



AgEcon SEARCH

RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

Earthworm services: an agroecological perspective

Ortiz-Ceballos, Ángel Isauro^{1*}; Lara-González, Rogelio¹; Cuevas-Díaz, María del Carmen²; Martínez-Velázquez, Katia Jassiel¹

¹ Instituto de Biotecnología y Ecología Aplicada (INBIOTECA), Universidad Veracruzana, Av. de las Culturas Veracruzanas 101, Col. E. Zapata, 91090, Xalapa, Veracruz, México.

² Facultad de Ciencias Químicas, Campus Coatzacoalcos, Universidad Veracruzana, Av. Universidad Km 7.5, Col. Santa Isabel, 96538, Coatzacoalcos, Veracruz, México.

* Correspondence: angortiz@uv.mx

ABSTRACT

Objective: To review and discuss the invisible and silent role of the activity of earthworms, which are considered “agroecosystem engineers”.

Design/methodology/approach: A database search of scientific articles published in Mexico and worldwide was performed.

Results: The literature reviewed shows that earthworms constitute the most abundant biomass in the vast majority of tropical agroecosystems. In addition, earthworms have long been shown to improve a) soil structure; b) interaction with symbiotic microorganisms; c) nutrient mineralization and availability; d) pollutant removal; e) regulation of foliar herbivory; and f) crop yields.

Limitations on study/implications: Most studies have been conducted in laboratories and greenhouses.

Findings/conclusions: Earthworms increase soil quality and agricultural productivity. Their protection, promotion, and management are suggested in order to manage, preserve, and restore soil health, as well as to ensure a sustainable crop production.

Keywords: Regenerative Agriculture, Environmental Services, Traditional Agriculture, Bioindicators, Bioremediation.

Citation: Ortiz-Ceballos, Á. I., Lara-González, R., Cuevas-Díaz, M. del C., & Martínez-Velázquez, K. J. (2021). Earthworm services: an agroecological perspective. *Agro Productividad*. <https://doi.org/10.32854/agrop.v14i12.2029>

Editor in Chief: Dr. Jorge Cadena Iñiguez

Received: May 7, 2021.

Accepted: December 13, 2021.

Published on-line: December 30, 2021.

Agro Productividad, 14(12), December 2021. pp: 99-109.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



INTRODUCTION

The presence of earthworms in crop fields is as old as agriculture. Plants have likely evolved along with earthworms (Blakemore, 2009; Ortiz-Ceballos *et al.*, 2019); in other words, they are an essential biological component of sustainable agroecosystems. However, conventional agriculture is frequently criticized for its negative impact on soil quality and human health. A better management of earthworms living in crop fields can solve this problem (Bertrand *et al.*, 2015). In fact, agricultural management studies and programs aimed at increasing soil fertility, degrading organic pollutants, and increasing crop yields, among other things, do not usually take earthworms into consideration.

Before the development of artificial fertilizers and agricultural mechanization, the essential role that earthworms play in agroecosystems had already been suggested by Aristotle, Darwin, and other scientists (Van Groenigen *et al.*, 2019). However, earthworms

are commonly known and referred to as *Eisenia fetida* (used in worm composting or vermicomposting), when in fact the soils of various terrestrial ecosystems and agroecosystems are home to a vast diversity of earthworms (Villalobos-Maldonado *et al.*, 2017). Scientists see earthworms as “ecosystem engineers” as a result of the profound agroecological impact they have on the physicochemical and biological properties of soil (Blakemore, 2009). Most of the studies focused on earthworms have used species adapted to crops, most of which are considered invasive; for instance, in the case of the tropical regions of Mexico and the world, it is very common to find the *Pontoscolex corethrurus* earthworm in conventional agroecosystems—which use fertilizers, herbicides, pesticides, and tillage—and in industrial and urban areas—polluted with heavy metals, crude oil, and others (Taheri *et al.*, 2018; Ortiz-Gamino *et al.*, 2020; Ortiz-Ceballos *et al.*, 2019). In Mexico, the native species *Balanteodrilus pearsei* has a remarkable presence in traditional agroecosystems (Ortiz-Ceballos *et al.*, 2004; Huerta *et al.*, 2005; Fragoso and Rojas, 2014; Fragoso *et al.*, 2015). In this review, written from an agroecological viewpoint, we analyze the largely ignored earthworm services and their potential to encourage agricultural sustainability in Mexico.

Species diversity in Mexico and the world

Earthworms are segmented worms with terrestrial habits. Their lifecycle is synchronized with the soil’s temperature and moisture and their length (1 cm-1 m) and width (2mm-3 cm) may vary. They belong to the phylum Annelida, class Clitellata, and order Crassicitellata (Fragoso and Rojas, 2014). Currently, 5,900 to 6,000 species live in the majority of moist soils in the world; however, it is unlikely to find them in arid and cold areas (Fragoso and Rojas, 2014). There are more earthworm species in Mexico—102 species, equally distributed among native and introduced species—than in several European countries, while in Latin America only Brazil, Colombia, and Ecuador have more species (Fragoso and Rojas, 2014). The most studied tropical regions have been eastern and southeastern Mexico. Veracruz, for instance, has the largest number of known species, followed by Chiapas, Tamaulipas, and Tabasco (Fragoso and Rojas, 2014). The species diversity in tropical agroecosystems is larger than in temperate ones: it varies between four and six species and is rarely larger than ten (Fragoso and Rojas, 2014).

Ecological categories and/or functional groups

Earthworms are grouped in ecological categories or functional groups based on their color, size and body shape, location in the soil, burrowing capacity, and food preference (Bertrand *et al.*, 2015; Van Groenigen *et al.*, 2019). Unpigmented endogeic earthworms build horizontal tunnels in the topsoil and consume soil, organic matter, and soil organisms. Meanwhile, epigeic earthworms live in the soil surface and feed on decaying vegetable material. Finally, the anecic earthworm species are pigmented, they build permanent vertical tunnels or burrows in the mineral layers of the soil, feed on vegetable material, and ingest soil (Bertrand *et al.*, 2015; Van Groenigen *et al.*, 2019).

In Mexico, 92% of earthworms are endogeic (soil feeders). The ten most common species in agricultural soils are: a) introduced species: *Pontoscolex corethrurus*, *Octalasion tyrtaeum*, *Amyntas gracilis*, *Dichogaster bolau*, and *Aporrectodea trapezoides*; and b) native species:

Phoenicodrilus taste, *Balanteodrilus pearsei*, *Diplostrema murchiei*, *Protozapotecia aquilonalis*, and *Lavello-drilus parvus* (Fragoso and Rojas, 2014). By contrast, the widely known epigeic *Eisenia fetida* (“California red worm”) does not dwell in Mexican agricultural soils.

Population size

Earthworm abundance and diversity are determined by crop type, agricultural practices, and the organic residues added to the soil (Manono, 2016). The change in land use also alters the diversity, abundance, and distribution of earthworms. In addition, their survival depends on moisture, temperature, texture, pH, and on symbiont soil microorganisms (Bertrand *et al.*, 2015). Earthworms are therefore assessed for their abundance and biomass. In the tropical regions of Mexico, earthworms have been found in the following type of soils: Arenosols, Fluvisols, Vertisols, Acrisols, Luvisols, Phaeozems, Leptosols, and Andosols. A greater abundance (ind/m²) of earthworms in these soils has been registered in grasslands (76-704), followed by lands used for coffee (482), cocoa (170), citrus (145), eucalyptus (115), maize (51-222), home gardens (20-110), rain forests (31-170), fallow (298), and others (Ortiz-Ceballos *et al.*, 2005; Huerta *et al.*, 2005; Uribe *et al.*, 2012; García-Pérez *et al.*, 2017).

Soil structure

Earthworms choose mineral and organic particles according to the ecological categories to which they belong (Bertrand *et al.*, 2015; Sánchez-Hernández, 2019). When endogeic and anecic earthworms consume soil for food and to burrow (to build galleries and nests), they mix it in their intestine and produce aggregates (excreta) that contain fragments of the organic matter, organisms, and minerals that were found in the ingested soil. Consequently, earthworm activity contributes to soil formation through the improvement of porosity and aggregation by providing more (Bertrand *et al.*, 2015): a) water flow and retention; b) gas exchange; c) creation of habitats for organisms (microfauna and mesofauna); d) availability of easily absorbed nutrients; e) root growth and carbohydrate release; and f) nutrient absorption for plants.

Earthworm soil ingestion rates are highly variable: 1-30 g of dry soil/g fresh weight/day (Bertrand *et al.*, 2015). Ingestion has a negative relation to age and size: juveniles consume more soil than adults, while smaller ones consume more than larger ones (Bertrand *et al.*, 2015). Therefore, earthworms are capable of regenerating the structure of compacted soils.

Symbiont microorganisms

The most common impact of earthworm activity can be seen on soil microorganisms and it takes place through two compartments: gastrointestinal tract (internal) and movement and feeding (external), associated with the improvement of soil structure (Bertrand *et al.*, 2015; Medina-Sauza *et al.*, 2019; Li *et al.*, 2021). In the first case, some studies have demonstrated the presence of symbiont microorganisms that dwell in the gastrointestinal tract (bioreactor). In addition, earthworm eggs and nephridia (excretory organs) host symbiotic microbiomes (Aira *et al.*, 2018; Li *et al.*, 2021). In the second case, the earthworm mechanical activity modifies habitats and microbial communities that dwell in the soil.

The latter obtain a double benefit from earthworms' movement: they either adhere to their bodies or they are ingested by earthworms, survive, and are subsequently scattered (Aira *et al.*, 2018; Medina-Sauza *et al.*, 2019; Li *et al.*, 2021). Tunnel walls, excreta, and nests are microenvironments with a high microbial and enzyme activity (Van Groenigen *et al.*, 2019). Therefore, the presence of earthworms in the soil promotes a greater abundance of symbiont microorganisms of the phyla Proteobacteria, Actinobacteria, Firmicutes, Acidobacteria, Planctomycetes, Bacteroidetes, Nitrospirae, and Chloroflexi, that are essential for the survival of earthworms; these microorganisms are capable of degrading organic matter, removing pollutants, releasing easily-absorbed nutrients, and promoting plant growth (Ortiz-Ceballos *et al.*, 2019; Medina-Sauza *et al.*, 2019; Li *et al.*, 2021).

Soil detoxification

Bioremediation has become a usual means to reduce the concentration and toxicity of soil pollutants (Hickman and Reid, 2008; Datta *et al.*, 2016; Villalobos-Maldonado *et al.*, 2017; Sánchez-Hernández, 2019). During the last decade, different studies have pointed out that the impact of the physical (improvement of airing and aggregation), chemical (alteration of pH and OM), and biological activity of endogeic and anecic earthworms on the degradation of crude oil, heavy metals, pesticides, and herbicides, among other things has increased (Hickman and Reid, 2008; Datta *et al.*, 2016; Sánchez-Hernández, 2019). Environmental works that seek to remedy polluted soils do not take earthworms into consideration (Hickman and Reid, 2008; Datta *et al.*, 2016; Sánchez-Hernández, 2019), despite the fact that *P. corethrurus*, *Glossodrilus* sp., *Dichogaster saliens*, *Protozapotecia australis*, and *Onychochaeta windlei* earthworms dwell in soils that have been polluted by the oil industry of Veracruz and Tabasco (Zavala *et al.*, 2013; Hernández-Castellanos *et al.*, 2013a; García-Segura *et al.*, 2018). In addition, toxicological trials have shown that *P. corethrurus* avoids and/or repels concentrations above 10,000 mg of total crude petroleum hydrocarbons (TPH)/kg of dry soil and the median lethal concentration (CL₅₀) of 3,067.3 mg TPH/kg (Cuevas-Díaz *et al.*, 2017). In Mexico, bioremediation studies showed that the presence of *P. corethrurus* and organic amendments reach a 35.6% reduction of benzo(a) pyrene (Hernández-Castellanos *et al.*, 2013b) and 86.0% of TPH (Rodríguez-Campos *et al.*, 2019). Furthermore, earthworms have been found to increase the availability and mobility of essential (Zn, Cu, Mn, Fe) and non-essential (Cd, Pb, Hg) metals in both polluted and non-polluted soils (Taheri *et al.*, 2018). *P. corethrurus*, for instance, significantly reduced the amount of Pb; additionally, it promotes the Pb phytoextraction capacity of *Lantana camara* (Taheri *et al.*, 2018). Finally, this species tolerates Carbaril (insecticide) concentrations, but Carbendazim (fungicide) and Carbofuran (insecticide) have a lethal effect on it. The response of *P. corethrurus* to herbicides (glyphosate) is variable: the use of glyphosate in coffee crops reduces earthworm abundance and biomass (García-Pérez *et al.*, 2014), but it does not affect reproduction in the laboratory (García-Pérez *et al.*, 2016). Hickman and Reid (2008) and Datta *et al.* (2016) have therefore suggested that endogeic earthworms can be used as indicators of agricultural, industrial, and urban soil health, as well as to restore degraded soils.

Nutrient availability

Since they consume and degrade a vast diversity of organic materials, earthworms directly affect soil fertility, increasing total OM (40-48%), total P, and total N concentrations (Van Groenigen *et al.*, 2019). This is the result of biochemical transformation processes that occur in the digestive tract of earthworms and that involve: a) production of endogenous cellulases (Ean-Eg, EF-EG2, and GHF9); b) association with intestinal microbiota (Protobacteria, Firmicutes, Actinobacteria, Chloroflexi, and Bacteroidetes); c) gene expression (transcriptome) that adjusts their digestive system (salivation, gastric acid, and pancreatic secretion); d) improvement of the digestive efficiency based on caecum type; and e) association with nephridial bacteria (Pedobacter) (Ortiz-Ceballos *et al.*, 2019). It has thus been demonstrated that total element concentration substantially increases in earthworm excreta: 241% and 84% for mineral N and available P, respectively (Van Groenigen *et al.*, 2019); moreover, there is a significant increase in pH (0.5 units), in cation exchange capacity (40%), and in base saturation (27%). In addition, earthworms accumulate, store, and recycle carbon and nitrogen in their biomass. They have a low carbon assimilation efficiency (2-27%; maximum: 70%), depending on the species, density, organic matter quality, and temperature. Nonetheless, the amount of nitrogen circulating through their biomass is higher than carbon—the estimated values fluctuate between 60 and 100 kg/ha/year—, which suggests an important flow of this nutrient in agroecosystems. Therefore, an appropriate management of organic residues or management practices (cover crops, intercropping, crop rotation, and no-till farming or minimum tillage), can maintain abundant earthworm populations, in order to synchronize the release of easily absorbed nutrients that will then be available for plants when they need it. This suggests the need to design and improve agroecosystems that maintain soil fertility to achieve a sustainable crop production (Bertrand *et al.*, 2015)—for instance cocoa, coffee, maize, and other agroecosystems in which the farmers of southeastern Mexico are involved (Brown *et al.*, 2004; Ortiz-Ceballos *et al.*, 2005; Huerta *et al.*, 2005; Juárez-Ramón and Fragoso, 2014; Fragoso *et al.*, 2015; García-Pérez *et al.*, 2017). Finally, earthworms are soil improving agents that cannot be studied separately from agroecosystems (Van Groenigen *et al.*, 2019) (Figure 1).

Earthworm-plant-insect interaction

Almost nothing is known about the effects of soil organisms on a vast range of natural enemies: predators and parasitoids (Wurst, 2013; Heinen *et al.*, 2018; Thakur *et al.*, 2021). Although conceptual frameworks are well developed and some interactions are well studied (*e.g.*, mycorrhizae), gaps still exist regarding the biodiversity knowledge about other taxa that are closely associated with plant roots, such as earthworms (Shelef *et al.*, 2019; Li *et al.*, 2021). Soil organisms play a significant role in the configuration of plant-insect interactions in the field, with general patterns for some taxa, such as earthworms (Heinen *et al.*, 2018). Results show that plants use earthworm excreted nutrients and assimilate them into their roots, leaf tissue, and phloem sap, which is sucked by aphids (Shelef *et al.*, 2019; Thakur *et al.*, 2021). This, in turn, shows that earthworms in the soil and aphids on the plants are functionally interconnected. Earthworm presence increased the production of the plants'



Figure 1. Effects of the native tropical earthworm *Balanteodrilus pearsei* on the growth of the corn crop. Trays with labels: Green=Soil+Legume Foliage+Earthworm; Blue=Soil+Legume Foliage; Red=Soil+Earthworm; Yellow=Soil+Earthworm.

chemical defenses against cell feeders (trips) by 31% and their resistance against trips by 81%. Both results were associated to earthworm abundance and diversity (Xiao *et al.*, 2017). Results suggest the need of a better integration of soil fauna into plant-herbivore interaction studies, both in applied and basic research. This opens up opportunities to explore the manipulation of soil organisms in agriculture or ecosystem restoration. Some groups can be promising agents for the improvement and protection of crop yield and can affect plant diversity on the soil at a community level, which allows the use of soil organisms to guide vegetation development (Wurst, 2013; Heinen *et al.*, 2018) (Figure 2,3,4,5).

Plant growth and productivity

Epigeic, endogeic, and anecic earthworm activity has an important beneficial effect on plant growth and productivity because it: a) provides a greater amount of nutrients; b) improves soil structure; c) stimulates microbial symbionts of plants; d) controls pests and illnesses; and e) produces plant growth regulating substances (Ortiz-Ceballos *et al.*, 2007; Van Groenigen *et al.*, 2014). During their assessment of the three main basic crops (corn, wheat, and rice) and pastures in 58 studies conducted in almost every continent—

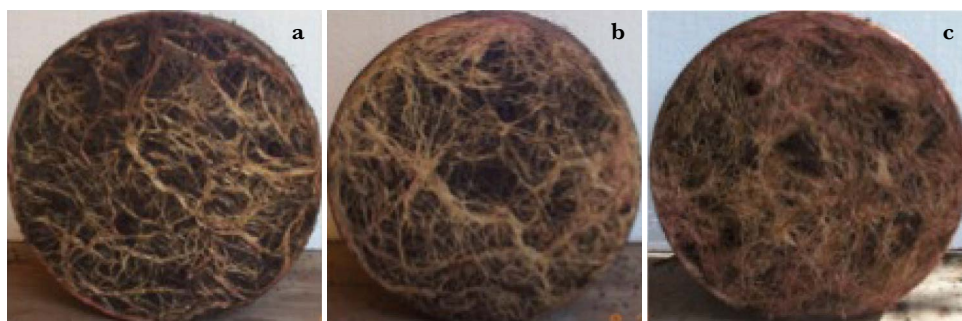


Figure 2. Effect of the native tropical earthworm *Balanteodrilus pearsei* on the growth of the roots of the corn crop: a) Soil+Earthworm; b) Soil+Legume Foliage; c) Soil+Earthworm+Legume Foliage.



Figure 3. Construction of galleries and production of excreta of the native tropical earthworm *Balanteodrilus pearsei*.



Figure 4. Exotic tropical earthworm *Pontoscolex corethrurus*.



Figure 5. Construction of galleries and production of excreta of the exotic tropical earthworm *Pontoscolex corethrurus*.



Figure 6. Cocoon and excreta production of the endogenous earthworm *Pontoscolex corethrurus*.

save in Antarctica—, Van Groenigen *et al.* (2014) determined that earthworms significantly increased crop yields (25%), aerial biomass (23%), roots (20%), and total biomass (21%). The most important effects on grain production are achieved with a $> 30\text{-}40\text{ g fresh weight/m}^2$ biomass (Van Groenigen *et al.*, 2014). Nevertheless, ecological, and agricultural studies have been conducted for the handling of only 11 out of 102 species in Mexico. Among them *P. corethrurus*, *Polypheretima elongate*, and *B. pearsei* stand out as a result of their potential *in situ* use in agroecology and/or in regenerative agriculture (Fragoso and Rojas, 2014). For instance, the presence of *B. pearsei* and *P. corethrurus* earthworms with the velvetbean legume (*Mucuna pruriens* var. *utilis*) significantly increased the growth and production of corn, vanilla, and Roma tomato crops (Ortiz-Ceballos *et al.*, 2007); moreover, used in nurseries, they boosted the growth of *Abies religiosa* (Sánchez-Velásquez *et al.*, 2019) and *Quercus insignis* forest seedlings (Avenidaño-Yáñez *et al.*, 2017). However, domestication has turned hundreds of traditional plant species to intensive farming (Porter and Sachs, 2020). Farming practices and intense selective breeding used to increase yields can involve a hidden cost: the interruption of interactions between plants and earthworms (Porter and Sachs, 2020). It is therefore suggested that, in order to improve a sustainable agricultural production, agroecological research must develop methods to optimize relations between cultivated plants and soil organisms (Porter and Sachs, 2020).

CONCLUSIONS

Over the last 150 years, the relevance of earthworms and their evolution with domesticated plants have been attested (Braga *et al.*, 2016). Therefore, it is very likely that earthworm services contribute to increase agricultural sustainability improving human health (Bertrand *et al.*, 2016). This suggests the need of long-term field studies about the impact of earthworms on crop production. In addition, agricultural grants and funding are required to design and promote agroecosystems that take into account the intrinsic value of earthworms and the effect of crop practices on earthworm diversity, abundance, and activity (Bertrand *et al.*, 2015; Scown *et al.*, 2020).

REFERENCES

- Aira, M., Pérez-Losada, M., & Domínguez, J. (2018). Diversity, structure and sources of bacterial communities in earthworm cocoons. *Scientific Reports* 8: 6632 <https://doi.org/10.1038/s41598-018-25081-9>
- Avendaño-Yáñez M.L., Ortiz-Ceballos A.I., Sánchez-Velásquez L.R., Pineda-López M.R., Meave, J.A. (2014). Synergic Effect of *Mucuna pruriens* var. *utilis* (Fabaceae) and *Pontoscolex corethrurus* (Oligochaeta, Glossoscolecidae) on the Growth of *Quercus insignis* (Fagaceae) Seedlings, a Native Species of the Mexican Cloud Forest Seedlings, a Native Species of the Mexican Cloud Forest. *Open Journal of Forestry* 4(1): 1–7. <https://doi.org/10.4236/ojf.2014.41001>
- Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., & Roger-Estrade, J. (2015). Earthworm services for cropping systems. A review. *Agronomy for Sustainable Development* 35: 553-567. <https://doi.org/10.1007/s13593-014-0269-7>
- Blakemore, R. J. (2009). Cosmopolitan Earthworms-A Global and Historical Perspective. In *Annelids in Modern Biology* (pp. 257–283). <https://doi.org/10.1002/9780470455203.ch14>
- Braga, L. P. P., Yoshiura, C. A., Borges, C. D., Horn, M. A., Brown, G. G., Drake, H. L., & Tsai, S. M. (2016). Disentangling the influence of earthworms in sugarcane rhizosphere. *Scientific Reports* 6: 1–13. <https://doi.org/10.1038/srep38923>
- Brown, G. G., Moreno, A. G., Barois, I., Fragoso, C., Rojas, P., Hernández, B., & Patrón, J. C. (2004). Soil macrofauna in SE Mexican pastures and the effect of conversion from native to introduced pastures. *Agriculture, Ecosystems and Environment* 103(2): 313–327. <https://doi.org/10.1016/j.agee.2003.12.006>
- Datta, S., Singh, J., Singh, S., & Singh, J. (2016). Earthworms, pesticides and sustainable agriculture: a review. *Environmental Science and Pollution Research* 23(9): 8227–8243. <https://doi.org/10.1007/s11356-016-6375-0>
- Cuevas-Díaz, M.C., Vázquez-Luna, D., Martínez-Hernández, S., Guzmán-López, O., & Ortiz-Ceballos, A. I. (2017). Sensitivity of the Endogeic Tropical Earthworm *Pontoscolex corethrurus* to the Presence of Heavy Crude Oil. *Bulletin of Environmental Contamination and Toxicology* 99(2): 154–160. <https://doi.org/10.1007/s00128-017-2126-2>
- Fragoso, C., & Rojas, P. (2014). Biodiversity of earthworms (Annelida: Oligochaeta: Crassicitellata) in Mexico. *Revista Mexicana de Biodiversidad* 85: S197-S207 <https://doi.org/10.7550/rmb.33581>
- Fragoso, C., Leyequién E., Carcía-robles, M., Montero-Muñoz J., Rojas, P. (2015). Dominance of native earthworms in secondary tropical forests derived from slash-and-burn Mayan agricultural practices (Yucatán, Mexico). *Applied Soil Ecology* 104: 116-124. <https://doi.org/10-1016/j.apsoil.2015.12.005>
- García-Pérez, J.A., Alarcón-Gutiérrez, E., Perroni, Y., Barois, I. (2014). Earthworm communities and soil properties in shaded coffee plantations with and without application of glyphosate. *Applied Soil Ecology* 83: 230–237. <http://dx.doi.org/10.1016/j.apsoil.2013.09.006>
- García-Pérez, J.A., Alarcón, E., Hernández, Y., Hernández, C., (2016). Impact of litter contaminated with glyphosate-based herbicide on the performance of *Pontoscolex corethrurus*, soil phosphatase activities and soil pH. *Applied Soil Ecology* 104: 31–41. <http://dx.doi.org/10.1016/j.apsoil.2016.03.007>
- García-Pérez, J.A., Barois, I., Bueno, J., Fragoso, C., Kram S., Meza E., Morón M.A., Negrete S., Rojas, P., de los Santos M., Sormani, C. (2017). Conservación y manejo de la biodiversidad del suelo en la sierra de Santa Marta, Los Tuxtlas Veracruz México: La macrofauna del suelo en la sierra de Santa Marta. En: Reynoso, V.H., Coates, R.I. y Vázquez Cruz M.L. (eds.) Avances y perspectivas en la investigación de los bosques tropicales y sus alrededores. La región de los Tuxtlas. Instituto de biología, UNAM. México. 195-238 pp. [file:///Users/Usuario/Downloads/2017_Garcaetal._Cap.13.LaMacrofaunadelsueloenlasierradeSantaMarta%20\(1\).pdf](file:///Users/Usuario/Downloads/2017_Garcaetal._Cap.13.LaMacrofaunadelsueloenlasierradeSantaMarta%20(1).pdf)
- García-Segura, D., Castillo-Murrieta, I. M., Martínez-Rabelo, F., Gomez-Anaya, A., Rodríguez-Campos, J., Hernández-Castellanos, B., Contreras-Ramos, S. M., & Barois, I. (2018). Macrofauna and mesofauna from soil contaminated by oil extraction. *Geoderma* 332: 180–189. <https://doi.org/10.1016/J.GEODERMA.2017.06.013>
- Heinen, R., Biere, A., Harvey, J. A., & Bezemer, T. M. (2018). Effects of Soil Organisms on Aboveground Plant-Insect Interactions in the Field: Patterns, Mechanisms and the Role of Methodology. *Frontiers in Ecology and Evolution* 6: 106. <https://doi.org/10.3389/fevo.2018.00106>
- Hernández-Castellanos, B., Ortiz-Ceballos, A.I., Martínez-Hernández, S., Noa-Carrazana, J. C., Luna-Guido, M., Dendooven, L., & Contreras-Ramos, S. M. (2013). Removal of benzo (a) pyrene from soil using an endogeic earthworm *Pontoscolex corethrurus* (Müller, 1857). *Applied Soil Ecology* 70: 62-69. <https://doi.org/10.1016/j.apsoil.2013.04.009>
- Hernández-Castellanos B, J. Zavala-Cruz, S. Martínez-Hernández, L. Dendooven, S.M. Contreras-Ramos, J.C. Noa-Carrazana, C. Fragoso, A. I. Ortiz-Ceballos. (2013). Earthworm Populations in an Aged

- Hydrocarbon Contaminated Soil. *Research Journal of Environmental Sciences* 7(1): 27–37. <https://doi.org/10.3923/rjes.2013.27.37>
- Hickman, Z. A., & Reid, B. J. (2008). Earthworm assisted bioremediation of organic contaminants. *Environment International* 34(7): 1072–1081. <https://doi.org/10.1016/j.envint.2008.02.013>
- Huerta, E., Rodríguez-Olán, J., Evia-Castillo, I., Montejó-Meneses, E., de la Cruz-Mondragón, M., & García-Hernández, R. (2005). La diversidad de lombrices de tierra (annelida, oligochaeta) en el estado de Tabasco, México. *Universidad y Ciencia* 21(42): 75-85.
- Juárez-Ramón, D., & Fragoso, C. (2014). Comunidades de lombrices de tierra en sistemas agroforestales intercalados, en dos regiones del centro de México. *Acta Zoológica Mexicana (N.S.)* 30(3): 637–654. <https://doi.org/10.21829/azm.2014.30383>
- Li, H., Yang, X. R., Wang, J., Zhou, G. W., Zhang, Y., Sen, Lassen, S. B., ... Su, J. Q. (2021). Earthworm gut: An overlooked niche for anaerobic ammonium oxidation in agricultural soil. *Science of the Total Environment* 752: 141874. <https://doi.org/10.1016/j.scitotenv.2020.141874>
- Manono, B. (2016). Agro-ecological Role of Earthworms (Oligochaetes) in Sustainable Agriculture and Nutrient Use Efficiency: A Review. *Journal of Agriculture and Ecology Research International* 8(1): 1–18. <https://doi.org/10.9734/jaeri/2016/24517>
- Medina-Sauza, R. M., Álvarez-Jiménez, M., Delhal, A., Reverchon, F., Blouin, M., Guerrero-Analco, J. A., ... Barois, I. (2019). Earthworms building up soil microbiota, a review. *Frontiers in Environmental Science* 7: 1–20. <https://doi.org/10.3389/fenvs.2019.00081>
- Ortiz-Ceballos, A. I., & Fragoso, C. (2004). Earthworm populations under tropical maize cultivation: The effect of mulching with velvetbean. *Biology and Fertility of Soils* 39(6): 438–445. <https://doi.org/10.1007/s00374-004-0732-8>
- Ortiz-Ceballos, A. I., Fragoso, C., & Brown, G. G. (2007). Synergistic effect of a tropical earthworm *Balanteodrilus pearsei* and velvetbean *Mucuna pruriens* var. *utilis* on maize growth and crop production. *Applied Soil Ecology* 35(2): 356–362. <https://doi.org/10.1016/j.apsoil.2006.07.009>
- Ortiz-Ceballos, A. I., Aguirre-Rivera, J. R., Salgado-García, S., & Ortiz-Ceballos, G. (2015). Maize-velvet bean rotation in summer and winter milpas: A greener technology. *Agronomy Journal* 107(1): 330–336. <https://doi.org/10.2134/agronj14.0276>
- Ortiz-Ceballos, A. I., Ortiz-Gamino, D., Andrade-Torres, A., Pérez-Rodríguez, P., & López-Ortega, M. (2019). *Pontosclex corethrurus*: A homeless invasive tropical earthworm? *PLoS ONE* 14(9): 1–13. <https://doi.org/10.1371/journal.pone.0222337>
- Ortiz-Gamino, D., Gregorio, J., Cunha, L., Martínez-Romero, E., Fragoso, C., & Ortiz-Ceballos, A. I. (2020). Population genetics and diversity structure of an invasive earthworm in tropical and temperate pastures from Veracruz, Mexico. *ZooKeys* 947: 49–69. <https://doi.org/10.3897/zookeys.941.49319>
- Porter, S. S., & Sachs, J. L. (2020). Agriculture and the Disruption of Plant–Microbial Symbiosis. *Trends in Ecology and Evolution* 35: 426-439. <https://doi.org/10.1016/j.tree.2020.01.006>
- Rodríguez-Campos, J., Perales-García, A., Hernández-Carballo, J., Martínez-Rabelo, F., Hernández-Castellanos, B., Barois, I., & Contreras-Ramos, S. M. (2019). Bioremediation of soil contaminated by hydrocarbons with the combination of three technologies: bioaugmentation, phytoremediation, and vermiremediation. *Journal of Soils and Sediments* 19: 1981-1994. <https://doi.org/10.1007/s11368-018-2213-y>
- Sánchez-Hernández, J. C. (2019). Bioremediation of Pesticide-Contaminated Soils by using Earthworms. In *Bioremediation of Agricultural Soils*. <https://doi.org/10.1201/9781315205137-9>
- Sánchez-Velásquez, L. R., Vásquez-Morales, S. G., Lara-González, R., Ortiz-Ceballos, A. I., del Rosario Pineda-López, M., & Hernández-Vargas, G. (2019). Does the earthworm favor the survival and growth of *Abies religiosa* (Kunth) Schltdl. & Cham. Seedlings in a nursery? *Revista Chapingo, Serie Ciencias Forestales y Del Ambiente* 26(1): 113–121. <https://doi.org/10.5154/r.chsca.2019.04.039>
- Scown, M. W., Brady, M. V., & Nicholas, K. A. (2020). Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. *One Earth* 3(2): 237–250. <https://doi.org/10.1016/j.oneear.2020.07.011>
- Shelf, O., Hahn, P. G., Pineda, A., Tejesvi, M. V., & Martínez-medina, A. (2020). *Below-Ground Interactions in Ecological Processes*. <https://doi.org/10.3389/978-2-88963-258-9>
- Taheri, S., Pelosi, C., & Dupont, L. (2018). Harmful or useful? A case study of the exotic peregrine earthworm morphospecies *Pontosclex corethrurus*. *Soil Biology and Biochemistry* 116: 277–289. <https://doi.org/10.1016/j.soilbio.2017.10.030>
- Thakur, M. P., Künne, T., Unsicker, S. B., Biere, A., Ferlian, O., Pruschitzki, U., ... Eisenhauer, N. (2021). Invasive earthworms reduce chemical defense and increase herbivory and pathogen infection in native trees. *Journal of Ecology* 109(2): 763–775. <https://doi.org/10.1111/1365-2745.13504>

- Uribe, S., Huerta, E., Geissen, V., Mendoza, M., Godoy, R., & Jarquín, A. (2012). *Pontoscolex corethrurus* (Annelida: Oligochaeta) indicador de la calidad del suelo en sitios de *Eucalyptus grandis* (Myrtaceae) con manejo tumba y quema. *Revista de Biología Tropical* 60(4): 1543–1552. <https://doi.org/10.15517/rbt.v60i4.2072>
- Van Groenigen, J. W., Lubbers, I. M., Vos, H. M. J., Brown, G. G., De Deyn, G. B., & Van Groenigen, K. J. (2014). Earthworms increase plant production: a meta-analysis. *Scientific Reports* 4: 6365. <https://doi.org/10.1038/srep06365>
- Van Groenigen, J. W., Van Groenigen, K. J., Koopmans, G. F., Stokkermans, L., Vos, H. M. J., & Lubbers, I. M. (2019). How fertile are earthworm casts? A meta-analysis. *Geoderma*, 338: 525–535. <https://doi.org/10.1016/j.geoderma.2018.11.001>
- Villalobos-Maldonado, J.J., Meza-gordillo, R., Enciso-Sáenz, S., Castaño-González, J.H., Rosales-Quintero, A., Lagunas-Rivera S., Gutiérrez-Micelli, F.A., Ruíz-Valdiviezo, V.M., Rincón-Rosales, R. (2017) Identificación molecular de bacterias en *Eisenia foetida* Savigny cultivadas, con potencial de remoción de contaminates orgánicos persistentes. *Agroproductividad* 10(5): 51-56
- Wurst, S. (2013). Plant-mediated links between detritivores and aboveground herbivores. *Frontiers in Plant Science* 4: 1–5. <https://doi.org/10.3389/fpls.2013.00380>
- Xiao, Z., Wang, X., Koricheva, J., Kergunteuil, A., Le Bayon, R. C., Liu, M., ... Rasmann, S. (2018). Earthworms affect plant growth and resistance against herbivores: A meta-analysis. *Functional Ecology* 32(1): 150–160. <https://doi.org/10.1111/1365-2435.12969>
- Zavala-Cruz, J., Fragoso, C., Martínez-Hernández, S., Ortiz-Ceballos, A. I., Dendooven, L., Hernández-Castellanos, B., Contreras-Ramos, S. M., & Noa-Carrazana, J. C. (2013). Earthworm Populations in an Aged Hydrocarbon Contaminated Soil. *Research Journal of Environmental Sciences* 7: 27-37. <https://doi.org/10.3923/rjes.2013.27.37>