSBF	Campina Grande do Sul, Morretes	NV	(8), (10)
Glossoscolex n.sp.29*	Endo-anecic	Qualitative	Guaraqueçaba	NV	(12)
Glossoscolex n.sp.37	N/D	Qualitative	Campina Grande do Sul	NV	(10)
Glossoscolex n.sp.38	N/D	Qualitative	Campina Grande do Sul	NV	(10)
Glossoscolex n.sp.39	N/D	Qualitative	Campina Grande do Sul	NV	(10)
Glossoscolex n.sp.41	N/D	TSBF	Cafeara	NT	(7)
Glossoscolex n.sp.42	N/D	Qualitative, TSBF	Entre Rios do Oeste, Marechal Cândido Rondon, Santa Helena	NT, NV	(5), (19)
Glossoscolex n.sp.43	N/D	TSBF	Jaguapitã	PA	(25)
Glossoscolex n.sp.44	N/D	Qualitative	Ponta Grossa	NT	(8)
Glossoscolex n.sp.45	N/D	Qualitative	São Jerônimo da Serra	NV	(8)
Glossoscolex sp.	N/D	Qualitative, TSBF	Londrina, Sertanópolis	NT, NV, PA	(1), (7), (8), (14), (17)
Family Ocnerodrilidae					
Belladrilus emiliani	Endogeic	TSBF	Arapongas, Londrina, Rolândia	NT, PC	(6)
Belladrilus n.sp.2	N/D	Qualitative, TSBF	Entre Rios do Oeste, Marechal Cândido Rondon	NT, NV	(5), (19)
Belladrilus n.sp.3	Endogeic	TSBF	Arapongas	NT	(6)
Belladrilus n.sp.4	N/D	TSBF	Jaguapitã	PA	(25)
Belladrilus sp.	N/D	Qualitative, TSBF	Londrina	CT, PA	(1), (7)
Haplodrilus michaelseni	Endogeic	Qualitative	Londrina	NV	(8)
Haplodrilus n.sp.1	Endogeic	TSBF	Rolândia	NT	(2)
Kerriona n.sp.1	N/D	Qualitative, TSBF	Antonina	NV	(10)
Kerriona n.sp.2	N/D	Qualitative	Antonina, Campina Grande do Sul, Morretes	NV	(8), (10)
Kerriona n.sp.3	N/D	Qualitative	Matinhos	NV	(8)
Kerriona n.sp.4	N/D	TSBF	Ponta Grossa	NV	(8)

Continue

Continuation

Earthworms	Ecological category	Sampling method	Municipality	LUS	Reference
Ocnerodrilidae n.sp.1	N/D	Qualitative, TSBF	Entre Rios do Oeste, Marechal Cândido Rondon, Mercedes, Santa Helena, Toledo	NV, NT	(5), (19)
Ocnerodrilidae n.sp.15	N/D	TSBF	Rolândia, Toledo	NT	(2)
Ocnerodrilidae n.sp.25	N/D	TSBF	Jaguapitã	NV, PA	(25)
Ocnerodrilidae sp.	N/D	Qualitative, TSBF	Campina Grande do Sul, Campo Mourão, Faxinal, Guaraniaçu, Londrina, Mauá da Serra, Ortigueira	NT, NV	(1), (8), (10), (14)
Family Rhinodrilidae					
*Andiorrhinus duseni**	Endo-anecic	Qualitative, TSBF	Antonina, Campina Grande do Sul, Colombo, Curitiba, Faxinal, Fernandes Pinheiro, Irati, Lapa, Londrina, Mauá da Serra, Ortigueira, Ponta Grossa, Quatro Barras, São Jerônimo da Serra	FP, GL, NT, NV, PA	(7), (8), (10), (13), ,(14), (15), (21), (24), (31)
Urobenus brasiliensis	Epi-endogeic	Qualitative, TSBF	Antonina, Cambé, Campina Grande do Sul, Colombo, Entre Rios do Oeste, Faxinal, Foz do Iguaçu, Itaipulândia, Lapa, Londrina, Marechal Cândido Rondon, Mauá da Serra, Mercedes, Santa Helena, São Jerônimo da Serra, Sertanópolis, Toledo	FP, NT, NV	(2), (5), (7), (8), (10), (13), (14)1, (19), (21), (31) (32)

N/D: not determined; *: *minhocuçu* (large earthworm species); **: species unique to Paraná. Land-use system classes: AF: agroforestry system; CT: conventional tillage; MT: minimum tillage; NT: no-tillage; FP: forest plantation; GL: Grass Lawn; IS: integrated system; NV: native vegetation; PA: pasture; PC: perennial crops. Numbers refer to the References: (1) Azevedo et al. (2010); (2) Barreto (2019); (3) Bartz et al. (2009); (4) Bartz et al. (2012); (5) Bartz et al. (2013); (6) Bartz et al. (2014); (7) Brown and James (2007); (8) Brown (2008); (9) Brown et al. (2009); (10) Cardoso et al. (2014); (11) Chang (1997); (12) de Meijer (2017); (13) Demetrio et al. (2018); (14) Dudas (2020); (15) Feijoo et al. (2017); (16) Feijoo et al. (2018); (17) Fernandes et al. (2009); (18) Ferreira et al. (2018); (19) Gorte (2016); (20) Korasaki et al. (2007); (21)Lima (2011); (22)Maschio et al. (2010); (23)Maschio et al. (2014); (24)Michaelsen (1918); (25)Nunes et al. (2006); (26)Peixoto and Marochi (1996); (27)Ressetti et al. (2006); (28)Ressetti et al. (2008); (29)Römbke et al. (2009); (30)Santana et al. (2013); (31)Silva et al. (2019); (32)Silvano et al. (2010); (33)Tanck et al. (2000); (34)Voss (1986); (35)Zicsi & Csuzdi (1987); (36)Zicsi & Csuzdi (1999).

The number of counties with earthworm reports (at the level of class, family, genus and/or species) increased from 43 in 2007 (Sautter et al., 2007) to 61 in 2021. However, this still corresponds to only 15 % of the counties in the state (Figure 2), indicating that intense future sampling efforts are still needed. Of the counties having earthworm records, 51 had identification at the species level, with 14 counties having 100 % occurrence of exotic species and nine having 100 % native species only (Figure 3).

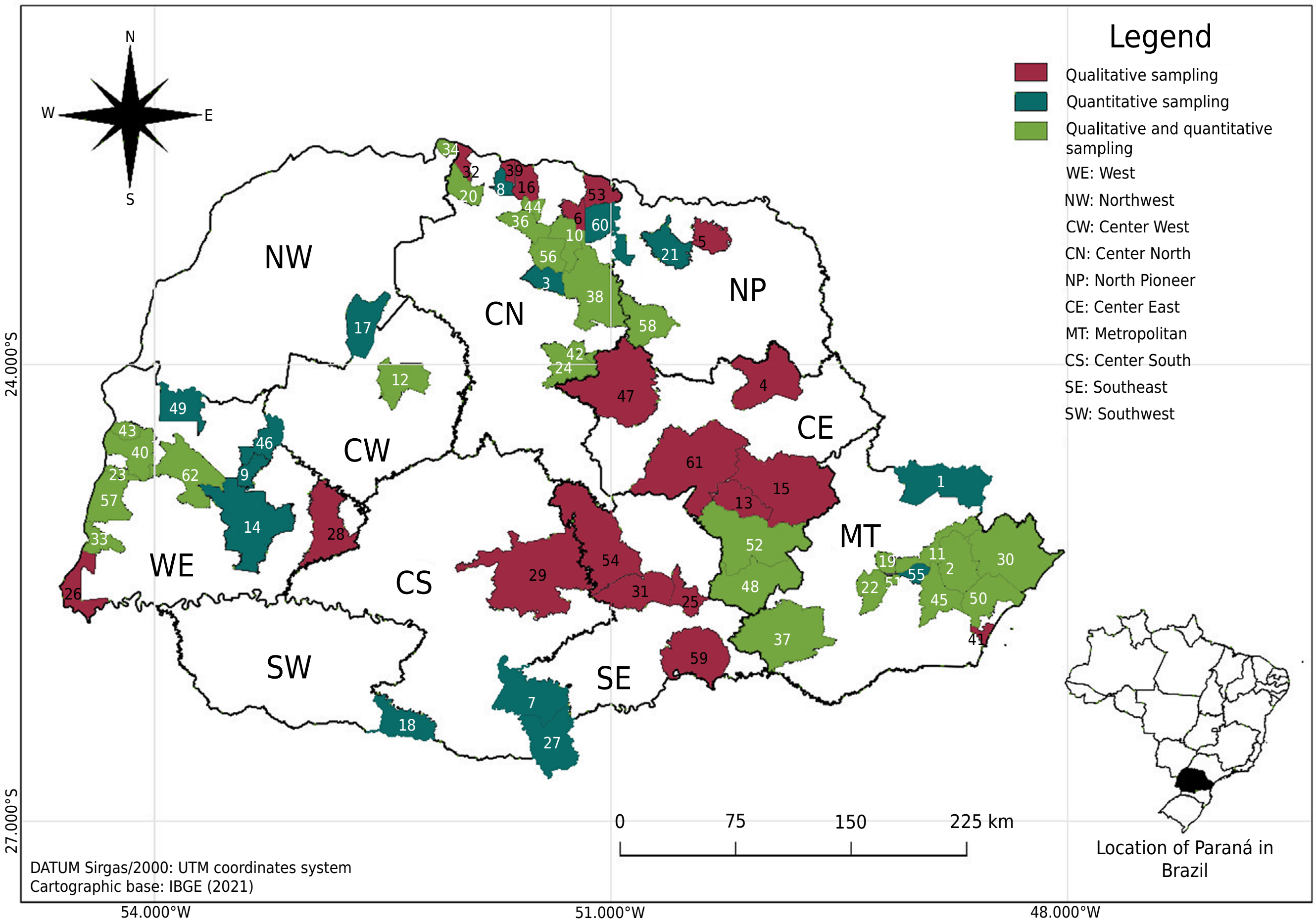

Figure 2. Counties with records of earthworms in the state of Paraná, considering the different sampling methods in each geopolitical region. 1- Adrianópolis; 2- Antonina; 3- Arapongas; 4- Arapoti; 5- Bandeirantes; 6- Bela Vista do Paraíso; 7- Bituruna; 8- Cafeara; 9- Cafelândia, 10- Cambé; 11- Campina Grande do Sul; 12- Campo Mourão; 13- Carambeí; 14- Cascavel; 15- Castro; 16- Centenário do Sul; 17- Cianorte; 18- Clevelândia; 19- Colombo; 20- Colorado; 21- Cornélio Procópio; 22- Curitiba; 23- Entre Rios do Oeste; 24- Faxinal; 25- Fernandes Pinheiro; 26- Foz do Iguaçu; 27- General Carneiro; 28- Guaraniaçu; 29- Guarapuava; 30- Guaraqueçaba; 31- Irati; 32- Itaguajé; 33- Itaipulândia; 34- Jardim Olinda; 35- Jataizinho; 36- Jaguapitã; 37- Lapa; 38- Londrina; 39- Lupionópolis; 40- Marechal Cândido Rondon; 41- Matinhos; 42- Mauá da Serra; 43- Mercedes; 44- Miraselva; 45- Morretes; 46- Nova Aurora; 47- Ortigueira; 48- Palmeira; 49- Palotina; 50- Paranaguá; 51- Pinhais; 52- Ponta Grossa; 53- Primeiro de Maio; 54- Prudentópolis; 55- Quatro Barras; 56- Rolândia; 57- Santa Helena; 58- São Jerônimo da Serra; 59- São Mateus do Sul; 60- Sertanópolis; 61- Tibagi; 62- Toledo.

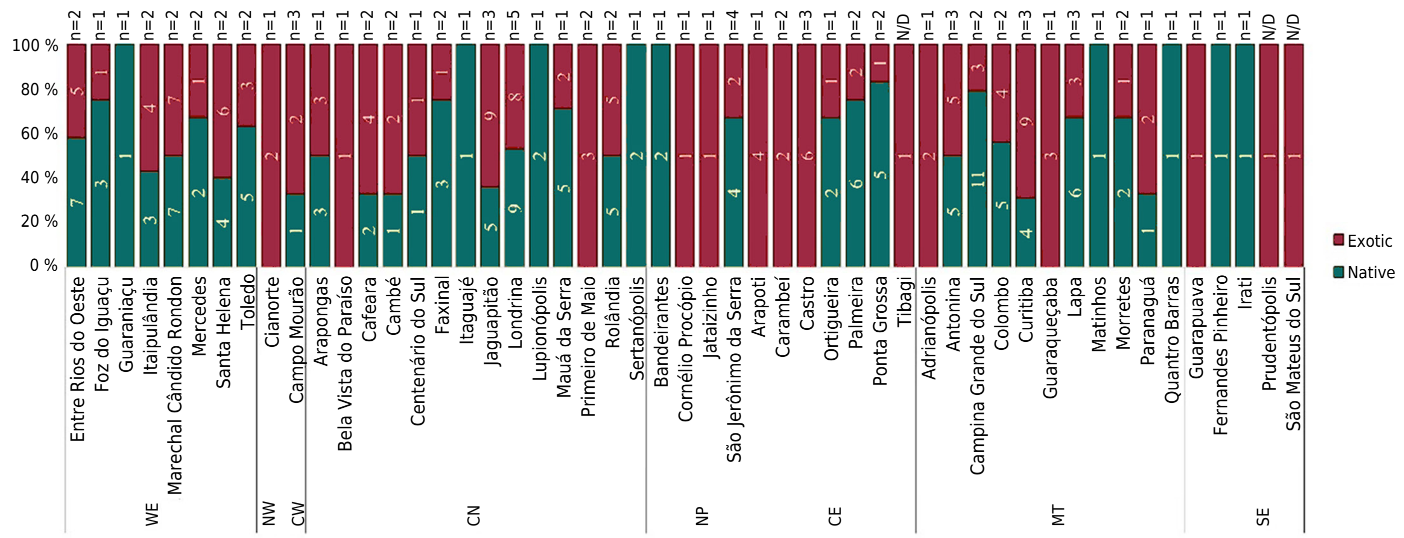

Figure 3. Counties in the state of Paraná with data on earthworm species and the proportion (%) of native and exotic species encountered. The numbers inside the bars indicate the number of species; n: number of sites for each land-use system assessed in each county. Regions of the state: West (WE), Northwest (NW), Center West (CW), Center North (CN), North Pioneer (NP), Center East (CE), Metropolitan (MT), Southeast (SE). N/D: land-use system not determined.

Considering the state's regions, the Metropolitan (n = 12/36), Center East (n = 7/17) and Southeast (n = 6/20) have more than 30 % of their counties sampled, while the Center North (n = 16/66) and West regions (n = 11/51) have 24 and 22 %, respectively. The only one without species record is the Southwest region (n = 1/44), which had a single study on soil macrofauna in Clevelândia (Trogello et al., 2008) without earthworm identification. It is also worth mentioning that the Center West (n = 1/29) and Center South (n = 1/19) regions have only one county with data, corresponding to 3 and 5 %, respectively, of the proportion of counties that make up these regions. Further sampling efforts are needed to address these major gaps in the knowledge of the earthworm fauna in these regions.

Earthworm species richness and proportion of native and exotic species in land-use systems

Land-use intensity and soil management practices can have profound impacts, both positive and negative, on earthworm abundance, biomass and species richness (Brown and Domínguez, 2010). The richness in each LUS, ranged from a maximum of 67 spp. in native vegetation, followed by NT agricultural systems (37 spp.) and pastures (22 spp.). The lowest richness was found in forest plantations (8 spp.), perennial cropping systems (7 spp.) and agroforestry systems (5 spp.) (Figure 4). Furthermore, in these latter systems, communities tended to be dominated by exotic species, but these LUS had a very low number of sampling sites (n = 3), so further sampling efforts are needed to confirm these results. Only in native vegetation and NT systems were more native species found overall (considering all sites) than exotics.

Local differences in site history and environmental conditions are important. For instance, in a study conducted in three forest fragments in Londrina (North Central region), Korasaki et al. (2007) found only native species (*Urobenus brasiliensis* and *Glossoscolex* sp.) in the most well preserved fragments, while the other two more disturbed forests had mainly exotic species (*Amynthas gracilis* and *Pontoscolex corethrurus*). In Colombo, two studies comparing native vegetation with *Araucaria, Pinus*, and *Eucalyptus* spp. plantations in Colombo (Silva et al., 2019; Maschio et al., 2014) found a total of eight species: four native (*U. brasiliensis*, *Andiorrhinus duseni*, *Fimoscolex nivae* and *Glossoscolex embrapaensis*) and four exotic (*P. corethrurus*, *A. gracilis*, *A. corticis* and *M. schmardae*). The exotic species

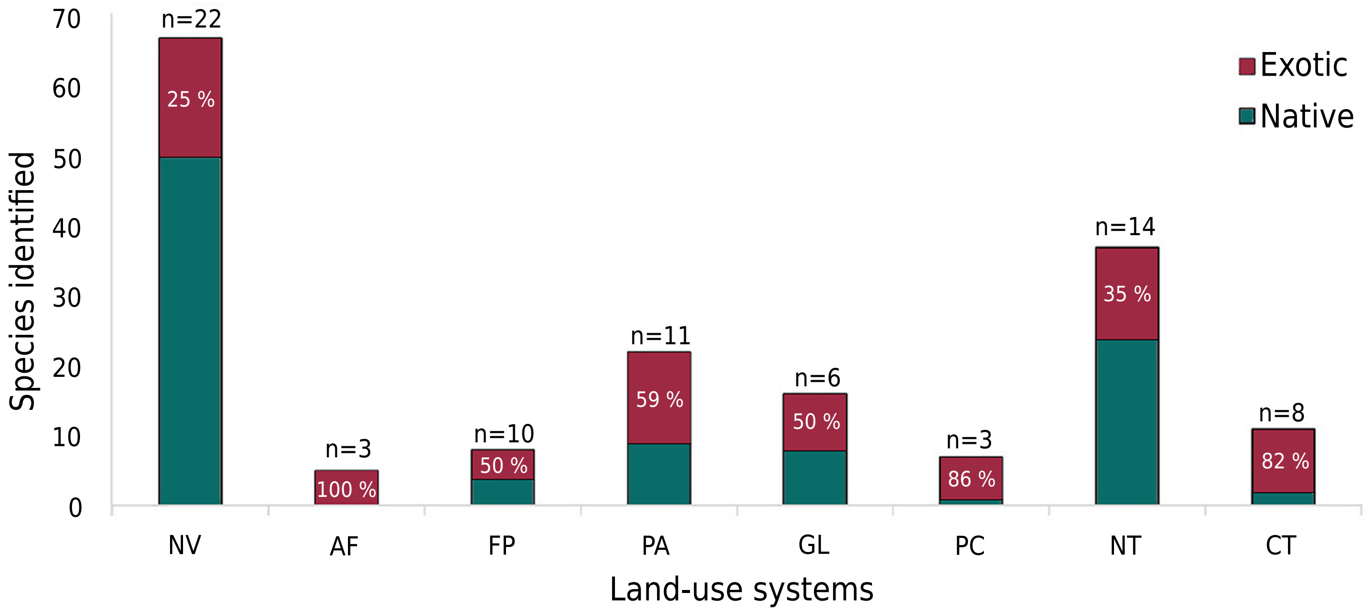

Figure 4. Proportion of native and exotic earthworm species in various land-use systems in Paraná, Brazil. Land-use classes: NV: native vegetation; AF: agroforestry system; FP: forest plantation; PA: pasture; GL: grass lawn; PC: perennial crops; NT: no-tillage; CT: conventional tillage. n: number of studies with species identification in each LUS.

were more abundant in *Pinus* and *Eucalyptus* spp. plantations, probably due different soil properties, the use of these forestry lots for agricultural crops in the past, and the possible inoculation with seedlings containing soil contaminated with exotic earthworms.

This same condition is likely the cause of the predominance of exotic species in grass lawns (Figure 4), as transplants of grass sod and exotic trees can often be associated with earthworm inoculation like cocoons or small juveniles (Chang et al., 2021). Furthermore, the construction of new soils like Anthrosols or Technosols, involves transporting soil from other sites which may contain earthworms. The survival of exotic species in anthropic environments is expected due to their high adaptability (Chang et al., 2021). However, it is important to note that in these urban areas, native earthworm species (some of them new to science) were also found, so that soil transport may include native and exotic introduced species.

Pasture areas often have many earthworm species, as this habitat is conducive to their maintenance (Decaëns et al., 2004). However, the balance of native to exotic species may depend on if the pastures are renovated and planted with exotic grass species, or if they are dominated by native grasses (Brown et al., 2004), though little is known regarding this topic in Brazil. In the Coastal region, *P. corethrurus* dominated in the *Urochloa* sp. (ex-*Brachiaria* sp.) pastures (Römbke et al., 2009), while in Jaguapitã (Center North region), older pastures of *Panicum* and *Brachiaria* sp. had important numbers of native species (Nunes et al., 2006).

Although permanent crops generally can be more beneficial to earthworms than annual cropping systems (Bartz et al., 2009; Nadolny, 2017), these tend to be dominated by exotic species (Figure 4), particularly in more conventional management systems. For instance, Bartz et al. (2009) found five exotic species (*P. corethrurus*, *A. gracilis*, *Dichogaster gracilis* and *Dichogaster saliens*) in coffee plantations near Londrina, with predominance of *Dichogaster* spp. Furthermore, annual cropping systems can have important negative impacts on earthworms, particularly when they are tilled (Briones and Schmidt, 2017). Hence, it was not surprising that the areas under CT had very few species, and a dominance of exotics, which can be explained due to the intense soil disturbance in the superficial layers. Additionally, the continued use of machinery and pesticides in these production systems harms the survival of these organisms, especially the native species that are more susceptible (Demetrio et al., 2020). On the other hand, NT sites can be much more beneficial to earthworm communities, and Bartz et al. (2014) highlighted that even when found in smaller numbers, native species can be an indicator of better management practices providing a favorable environment for earthworms. Therefore, on some occasions, earthworm richness has been higher in NT sites than under native vegetation (e.g., Santos et al., 2018), though this is mainly due to the presence of exotic species under NT.

Earthworm abundance and biomass in different land-use systems

Highest mean earthworm density and biomass was observed in agroforestry systems (242 ind m^{-2} and 25.6 g m^{-2}, respectively), with density values more than twice higher than in any other LUS in Paraná (Figure 5). However, the low number of sites with this LUS limit any broader conclusions. Nonetheless, agroforestry systems in Brazil often have high abundance of earthworms (Nadolny et al., 2020), and these sites benefit from frequent pruning that enhances OM inputs and food availability to earthworms (Maschio et al., 2010). Furthermore, the presence of trees improves microclimate and edaphic conditions for these animals, although the age of the system is another important factor influencing earthworm abundance and biomass (Brown et al., 2009).

Abundance higher than 100 ind m^{-2} was observed in grass lawns (in addition to high biomass: 20.6 g m^{-2}), pastures, minimum tillage and under NT. Higher mean biomass in the grass lawn and pasture is due to the presence of larger individuals or species than in NT, where despite the high abundance, biomass is low due to the presence of small individuals of the Acanthodrilidae (*Dichogaster* spp.) and Ocnerodrilidae families (Table 1) (Demetrio et al., 2020). Under native vegetation and integrated systems, abundance was also relatively high (86 and 87 ind m^{-2}, respectively), though earthworm biomass recovered was very much higher in the former (14.1 g m^{-2}) than under the latter (<1 g m^{-2}) LUS, due to the higher individual earthworm biomass under native vegetation. In forestry plantations and permanent crops abundance was moderate (53 and 70 ind m^{-2}, respectively), though biomass was high (21.8 and 15.6 g m^{-2}), again due to the presence of larger earthworm species. The LUS with the lowest abundance and biomass was CT, with 37 ind m^{-2} and 0.3 g m^{-2} on average (Figure 5). This confirms previous results regarding soil tillage types and earthworm populations (Brown et al., 2003). Intense soil disturbance reduces earthworm populations by up to 60 % due to changes in soil structure (Paoletti, 1999; Brown et al., 2003; Ressetti et al., 2006). Furthermore, soil ploughing and harrowing directly exposes earthworms to predation (e.g., by birds) and solar radiation, as well as destroys their galleries (“houses”) (Curry, 2004). It can also reduce water and OM storage in soil and increase C mineralization and oxidation (Lavelle et al., 1998; Chan, 2001; Pasqualin et al., 2012; Bartz et al., 2014).

The relationship between land-use intensity and earthworm abundance and biomass was not clear-cut and was influenced by stark differences between native vegetation at one end and conventional tillage (lower abundance and biomass) at the other end of the spectrum. However, several LUS systems with intermediate intensity were also favorable to earthworms, although those that enhance OM inputs (food availability), and microclimate stability (e.g., presence of trees and/or soil cover, such as in AF, FP, PC, PA and GL) were particularly favorable for higher biomass.

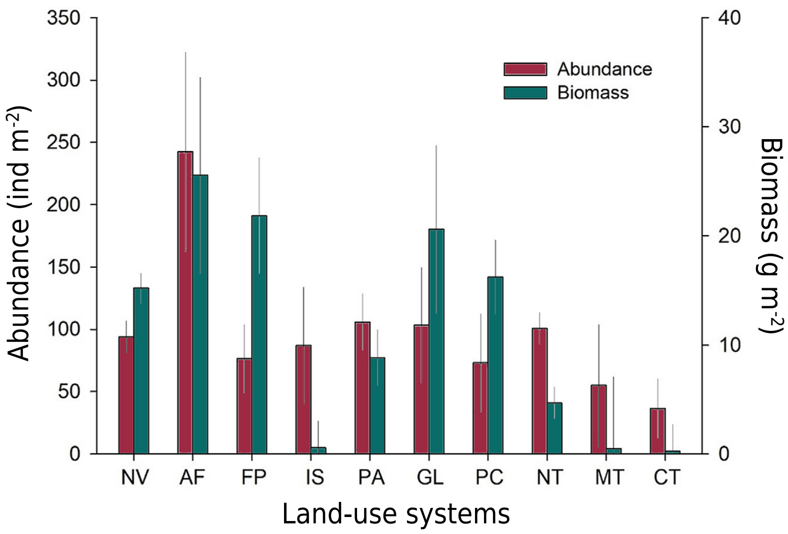

Figure 5. Earthworm abundance (ind m^{-2}, in grey bars) and biomass (g m^{-2}, in white bars) in land-use systems in the state of Paraná, Brazil. Native Vegetation (NV) (n = 181/155); Agroforestry (AF) (n = 5/4); Forest Plantation (FP) (n =35/16); Integrated Systems (IS) (n =10/4); Pasture (PA) (n = 52/39); Grass Lawn (GL) (n= 14/6); Perennial Crops (PC) (n =23/23); No-Tillage (NT) (n =174/133); Minimum Tillage (MT) (n = 18/7); and Conventional Tillage (CT) (n = 49/46). Lines in the bars: standard errors; n: number of sites in each LUS for abundance/biomass, respectively.

Biomass values were not always related to abundance, but rather to the size of the species found and the stage of development (juveniles or adults). For instance, in a study in the North Central and Center East regions of Paraná, Brown et al. (2003) observed similar values of abundance in both regions, but in the latter region biomass was higher due to the presence of *Amynthas* species, earthworms with higher individual size and body mass compared to other exotic species of smaller size like the *Dichogaster* spp. more abundant in the North Central region. These factors deserve further attention, particularly to assess bioturbation rates and impacts on soil structure and ecosystem service delivery.

Earthworm relationships with chemical and physical soil properties

The Principal Component Analysis (PCA) using data from 86 sites revealed a significant correlation ($p<0.001$) between soil properties (sum of bases, carbon, pH and phosphorus, clay content) and earthworm populations (Figure 6). Axes 1 and 2 explained 57 % of the data variability, and earthworm biomass was correlated with Axis 1 (41 % of the variation of data) and sandier and siltier soils (i.e., those with lighter texture), opposed to those with higher pH, C and clay contents and the sum of bases (i.e., higher soil fertility). Effectively, sites with NT were associated with heavier (clay) soils and higher soil fertility, but lower earthworm biomass, compared to forestry plantations with higher biomass, but that were on lower fertility, sandier soils. On the other hand, earthworm abundance and species richness were associated mainly with Axis 2 (16 %), which was related to soil P contents, that were higher in some NT sites.

Forest soils often also have high exchangeable acidity (Al+H) and low pH values, which could limit earthworm populations (Silva et al., 2019). Hence one can often find higher earthworm abundance in croplands than under native vegetation (e.g., Tanck et al., 2000; Nadolny, 2017; Silva et al., 2019). In the present case, earthworm abundance and richness were more related to soil P contents, while biomass was more related to soil texture. The results confirm previous trends and expectations and provide a useful guide towards future studies needed to clarify the relationships between earthworm populations and soil fertility in the soils of Paraná.

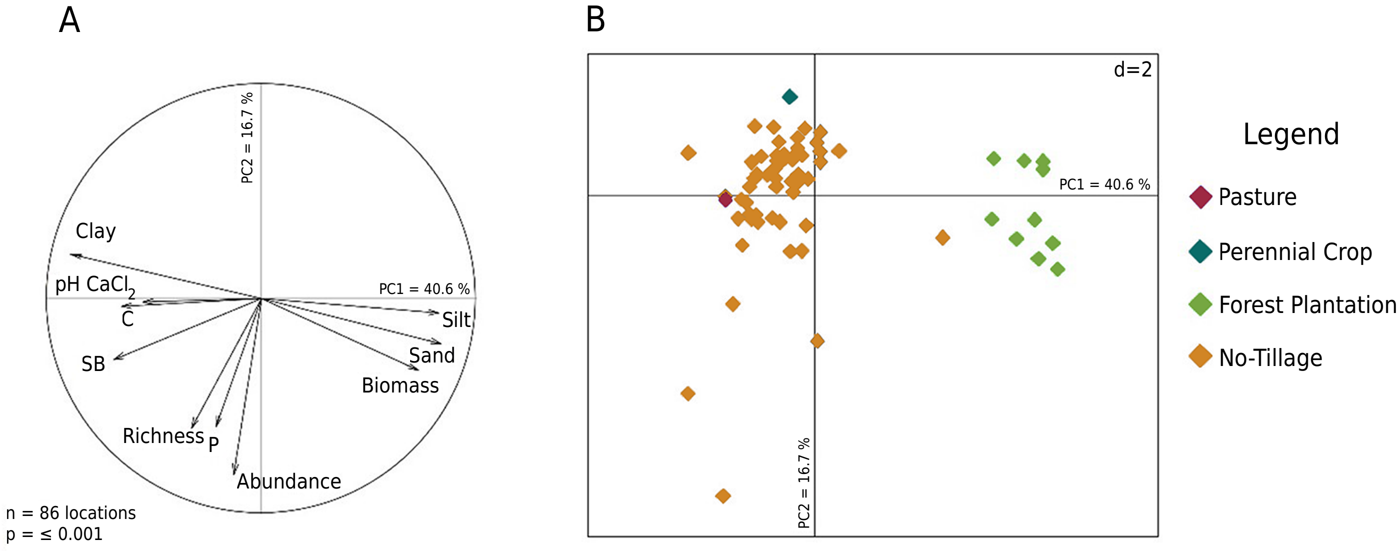

Figure 6. Principal Component Analysis of 86 sites under different land-use systems: forest plantation, pasture, perennial crop and no-tillage with significant ($p<0.001$) correlation between the soil chemical data (pH, phosphorus - P, carbon - C and sum of bases - SB), and physical data (clay, silt and sand contents) with the earthworm data (abundance in ind m^{-2}, biomass in g m^{-2}, species richness).

CONCLUSIONS

The 51 published studies on earthworm populations in Paraná revealed 90 species overall, collected in 51 counties in the state, of which 66 are native and 24 are exotic. This represents the highest known richness for a Brazilian state up to now, though further sampling will most likely reveal many other new species, particularly considering only 16 % of the counties have been sampled thus far. Sampling efforts should be particularly focused in the Southwest, Northwest, Central West, Central South, North Pioneer and Southeast, since only the West, Center North and Metropolitan regions have more than ten counties sampled. The Metropolitan area also has a large swath of native Atlantic Forest known for its high biodiversity and endemism, which also deserves particular attention in further sampling efforts.

Native vegetation had the highest proportion of native species, while most other LUS had more exotic than native species. Interestingly, many native species were also found in NT systems, indicating that these can support local species, although the abundance of exotics tended to be high, especially of Megascolecids (mainly *Amynthas* spp.) and Acanthodrilids (*Dichogaster* spp). Earthworm abundance and biomass were highest in less disturbed LUS such as agroforestry systems, native vegetation, forestry plantation, grass lawns, pastures and permanent crops, compared to the highest disturbance LUS including soil preparation (MT and CT). This reinforces the need for a better assessment of the practices that can stimulate earthworm populations in the more intensive LUS and assessments of the functional importance of higher earthworm populations in the less intensive LUS. This is particularly important considering the contributions of earthworms to soil structure and fertility, factors that need further attention in Paraná and Brazil in general.

Earthworm abundance and species richness were associated with soils having higher P contents, which may be related to higher P contents and fertilization in NT systems. On the other hand, earthworm biomass was more related to lighter soil texture.

Considering the currently known high earthworm richness and level of agricultural intensification and urbanization in Paraná, further earthworm samplings are necessary to access the unknown biodiversity and adequately assess the relationships between this earthworm diversity and land-use. Additionally, the relationships between soil chemical and physical properties, environmental variables, and the land-use and management history of the sites needs further studies to better understand the vectors influencing the occurrence and populations of these organisms. These efforts will provide a better basis for using these animals as bioindicators of soil quality in different land-use systems of Paraná.

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