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The first data regarding the effect of the exotic *Eisenia ventripapillata* (Oligochaeta, Lumbricidae) on the cation composition of soils in Western Siberia

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Summary. We have performed laboratory experiments to determine the impact of earthworms (exotic *Eisenia ventripapillata* and peregrine *Aporrectodea caliginosa*) on the water-soluble forms of ammonium, potassium, sodium, magnesium, calcium in Calcic Chernozem, Greyic Phaeozem, and Haplic Chernozem, which are widespread in the south of Western Siberia. The differences between the impacts made by the two above-mentioned species have been estimated according to the changes they make in the initial cation concentrations in soil. For *E. ventripapillata*, the obtained evidence regarding the influence of this species on soil characteristics is first-ever data. We found that *E. ventripapillata* and *A. caliginosa* changed the content of all cations in the soils under this study, but the nature of these changes varied from one soil type to another. In contrast to A. caliginosa, E. ventripapillata reliably increased the content of potassium and calcium ions in Calcic Chernozem. In comparison with the *A. caliginosa* influence, the *E. ventripapillata* variants reliably differed in the content of ammonium, potassium, and sodium ions in Greyic Phaeozem. In Haplic Chernozem, the ammonium, magnesium, and sodium ions content in the *E. ventripapillata* variants was reliably lower than in the *A. caliginosa* variants. Thus, the observed difference between native and exotic species in the effects on the content of available cations can trigger changes in the mineral nutrition of plants growing in the examined soils.

The article contains 2 Figures, 1 Table and 49 References.

Keywords: earthworms, exotic species, *Eisenia ventripapillata*, soil cations, laboratory microcosms; capillary electrophoresis

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Первые данные о влиянии экзотического *Eisenia ventripapillata* (Oligochaeta, Lumbricidae) на катионный состав почв Западной Сибири

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Аннотация. В лабораторном эксперименте исследовано влияние дождевых червей: экзотического *Eisenia ventripapillata* и перегринного *Aporrectodea caliginosa* на водорастворимые формы аммония, калия, натрия, магния, кальция в Calcic Chernozem, Greyic Phaeozem и Haplic Chernozem, распространенных на юге Западной Сибири. Различия во влиянии между видами оценивалось на основании изменения ими начальных концентраций катионов в почве. Для *E. ventripapillata* полученные данные о воздействии вида на характеристики почвы приводятся впервые. Установлено, что *E. ventripapillata* и *A. caliginosa* изменяли содержание всех катионов в исследуемых почвах. При этом в каждом типе почв изменения носили специфический характер. В Calcic Chernozem *E. ventripapillata* достоверно увеличивал содержание ионов калия и кальция в отличие от *A. caliginosa*. В Greyic Phaeozem варианты с *E. ventripapillata* достоверно отличались по содержанию ионов аммония, калия и натрия. В Haplic Chernozem содержание аммония, магния и кальция в вариантах с *E. ventripapillata* было достоверно ниже, чем в вариантах с *A. caliginosa*. Таким образом, наблюдаемая разница между перегринным и экзотическим видами во влиянии на содержание доступных катионов может спровоцировать изменения в минеральном питании растений, произрастающих на исследованных почвах.

Ключевые слова: дождевые черви, экзотические виды, *Eisenia ventripapillata,* катионы почвы, лабораторные микрокосмы, капиллярный электрофорез

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Introduction

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) identified five major global drivers of environmental change. One such factor is invasive species [1]. Invasive plant, insect, and vertebrate invasions into terrestrial ecosystems are thoroughly studied [2]. At the same time, soil invasions are invisible and hard to detect, so these processes are less highlighted in the relevant literature on the subject. Nonetheless, these invasions result in ecosystem shifts that are as serious as those caused by terrestrial invasions [3-4]. Earthworm invasions are a striking example of this process [5].

Changes in climatic conditions [6], including soil temperature rise [7], facilitate the range expansion of earthworm species [3, 8-9] and enhance the intensity of exotic earthworm species' invasions of new territories [9].

It has been reported that the increase of the average winter temperatures allowed earthworms of the genus *Amynthas* to expand their range into new areas [6, 9]. The appearance of exotic *Lumbricus terrestris* Linnaeus, 1758 in Romania is also considered to be related to climatic changes [10]. Likewise, the soil temperature rise is common in Russia [11]; Western Siberia is characterized as a region of accelerated warming [12]. For example, the soil freezing depth has decreased by 40 cm in the south of Western Siberia [13, 14]. This factor also contributed to the changes in the earthworm species composition in the area. According to Vsevolodova-Perel's data [15], ten species and two subspecies of Lumbricidae are distributed in the lowland territory of Western Siberia. The most recent survey, however, [13] lists 18 species and 4 subspecies for the same area. Earthworms are classified as ecosystem engineering organisms because they modify soil system functioning [16]. This impact can be both direct and indirect [17]. One effect caused by earthworms is shifting the chemical composition of the soil. The knowledge of this effect is important from several perspectives, especially when earthworms invade new territories, and their effects on soil differ from the impact made by the native earthworm species inhabiting the area.

The invasions of endogeic earthworms can most drastically modify soil chemical composition [18-19], nutrient redistribution [20], and the availability of nutrients (Ca, K, Mg, Na, NH_4) for plants [21-22] as earthworms ingest and transform a large amount of soil [23]. The exotic endogeic *Pontoscolex corethrurus* (Müller, 1857) changed the Mg, Ca, K, NH_4 content and pH in Colombian soils compared to the endogeic earthworms already inhabiting the area [24]. In addition, the exotic endogeic *Aporrectodea caliginosa* (Savigny, 1826*)* and *Octolasion lacteum* Örley, 1881 changed the ammonium content and pH in New Zealand soils, whereas the native species did not [25]. The directions of change caused by exotic species invasions in both cases depended on the soil type [24-25].

A. caliginosa is one of the most common endogeic earthworm species in the south of Western Siberia. At present, this species is widely distributed in the natural habitats throughout Omsk Oblast [13], in the southern taiga of Tyumen Oblast [26], and the forest-steppe of the Ob region [27]. The endogeic *Eisenia ventripapillata* Perel 1985 was first recorded in Omsk Oblast in 2018. Its range in Omsk Oblast is similar to that of *A. caliginosa,* and in several habitats the two species are found in sympatry [13, 14]. According to the Russian earthworm checklist, this species has not been registered in the country yet [15]. *E. ventripapillata* was registered in the Rudny Altai Mts, East Kazakhstan [28], and it was considered endemic to that area. Currently, no relevant publications describing the biology, ecology, and environmental impact of *E. ventripapillata* are available.

The impact of *E. ventripapillata* on the availability of soil cations can differ from that of *A. caliginosa*. The ground for such assumption is the outcomes of invasions of exotic endogeic earthworms in Colombia [24] and New Zealand [25], where soils had already been inhabited by endogeic earthworms before the invasions. As a result, the nutrient availability changes can give a competitive advantage to certain plant species [20] and reduce plant species diversity in communities [4].

This research aims to investigate the changes in the availability of cations (NH_4^+, K^+, Na^+, Mg^{2+}, Ca^{2+}) in three soil types of Western Siberia colonized by *E. ventripapillata* and to perform a comparative study of the impact of the exotic *E. ventripapillata* and peregrine *A. caliginosa* on the availability of soil cations.

Materials and methods

Two endogeic earthworm species were used in the experiment: exotic *E. ventripapillata* and peregrine *A. caliginosa*. Mature individuals were collected in the vicinity of Chernoluchie village located in Omsk District, Omsk Oblast (55°16'33" N, E 73°02'35" E). Three soil types were used in the study: **Calcic Chernozem** (**Cal**) (Sand 20%; clay 34%; silt 27%; humus 6.0%; pH 7.52; NH_4^+ 0.33 mg/kg; K+ 4.55 mg/kg; Na+ 88.8 mg/kg; Mg^{2+} 8.84 mg/kg, Ca^{2+} 39.3 mg/kg), **Greyic Phaeozem** (**Gre**) (Sand 11%; clay 61%; silt 17%; humus 3.5%; pH 6.03; NH_4^+ 3.9 mg/kg; K^+ 41.9 mg/kg; Na^+ 4.48 mg/kg; Mg^{2+} 4.35 mg/kg, Ca^{2+} 26.2 mg/kg), **Haplic Chernozem** (**Hap**) (Sand 18%; clay 44%; silt 18%; humus 5.2%; pH 6.86; NH_4^+ 1.07 mg/kg; K^+ 17.2 mg/kg; Na^+ 8.63 mg/kg; Mg^{2+} 8.63 mg/kg, Ca^{2+} 47.8 mg/kg). The sampling sites for the above-mentioned soil types were as follows: Hap – the research field station of the Omsk Ecological Station of Young Naturalists, Omsk City (54°58'50" N, 73°18'10" E); Cal – the OmSPU research field station, Omsk (55°02'38" N, 73°22'52" E); Gre – the vicinity of Chernoluchie village, Omsk District, Omsk Oblast (55°16'33" N, 73°02'35" E). The soil was dried and sifted using a 4-mm mesh sieve to remove macrofauna.

Two-liter plastic containers with perforated lids were employed for the experiment. Each container was filled with 1.6 liters of soil. Leaf litter of *Populus tremula* L., 1753 dry leaves weighing 8.00±0,05 g was placed on the soil surface for the approximation to natural conditions. Five individuals of a single earthworm species were placed into each container. The average earthworm biomass in the microcosms was 4.10±0.20 g/vessel for *A. caliginosa* and 3.99±0.26 g/vessel for *E. ventripapillata*. Before the start of the experiment, the earthworms were kept for two days in the containers with the same soil which was added to the microcosms. Microcosms without earthworm treatment were used as the control. Nine experiment variants were performed; five replicates of each variant were analyzed. All microcosms were kept in constant climate chambers at 12°C. The soil moisture content was maintained at 40% with deionized water. In 90 days, the soil samples were taken and dried at 60 °C.

The NH_4^+, K^+, Na^+, Mg^{2+}, Ca^{2+} content in the soil samples was determined with a capillary electrophoresis system “Capel 104T” (Lumex Instruments, Russia). The preparation of soil samples and aqueous soil extracts, the analysis of cation content were conducted following the Lumex Method M 03-08-2011 standardized technique. The conditions for conducting the analysis were as follows: a capillary with an effective length of 60 cm and a diameter of 75 μm; sample injection by a pressure of 30 mbar×sec; electric power: 25kW; temperature: 20 °C; photometric detector wavelength: 254 nm. The leading electrolyte for cations contained benzimidazole, tartaric acid, and 18-crown-6. The pH values of the aqueous extracts were measured using an “ANION-4100” pH-meter (SPE Infraspak-Analit, Russia) with an “ESK-10301” glass combination electrode (soil to water ratio was 1:5, ISO 10390). The experimental data were processed with the Chrom&Spec software for Windows.

All data were converted using the natural logarithm response ratio (LnRR) where LnRR (variable) = ln (coprolite property / control soil property). LnRR <0 implies a negative effect of earthworms on nutrient availability in each soil type, whereas LnRR> 0 implies their positive impact on nutrient availability. The normality of the data was evaluated by applying the Shapiro-Wilk test with Statistica 13.0 (StatSoft Inc., United States). The principal component analysis (PCA) was performed using the PAST 4.05 statistical software package [29] with a matrix of 45 samples and 6 variables. This method permits visualizing the data of a smaller set of variables, but at the same time, it retains maximum information from the original set of variables. The PCA results were presented as two-dimensional plots using the first two principal components with higher data variability. A two-factor ANOVA was employed to evaluate the effect of earthworms and the initial soil characteristics on the changes to cation availability. The reliability of the influence exerted by earthworms on the shifts in cation availability in comparison with LnRR = 0 and the differences in the effects caused by the species in each soil type was checked using Student’s t-test. ANOVA and t-test were performed utilizing the Statistica 13.0 software package (StatSoft Inc., United States).

Results and discussion

Changes in the chemical composition of soil driven by exotic earthworms are registered in various regions of the world [18-19, 25]. This is a threat to the stability of ecosystem functioning [9, 25]. In Russia, this problem remains underexplored, though it is reliably known that exotic earthworm species [30] are presented in Western Siberia [31], the European part of Russia [8], and in the Kamchatka Peninsula [32].

According to the results of this research, *E. ventripapillata* is able to change the availability of cations in all three studied soil types. This species lowered the soil pH and the content of accessible ammonium, potassium, and sodium in most soils, as well as magnesium in Gre. However, an increase in potassium and calcium accessibility was identified in Cal. Additionally, an increase in sodium availability was observed in Hap. The nature of the changes in cation availability depended on the soil type (Fig. 1).

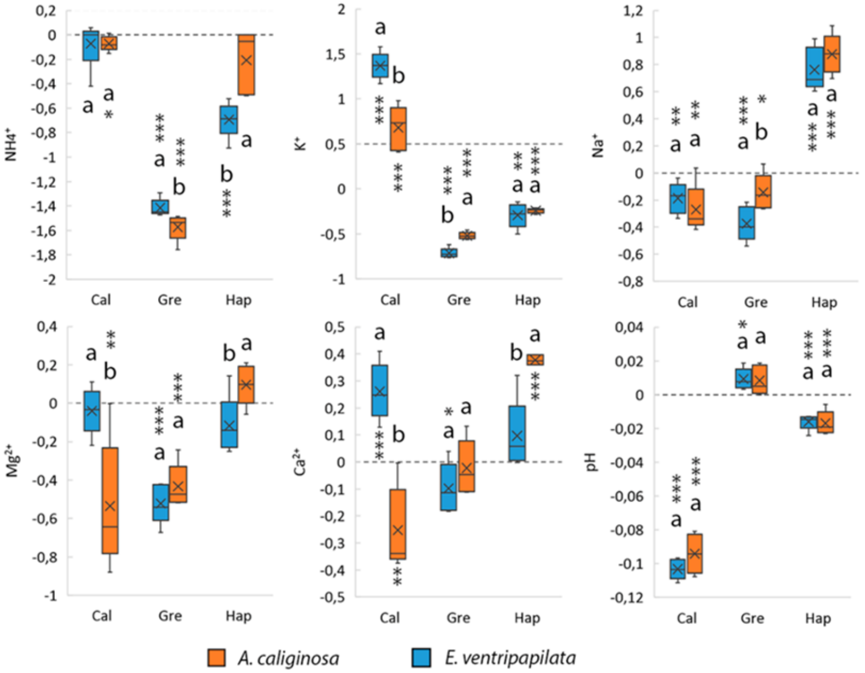

Fig. 1. Box-plot of the intensity of earthworm species effects (LnRR = Ln (variant / control) on the soil cation composition. The comparisons within the earthworm species are in lower-case letters. The variants with different letters are reliably dissimilar ($p \leq 0.05$). The dashed line represents the zero impact of earthworms (LnRR = 0). The significant variation from 0 was verified with a one-sample t-test, and it is indicated with asterisks («*»: $p < 0.05$; «**»: $p < 0.01$; «***»: $p < 0.001$). Cal - Calcic Chernozem, Gre - Greyic Phaeozem, Hap - Haplic Chernozem.

The PCA shows that *E. ventripapillata* and *A. caliginosa* modified the soil composition differently. The nature of these changes depended on the soil type for all cations (Fig. 2). Axis 1 explains 62.4% of the total inertia. This axis is positively correlated with NH_4^+ (r=0.92), K^+ (r=0.95) and, to a lesser extent, with Mg^{2+} (r=0.40) and Ca^{2+} (r=0.28). It is also negatively correlated with pH (r=-0.93). Axis 2 explains 29.6% of the total inertia. It is positively correlated with Na^+ (r=0.99), Mg^{2+} (r=0.72), and Ca^{2+} (r=0.65), but it is negatively correlated with K^+ (r=0.27).

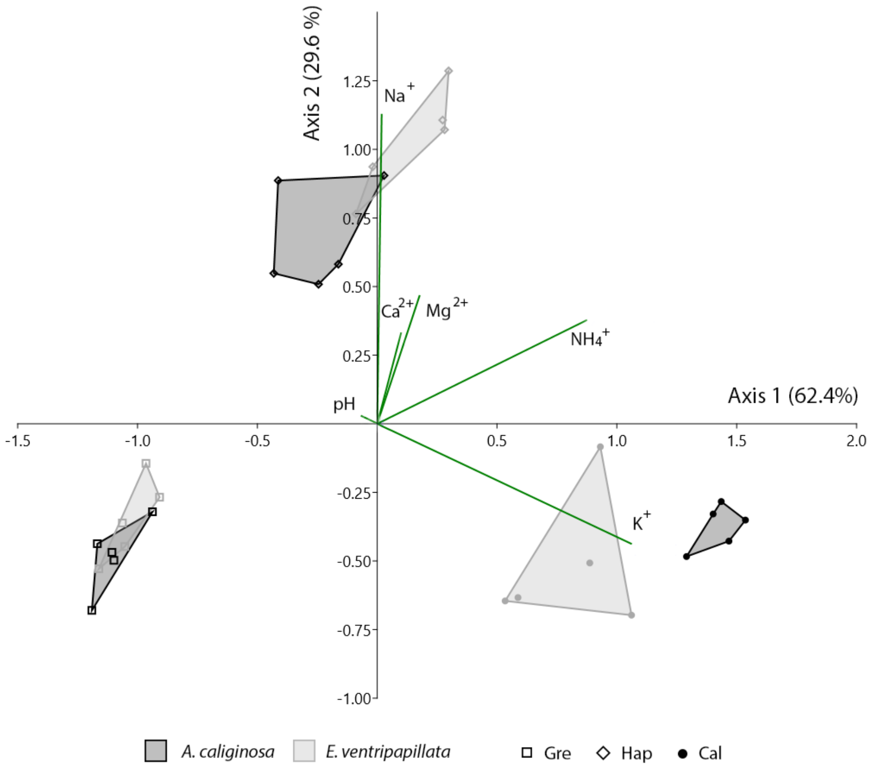

Fig. 2. PCA biplot of five different soil cations and pH. The factorial planes and the corresponding correlation vectors (superimposed on the plane) of the two earthworm species' influence on the changes in the soil cation composition were explored using the PCA method. Cal - Calcic Chernozem, Gre - Greyic Phaeozem, Hap - Haplic Chernozem.

According to the multivariate ANOVA (Table), the soil type factor affected changes in all cations ($p<0.001$), and the earthworm species influenced the concentration change of K^+ ($p<0.01$). The factor interaction was associated with changes in NH_4^+, K^+, Mg^{2+}, Ca^{2+} ($p<0.001$). Our results correspond to the conclusions drawn by other researchers stating that both soil type and the original content of elements determine the processes related to elemental soil composition changes caused by earthworms [21, 33]. This holds true for exotic endogeic *A. caliginosa* and *O. lacteum* in New Zealand [25] as the nature of their impact on the cation content also depends on the properties of soil.

ANOVA for each soil type (Fig. 1) demonstrates that the impact of the exotic *E. ventripapillata* on the water-soluble NH_4^+, K^+, Mg^{2+}, Ca^{2+} content differed from the effects caused by *A. caliginosa* ($p<0.05$) in most soils. The difference in the change of the Na^+ availability was only in Gre ($p<0.05$).

Multivariate ANOVA for testing the influence of the factors on the changes in the ion composition of three soil types with the LnRR index

	NH_4^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	pH
Species	4.03	9.31**	2.09	1.02	1.73	0.74
Soil	220.00***	422.70***	180.20***	18.00***	20.60***	533.60***
Type×Species	10.80***	31.80***	2.45	11.70***	35.78***	1.40

Note. «*»: $p < 0.05$; «**»: $p < 0.01$; «***»: $p < 0.001$.

The specific biological features of earthworm species can explain the observed differences in the Ca^{2+}, Mg^{2+} content, and pH in the soil. Calcium slowly returns to the soil in a form available to plants [34]. Earthworms contribute to an increase in the availability of calcium ions by producing calcium carbonate granules [34-35]. It is a species-specific process [36], which explain the difference in the changes of the Ca^{2+} content in the soil caused by *E. ventripapillata* and *A. caliginosa* in our research. The change in the magnesium content shows a pattern similar to calcium because earthworms' gut can be the major route for the release of these cations [37].

In our study, the soil pH after earthworm treatment differed from the pH of the original soil (Figure 1), but there is no significant difference between *E. ventripapillata* and *A. caliginosa*. Calcium carbonate production by earthworms can account for the pH increase in Gre (*A. caliginosa* $p<0.05$) which was less alkaline than the other soil types. *E. ventripapillata* and *A. caliginosa* decreased the soil pH in Cal and Hap ($p<0.001$) due to the activation of the nitrification process which leads to the release of protons [38]. Earthworm-driven pH decrease is rarely observed [33]; more often, earthworms contribute to soil alkalinization [39].

There is an evidence that earthworms stimulate the development of several functional groups of soil bacteria, including *Proteobacteria*, *Actinobacteria*, *Firmicutes* и *Acidobacteria* [40]. Consequently, it is correct to assume that the change in the availability of nutrients is related to the metabolic activity of bacteria and not the direct impact of earthworms [40-41]. Several authors note that the soil K^+ и Na^+ content is formed by microbial processes, including those occurring in earthworm gut [42]. In this research, the change in the K^+ content caused by *E. ventripapillata* differed from the effects produced by *A. caliginosa* ($p<0.001$) (Fig. 1). It can be explained by the specific features of the earthworm gut microflora and the soil aggregation process because they actively modify the microbial composition of soil and depend on the earthworm species identity [43-44]. It is also known that the availability of K^+ decreases when pH increases and vice versa [45], which was also confirmed by our data (Fig. 1). The availability of Na^+ also negatively correlates with the pH value [45]. However, our study did not reveal such dependence. Supposedly, the impact of microbiota is more significant, and it forms the species specificity (Fig. 2) [46]. At the same time, the increase in the water-soluble Na^+ form in the Hap soil ($p<0.001$) coincides with the data obtained by Wu [37] while studying the *P. corethrurus* impact on soil.

It is reported that a rise in the NH_4^+ content is associated with earthworm presence due to the increased mineralization of organic nitrogen [47]. In our study, earthworms either didn't change the NH_4^+ content (Fig. 1), which conforms to the results obtained by Bohlen & Edwards [48] or decreased the NH_4^+ content due to bacterial oxidation. The difference between *A. caliginosa* and *E. ventripapillata* (Fig. 1, 2) confirms the previously revealed dependence of soil nitrogen dynamics on the earthworm species [41]. This can be related to the species-specific difference of the gut bacterial composition and the earthworms casts responsible for nitrogen transformation [49].

Conclusions

The effects of *E. ventripapillata* mainly contribute to the lower availability of the water-soluble forms of ammonium, potassium, and sodium in soils. The content of available water-soluble cation forms in the soil after *E. ventripapillata* treatment differs from the impact made by *A. caliginosa*; the nature of these dissimilarities depends on soil characteristics. The potential replacement of *A. caliginosa*, a species that is widespread in Western Siberia, by the exotic *E. ventripapillata* species can cause a shift in the content of water-soluble K^+, Na^+, Mg^{2+}, Ca^{2+} и NH_4^+ in soils.

As the soil environment characteristics are much more diverse under natural condition than in laboratory settings, to fully understand the changes in nutrient availability related to *E. ventripapillata* invasion, it is necessary to carry out field research using various soil types and consider not only specific earthworm species but also earthworm communities.

References

1. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Diaz S, Settele J, Brondizio ES, Ngo HT, Gueze M, Agard J, Arneth A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Chowdhury RR, Shin YJ, Visseren-Hamakers IJ, Willis KJ, Zayas CN, editors. Bonn, Germany: IPBES secretariat. 2019. 56 p. doi: 10.5281/zenodo.3553579
2. Hendrix PF, Baker GH, Callaham MA, Damoff GA, Fragoso C, González G, James SW, Lachnicht SL, Winsome T, Zou X. Invasion of exotic earthworms into ecosystems inhabited by native earthworms. *Biological Invasions.* 2006;8:1287-1300. doi: 10.1007/s10530-006-9022-8
3. Hendrix PF, Callaham MA, Drake JM, Huang CY,1 James SW, Snyder BA, Zhang W. Pandora's box contained bait: the global problem of introduced earthworms. *Annual Review of Ecology, Evolution, and Systematics.* 2008;39:593-613. doi: 10.1146/annurev.ecolsys.39.110707.173426
4. Craven D, Thakur MP, Cameron EK LE Frelich, R Beauséjour, Blair RB, Blossey B, Burtis J, Choi A, Dávalos A, Fahey TJ, Fisichelli NA, Gibson K, Handa IT, Hopfensperger K, Loss SR, Nuzzo V, Maerz JC, Sackett T, Scharenbroch BC, Smith SM, Vellend M, Umek LG, Eisenhauer N. The unseen invaders: introduced earthworms as drivers of change in plant communities in North American forests (a metaanalysis). *Global Change Biology.* 2016;23(3):1065-1074. doi: 10.1111/gcb.13446

5. Frelich LE, Blossey B, Cameron EK, Dávalos A, Eisenhauer N, Fahey T, Ferlian O, Groffman PM, Larson E, Loss SR, Maerz JC, Nuzzo V, Yoo K, Reich PB. Side-swiped: ecological cascades emanating from earthworm invasions. *Frontiers in Ecology Environment.* 2019;17:502-510. doi: 10.1002/fee.2099
6. Singh J, Schädler M, Demetrio W, Brown GG, Eisenhauer N. Climate change effects on earthworms - a review. *Soil Organisms.* 2019;91(3):114-138. doi: 10.25674/so91iss3pp114
7. Lembrechts JJ, Aalto J, Ashcroft MB, De Frenne P, Kopecký M, Lenoir J, Luoto M, Maclean IMD, Roupsard O, Fuentes-Lillo E, García RA, Pellissier L, Pitteloud C, Alatalo JM, Smith SW, Björk RG, Muffler L, Backes AR, Cesarz S, Gottschall F, Okello J, Urban J, Plichta R, Svátek M, Phartyal SS, Wipf S, Eisenhauer N, Pușcaș M, Turtureanu PD, Varlagin A, Dimarco RD, Jump AS, Randall K, Dorrepaal E, Larson K, Walz J, Vitale L, Svoboda M, Higgens RF, Halbritter AH, Curasi SR, Klupar I, Koontz A, Pearse WD, Simpson E, Stemkovski M, Graae BJ, Sørensen MV, Høye TT, Calzado MRF, Lorite J, Carbognani M, Tomaselli M, Forte TGW, Petraglia A, Haesen S, Somers B, Van Meerbeek K, Björkman MP, Hylander K, Merinero S, Gharun M, Buchmann N, Dolezal J, Matula R, Thomas AD, Bailey JJ, Ghosn D, Kazakis G, de Pablo MA, Kemppinen J, Niittynen P, Rew L, Seipel T, Larson C, Speed JDM, Ardö J, Cannone N, Guglielmin M, Malfasi F, Bader MY, Canessa R, Stanisci A, Kreyling J, Schmeddes J, Teuber L, Aschero V, Čiliak M, Máliš F, De Smedt P, Govaert S, Meeussen C, Vangansbeke P, Gigauri K, Lamprecht A, Pauli H, Steinbauer K, Winkler M, Ueyama M, Nuñez MA, Ursu TM, Haider S, Wedegärtner REM, Smiljanic M, Trouillier M, Wilmking M, Altman J, Brůna J, Hederová L, Macek M, Man M, Wild J, Vittoz P, Pärtel M, Barančok P, Kanka R, Kollár J, Palaj A, Barros A, Mazzolari AC, Bauters M, Boeckx P, Benito Alonso JL, Zong Sh, Di Cecco V, Sitková Z, Tielbörger K, van den Brink L, Weigel R, Homeier J, Dahlberg CJ, Medinets S, Medinets V, De Boeck HJ, Portillo-Estrada M, Verryckt LT, Milbau A, Daskalova GN, Thomas HJD, Myers-Smith IH, Blonder B, Stephan JG, Descombes P, Zellweger F, Frei ER, Heinesch B, Andrews C, Dick J, Siebicke L, Rocha A, Senior RA, Rixen C, Jimenez JJ, Boike J, Pauchard A, Scholten T, Scheffers B, Klinges D, Basham EW, Zhang J, Zhang Zh, Géron Ch, Fazlioglu F, Candan O, Bravo JhS, Hrbacek F, Laska K, Cremonese E, Haase P, Moyano FE, Rossi C, Nijs I. A global database of near-surface temperature. *Global Change Biology*. 2020;26:6616-6629. doi: 10.1111/gcb.15123
8. Tiunov AV, Hale CM, Holdsworth AR, Vsevolodova-Perel TS. Invasion patterns of Lumbricidae into the previously earthworm-free areas of northeastern Europe and the western Great Lakes region of North America. *Biological Invasions*. 2006;8:223-1234. doi: 10.1007/s10530-006-9018-4
9. Eisenhauer N, Stefanski A, Fisichelli NA, Rice K, Rich R, Reich PB. Warming shifts 'worming': efects of experimental warming on invasive earthworms in northern North America. *Scientific Reports*. 2014;4:6890. doi: 10.1038/srep06890
10. Pop VV, Pop AA. Lumbricid earthworm invasion in the Carpathian Mountains and some other sites in Romania. *Biological Invasions*. 2006;8(6):1219-1222. doi: 10.1007/s10530-006-9017-5
11. Chen L, Aalto J, Luoto M. Significant shallow-depth soil warming over Russia during the past 40 years. *Global and Planetary Change*, 2021;197:103394. doi: 10.1016/j.gloplacha.2020.103394
12. Sada R, Schmalz B, Kiesel J, Fohrer N. Projected changes in climate and hydrological regimes of the Western Siberian lowlands. *Environmental Earth Sciences*. 2019;78(2):1-15. doi: 10.1007/s12665-019-8047-0
13. Golovanova EV. Alien species of earthworms in Western Siberia. In: Ecology and evolution: new challenges. Proc. of the International Symposium dedicated to the celebration of 100th anniversary of RAS Academician S. S. Shwartz. Ushakova KI., Veselkin DV, Vasiliev AG, editors. Ekaterinburg: Liberal Arts University - University for Humanities; 2019, pp. 494-495. In Russian, English summary.
14. Golovanova EV, Kniazev SY, Babiy KA, Tsvirko EI, Karaban K, Solomatin DV. Dispersal of earthworms from the Rudny Altai (Kazakhstan) into Western Siberia. *Ecologica Montenegrina*. 2021:45: 48–61. doi: 10.37828/em.2021.45.9.

15. Vsevolodova-Perel TS. The Earthworms of the Fauna of Russia. Kadaster and Key. Moscow: Nauka Publ.; 1997. 102 p. In Russian.
16. Jones CG. Lawton JH, Shachak M. Organisms as ecosystem engineers. *Oikos*. 1994;69(3):373-386. doi: 10.2307/3545850
17. Lavelle P. Faunal activities and soil processes: Adaptive strategies that determine ecosystem function. *Advances in Ecological Research.* 1997;27:93-132. doi: 10.1016/S0065-2504(08)60007-0
18. Resner K, Yoo K, Sebestyen SD, Aufdenkampe A, Hale C, Lyttle A, Blum A. Invasive Earthworms Deplete Key Soil Inorganic Nutrients (Ca, Mg, K, and P) in a Northern Hardwood Forest. *Ecosystems.* 2015;18:89-102 2015. doi: 10.1007/s10021-014-9814-0.
19. Ferlian O, Thakur MP, Gonzalez A, Emeterio L, Marr S, Rocha B, Eisenhauer N. Soil chemistry turned upside down: A meta-analysis of invasive earthworm effects on soil chemical properties. *Ecology*. 2020;101:e02936. doi: 10.1002/ecy.2936
20. Zaller JG, Wechselberger KF, Gorfer M, Hann P, Frank T, Wanek W, Drapela T. Subsurface earthworm casts can be important soil microsites specifically influencing the growth of grassland plants. *Biology and Fertility of Soils*. 2013;49:1097-1107. doi: 10.1007/s00374-013-0808-4
21. Mudrák O; Frouz J. Earthworms increase plant biomass more in soil with no earthworm legacy than in earthworm-mediated soil, and favour late successional species in competition. *Functional Ecology*. 2018;32(3):626-635. doi: 10.1111/1365-2435.12999
22. Bottinelli N, Jouquet P, Capowiez Y, Podwojewski P, Grimald M, Peng X. Why is the influence of soil macrofauna on soil structure only considered by soil ecologists? *Soil & Tillage Research*, 2015;146:118-124. doi: 10.1016/j.still.2014.01.007
23. Curry JP, Schmidt O. The feeding ecology of earthworms – a review. *Pedobiologia*. 2007;50:463-477. doi: 10.1016/j.pedobi.2006.09.001
24. Marichal R, Martinez AF, Praxedes C, Ruiz D, Carvajal AF, Oszwald J, Hurtado M, Brown GG, Grimaldi M, Desjardins T, Sarrazin M, Decaëns T, Velasquez E, Lavelle P. Invasion of Pontoscolex corethrurus (Glossoscolecidae, Oligochaeta) in landscapes of the Amazonian deforestation arc. *Applied Soil Ecology*. 2010;46:443-449. doi: 10.1016/j.apsoil.2010.09.001
25. Kim Y-N, Robinson B, Boyer S, Zhong H-T, Dickinson N. Interactions of native and introduced earthworms with soils and plant rhizospheres in production landscapes of New Zealand. *Applied Soil Ecology*. 2015;96:141-150. doi: 10.1016/j.apsoil.2015.07.008
26. Sergeeva EV. Vidovoe raznoobrazie pochvennykh bespozvonochnykh soobshchestv korennoy terrasy Irtysha [Species Diversity of Soil Invertebrate Communities of the Irtysh Root Terrace]. *Nauchnye vedomosti belgorodskogo gosudarstvennogo universiteta. seriya: estestvennye nauki.* 2014;17(28):70-75. In Russian.
27. Ermolov SA. Biotopical distribution of earthworms (Oligochaeta, Lumbricidae) in small river valleys of the forest-steppe Ob region. *Russian Journal of Ecosystem Ecology*. 2019;4(2). In Russian, English summary. doi: 10.21685/2500-0578-2019-2-5
28. Perel' TS. Osobennosti fauny dozhdevykh chervey (Oligochaeta, Lumbricidae) v altayskikh refugiumakh nemoral'noy rastitel'nosti. *Doklady Akademii Nauk SSSR*. 1985;283(3):752-756
29. Hammer Ø, Harper DAT, Ryan PD. PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica.* 2001;4(1):9. Avaliable at: http://palaeo-electronica.org/2001_1/past/issue1_01.htm
30. Shekhovtsov SV, Golovanova EV, Peltek SE. Different dispersal histories of lineages of the earthworm Aporrectodea caliginosa (Lumbricidae, Annelida) in the Palearctic. *Biological Invasions*. 2016,18(3):751-761. doi: 10.1007/s10530-015-1045-6
31. Shekhovtsov SV, Bazarova NE, Berman DI, Bulakhova NA, Golovanova EV, Konyaev SV, Krugova TM, Lyubechanskii II, Peltek SE. DNA barcoding: how many earthworm species are there in the south of West Siberia? *Russian Journal of Genetics: Applied Research*. 2017;7:57-62. doi: 10.18699/VJ15.110
32. Shekhovtsov SV, Golovanova EV, Peltek SE. Invasive lumbricid earthworms of Kamchatka (Oligochaeta). *Zoological Studies*. 2014;53(1):52. doi: 10.1186/s40555-014-0052-0

33. Jouquet P, Bottinelli N, Podwojewski P, Hallaire V, Tran Duc T. Chemical and physical properties of earthworm casts as compared to bulk soil under a range of different land-use systems in Vietnam. *Geoderma*. 2008;146(1-2):231-238. doi: 10.1016/j.geoderma.2008.05.030
34. Petrochenko KA, Kurovsky AV, Babenko AS, Yakimov YuE. Leaf litter-based vermicompost as promising calcium fertilizer. *Vestnik Tomskogo gosudarstvennogo universiteta. Biologiya - Tomsk State University Journal of Biology*. 2015;2(30):20-34. In Russian, English summary. doi: 10.17223/19988591/30/2
35. Versteegh EAA, Black S, Hodson ME. Environmental controls on the production of calcium carbonate by earthworms. *Soil Biology and Biochemistry*. 2014;70:159-161. doi: 10.1016/j.soilbio.2013.12.013
36. Canti MG, Piearce TG. 2003. Morphology and dynamics of calcium carbonate granules produced by different earthworm species: The 7th International Symposium on Earthworm Ecology Cardiff Wales 2002. *Pedobiologia*. 2003;47:511-521. doi: 10.1078/0031-4056-00221
37. Wu J, Zhang C, Xiao L, Motelica-Heino M, Ren Z, Deng T, Dai J. Impacts of earthworm species on soil acidification, Al fractions, and base cation release in a subtropical soil from China. *Environmental Science and Pollution Research*. 2020;27(27):33446-33457. doi: 10.1007/s11356-019-05055-8
38. Scharenbroch BC, Johnston DP. A microcosm study of the common night crawler earthworm (Lumbricus terrestris) and physical, chemical and biological properties of a designed urban soil. *Urban Ecosystems*. 2011;14(1):119-134. doi: 10.1007/s11252-010-0145-4
39. Van Groenigen JW, Van Groenigen KJ, Koopmans GF, Stokkermans L, Vos HMJ, Lubbers IM. How fertile are earthworm casts? A meta-analysis. *Geoderma*. 2019;338:525-535. doi: 10.1016/j.geoderma.2018.11.001
40. Schlatter D, Baugher C, Kendall K, Huggins D, Johnson-Maynard J, Paulitz T. Bacterial communities of soil and earthworm casts of native Palouse Prairie remnants and no-till wheat cropping systems. *Soil Biology and Biochemistry*. 2019;139:107625. doi: 10.1016/j.soilbio.2019.107625
41. Medina-Sauza RM, Álvarez-Jiménez M., Delhal A, Reverchon F, Blouin M, Guerrero-Analco JA, Cerdán CR, Guevara R, Villain L., Barois I. Earthworms building up soil microbiota, a review. *Frontiers in Environmental Science*. 2019;7:81. doi: 10.3389/fenvs.2019.00081
42. Iordache M, Tudor C, Brei L. Earthworms diversity (Oligochaeta: Lumbricidae) and casting chemical composition in an urban park from Western Romania. *Polish Journal Environmental Studies*. 2021;30:645-654. doi: 10.15244/pjoes/123187
43. Frazao J, de Goede RGM, Capowiez Y, Pulleman MM. Soil structure formation and organic matter distribution as affected by earthworm species interaction and crop residues placement. *Geoderma*. 2019;338:453-463. doi: 10.1016/j.geoderma.2018.07.033
44. Sapkota R, Santos S, Farias P, Krogh PH, Winding A. Insights into the earthworm gut mult-kingdom microbial communities. *Science of The Total Environment*. 2020;727:138301. doi: 10.1016/j.scitotenv.2020.138301
45. Sharpley AN. Effect of soil pH on cation and anion solubility. *Communications in Soil Science and Plant Analysis*. 1991;22(9-10): 827-841.
46. Luo AX, Wang M, Hu G, Weng B. Seasonal Change of Microbial Diversity and Its Relation with Soil Chemical Properties in Orchard. *PLoS ONE*. 2019;14(12):e0215556. doi: 10.1371/journal.pone.0215556
47. Chapuis-Lardy L, Brauman A, Bernard L, Pablo AL, Toucet J, Mano MJ, Weber L, Brunet D, Razafimbelo T, Chotte JL, Blanchart E. Effect of the endogeic earthworm Pontoscolex corethrurus on the microbial structure and activity related to CO_2 and N_2O fluxes from a tropical soil (Madagascar). *Applied Soil Ecology*. 2010;45(3):201-208. doi: 10.1016/j.apsoil.2010.04.006
48. Bohlen PJ, Edwards CA. Earthworm effects on N dynamics and soil respiration in microcosms receiving organic and inorganic nutrients. *Soil Biology and Biochemistry*. 1995;27:341-348. doi: 10.1016/0038-0717(94)00184-3

49. Kostina NV, Bogdanova TV, Umarov MM. Biological activity of the coprolites of earthworms. *Moscow University Soil Science Bulletin.* 2011;66:18-23. doi: 10.3103/S0147687411010029

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