Functional diversity of earthworm communities in forests in the south of the Russian Far East

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Abstract. Key species of soil macrofauna – large soil saprophages, i.e. earthworms – have been studied in unique in terms of floristic and faunal diversity, as well as the most preserved forests of the southern Russian Far East. The results of studying taxonomic and functional diversity of earthworms, their biomass and abundance and patterns of temporal spatial distribution in summer seasons, are presented. The complete set of the main functional groups of earthworms (epigeic, epi-endogeic, endogeic and anecic) was found only in the best-preserved valley forests, with no traces of logging and fires over the last century. The earthworm community is not complete (one or two functional groups are missing) in one of valley forest that was partially cut down and affected by fires in recent decades and in hillside forests. Horizontal spatial distribution was analysed for the epi-endogeic and endogeic groups of earthworms, dominating in terms of biomass and occurrence. It was found that, in the summer season, the group of epi-endogeic species showed the "covering" type of distribution (regular distribution without aggregation), whereas the group of endogeic species showed the "spotty" type of distribution (aggregated distribution).

Keywords: biodiversity, biomass, fractal design, functional groups, invertebrates, litter, polydominant forest, Red List species, saprophages, soil, spatial distribution.

1. Introduction

Modern studies of the structure and diversity of soil invertebrates make sense in the most preserved forest ecosystems that have not been exposed to anthropogenic impacts for a long time. Technogenic impacts (Dunger et al., 2001; Dunger & Voigtländer, 2005; Hüttl & Weber, 2001; Prescott et al., 2019; Mordkovich & Lyubechanskii, 2019) and fires (Wikars & Schimmel, 2001; Buckingham et al., 2019) are the most destructive for soil; they can result in a serious decrease in the diversity and functions of soil biota, the recovery of which proceeds extremely slowly and depends on the extent and duration of the disturbance. The polydominant forests of the southern Far East are of great interest for ecological and taxonomic studies of all biota components, as they are characterised by the floristic and faunal diversity and endemism that are unusually high for Russia. The territory of Southern Primorye alone is home to more than 2.500 species of vascular plants, with at least 250 species of trees, shrubs and woody vines. There are 127 endemic plant species in Primorsky Krai and 156 in Khabarovsk Krai (Kozhevnikov &

Kozhevnikova, 2014). The southern Far East is an endemic habitat of the largest beetle in Russia, *Callipogon relictus* Semenov, 1899 (Cerambycidae) (Kuprin & Bezborodov, 2012; Kuprin & Kharchenko, 2013; etc.), which is included in the Red List of the Russian Federation as a threatened species (category II). The most diverse and unique fauna amongst soil invertebrates is that of the oribatid mites (Ryabinin, 2011), collembolans (Kuznetsova et al., 2019) and millipedes (Mikhaleva, 2017). There are four earthworm families: Lumbricidae, Criodrilidae, Megascolecidae and Moniligastridae, while only one family, the Lumbricidae, is mainly represented throughout most of the territory of Russia. At the same time, *Drawida ghilarovi* Gates, 1969, a representative of the tropical family Moniligastridae, is endemic to the southern Far East and is typical for a number of forest, meadow and meadow-marsh communities (Ganin & Atopkin, 2018); however, the species is declining in number and is on the Red List of the Russian Federation (category II).

Biodiversity and uniqueness of the flora and fauna of the southern Far East and the preservation of tertiary relics are a result of the complex geological history of this region, which was defined by the collision of the Indian and Asian tectonic plates 70 million years ago and which allowed tropical species to settle in this territory (Easton, 1981). Moreover, the monsoon climate and heterogeneous terrain, i.e. mid-mountain, low-mountain and hillocky areas with complex differentiation of plant and soil groupings (Starozhilov, 2010), create a variety of conditions that essentially distinguish this region from others within the territory of Russia.

At the same time, the forests of Southern Primorye have also been exposed to human economic activity (Naumov, 2012); therefore, when assessing the ecosystem functions of forests, it is necessary to identify the most preserved forest areas, which are characterised by a stable structural and functional diversity of all biota components. One of important criteria of forest ecosystem sustainability is the state of key species populations (Smirnova & Toropova, 2016), amongst which earthworms are of great importance in the soil fauna of mixed and broad-leaved forests.

The objective of this work is to assess the earthworm community as an indicator group of the state of forest ecosystems. The aims of this study were: 1) to assess the diversity, abundance, biomass and composition of the functional groups of earthworms and 2) to assess the patterns of temporal spatial distribution of the dominant groups of earthworms: epi-endogeic and endogeic.

2. Study area

The research was carried out in three nature reserves of Southern Primorye (Fig. 1, Fig. 2). Within plant communities (the names of vascular plants are given according to World Flora

Online, 2012), five forest sites (FS) were identified where faunal and quantitative earthworm recordings were performed (henceforth FS 1–5):

FS 1. Kedrovaya Pad Nature Reserve – valley fir-cedar (*Abies nephrolepis* (Trautv. ex Maxim.) Maxim., *Pinus koraiensis* Siebold & Zucc.) broad-leaved forest with ferns (*Dryopteris crassirhizoma* Nakai) and dead cover (about 50%); 101 m above sea level.

FS 2. Ussuri Nature Reserve, Komarovskoye forest district and Turov Hill – cedar (*Pinus koraiensis*) broad-leaved forest with sedges (*Carex* spp.,) and small-herb (*Oxalis acetosella* L.) in cover; hillside forest (207 m above sea level).

FS 3. Ussuri Nature Reserve, Komarovskoye forest district and Grabovaya Hill (slope). Fir-hornbeam (*Abies nephrolepis*) forest with dead cover (about 80%) and small-herb (*Oxalis acetosella*); hillside forest (350 m above sea level).

FS 4. Ussuri Nature Reserve, Suvorov forest district and Anikin river valley – valley forest with elm (*Ulmus japonica* (Rehder) Sarg.), ash (*Fraxinus mandshurica* Rupr.) and cedar (*Pinus koraiensis*) with cover of ferns (*Athyrium sinense* Rupr, *Dryopteris crassirhizoma*, *Hylomecon vernalis* Maxim.) and tall-herbs (*Impatiens noli-tangere* L., *Cardamine leucantha* (Tausch) O.E.Schulz)); 156 m above sea level.

Forest sites 1–4 are the best-preserved forests, with no traces of logging and fires over the last century.

FS 5. Komsomolsky Nature Reserve and Gorin river valley – valley cedar (*Pinus koraiensis*) broad-leaved forest with a cover of ferns (*Leptorumohra amurensis* Tzvelev) and small-herbs (*Maianthemum bifolium* (L.) F.W. Schmidt, *Viola sacchalinensis* H. Boissieu, *Cornus canadensis* L., *Waldsteinia ternata* subsp. *trifolia* (Rochel ex W.D.J. Koch) Teppner); 239 m above sea level. This site was partially cut down and affected by fires in recent decades.

The soil type of all the surveyed test plots (sites) is forest brown soil with a well-defined horizon of litter (4 to 10 cm) from mixed leaf litter of coniferous and deciduous species of trees and shrubs.

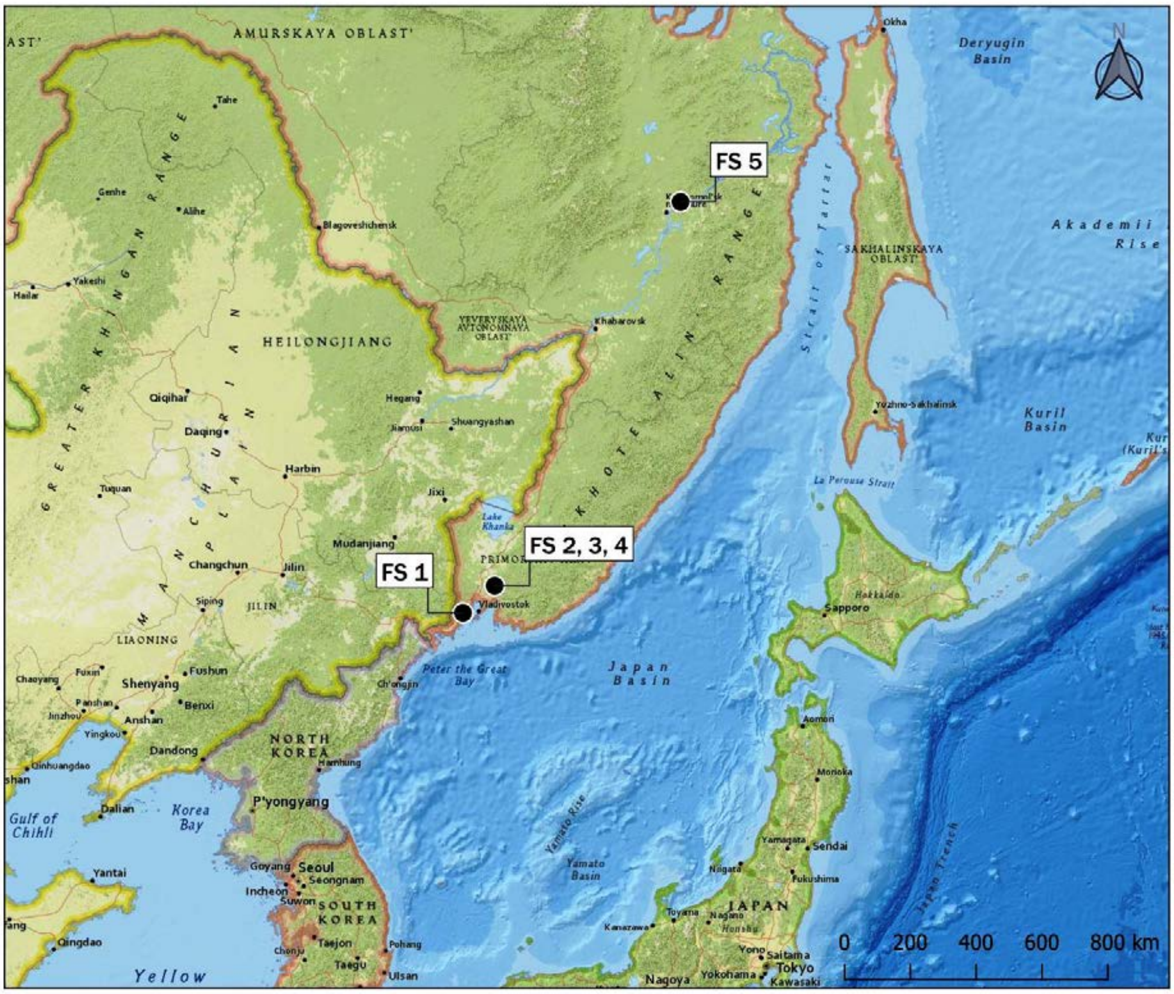

Figure 1. The map of the test plots. Note: FS 1 – Kedrovaya Nature Pad Reserve, FS 2, 3 and 4 – Ussuri Nature Reserve, FS 5 – Komsomolsky Nature Reserve

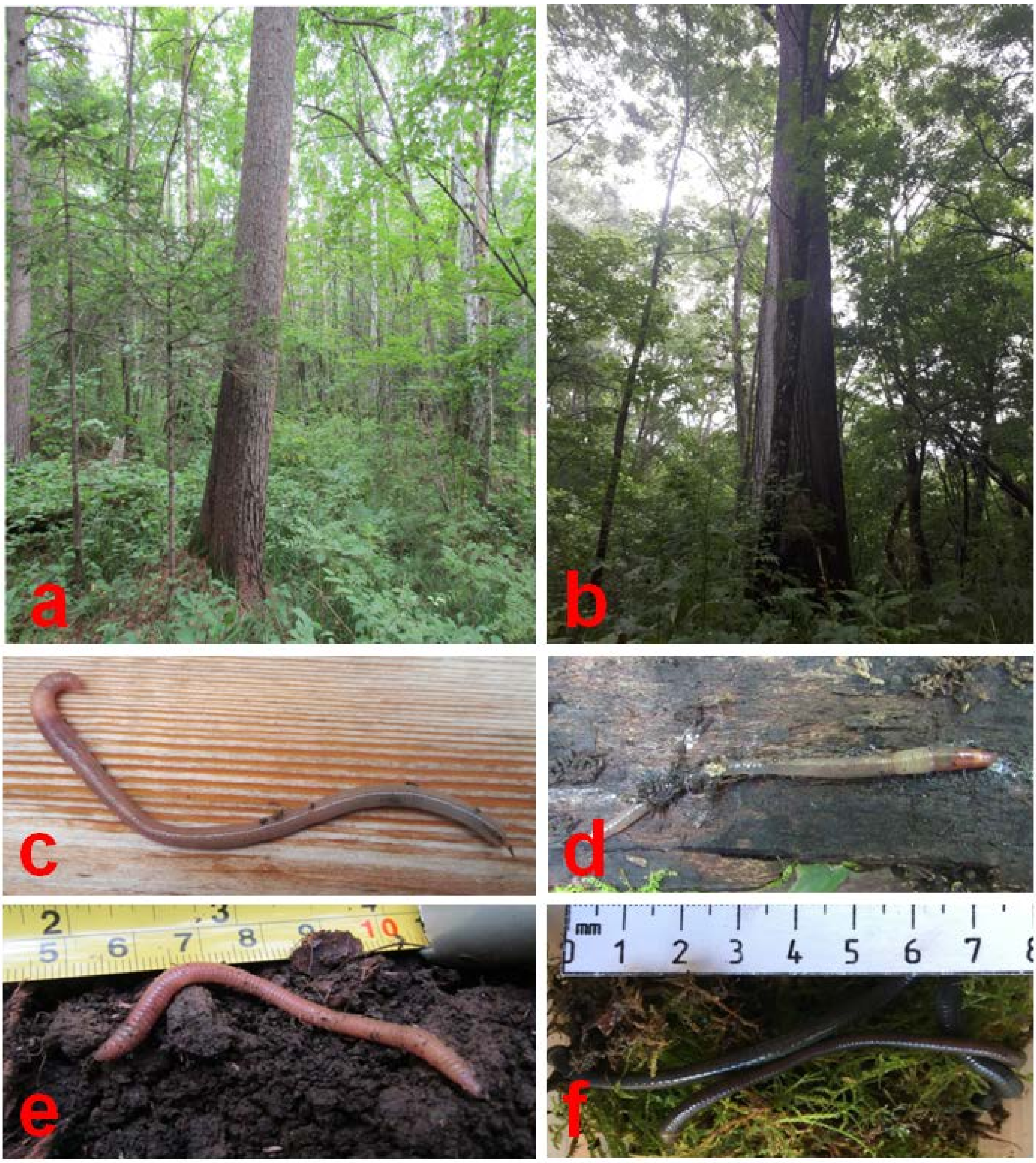

Figure 2. Pictures of forest habitats and different earthworms' species. Note: a – Komsomolsky Nature Reserve, b – Ussuri Nature Reserve, c – *Eisenia nordenskioldi,* d – *Octolasion lacteum,* e – *Eisenia* sp. (juv.), f – *Drawida ghilarovi*

3. Materials and Methods

The material was collected during the summers (July–August) of 2016–2018. To evaluate diversity and spatial distribution of earthworms, we used fractal design that allows assessing the distribution parameters of groups of organisms at different spatial levels; this method was developed by A.I. Azovsky to count collembolans (Saraeva et al., 2015) and was adapted for earthworms (Geraskina & Kuznetsova, 2017).

In each forest type (forest site), one series of 27 soil samples (10x10 cm) was taken, depth - 30 cm. Each set of samples includes three groups (nine samples in one group), at a distance of 10 m from each other. Each group includes three subgroups (three samples in one subgroup), at a distance of 20 cm from each other. The distance between individual samples within subgroups is 5 cm (Fig. 3). The abundance and biomass of earthworms are calculated per m^2. The Casey Index was calculated to assess the spatial distribution within 1 m^2 and the degree of aggregation of individuals: $Ic = (S^2 – M)/M^2$, where M is the average species abundance and S^2 the dispersion. At $Ic < 0$ the distribution is uniform, at $Ic = 0$ it is random and at $Ic > 0$ it is aggregated (Saraeva et al., 2015).

Spatial distribution of the types of individuals can be convincingly evaluated only if the species abundance has at least one specimen per sample (Saraeva et al., 2015). Due to the fact that the obtained data on abundance of almost all species was lower than this, we considered the spatial distribution of the most numerous groups, i.e. epi-endogeic and endogeic species.

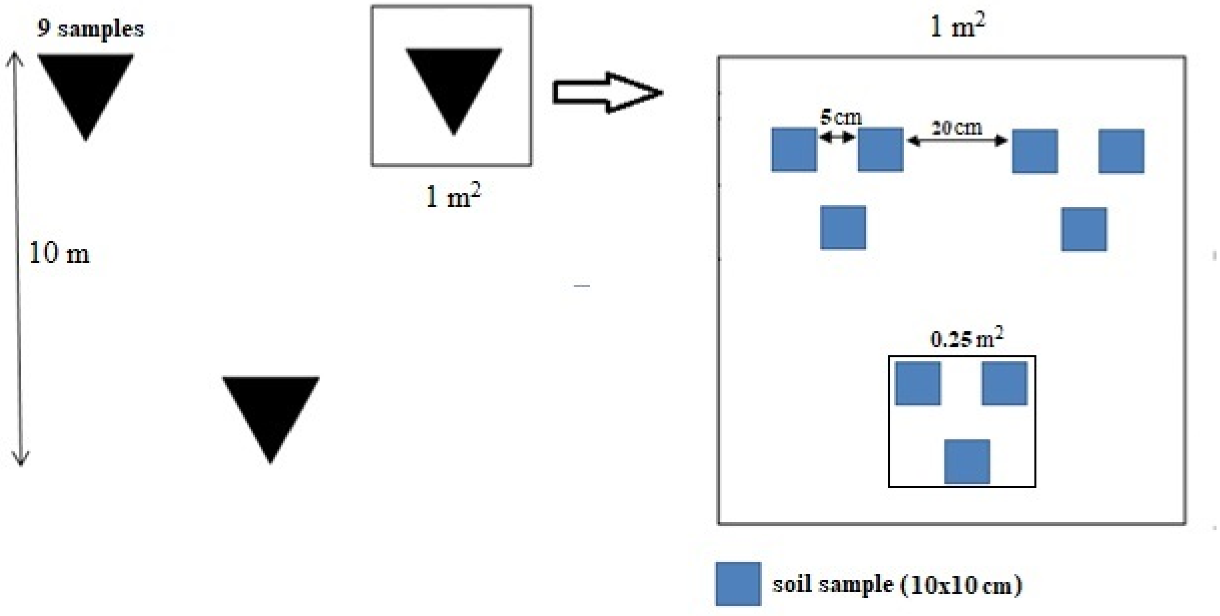

Figure 3. Fractal design for assessing the horizontal earthworm distribution (Saraeva et al., 2015, Geraskina & Kuznetsova, 2017)

In addition to quantitative assessment, faunal collections of earthworms in dead wood of coniferous and deciduous tree species at decomposition stages 2–3 (Ashwood et al., 2019) were carried out in the valley forests of FS 4 and FS 5.

Soil parameters, i.e. soil temperature, humidity and acidity (assessed with PH 300 electronic soil indicator) were measured in the studied forest types. During the accounting periods, the temperature of the litter horizon ranged from 13 to 17°C, the mineral horizon from

10 to 15°C and the pH from 5.5 to 6.5. As for moisture, the soil of the studied territories is usually moderately moist: 30–40% in hillside forests (FS 2–3) or humidity excesses 40–50% in valley forests (FS 1, 4, 5).

Earthworms were placed in 96% ethyl alcohol. The biomass of earthworms was determined by weighing the fixed earthworms with a full gut. The species composition and functional groups of earthworms were established by Cadastre from the Fauna of Russia (Vsevolodova-Perel, 1997). When comparing samples, the Kruskall-Wallis test was used to identify significant differences ($p<0.05$).

4. Results and discussion

4.1. Taxonomic and functional diversity of earthworms

In the course of research, nine species of earthworms, belonging to two families and four functional groups, were found in the polydominant forests in the southern Far East (Table 1). The Lumbricidae family includes eight species, of which six are cosmopolitans (epigeic – *Dendrobaena octaedra* (Savigny, 1826), *Dendrodrilus rubidus tenuis* (Eisen, 1874)*;* epi-endogeic *Lumbricus rubellus* Hoffmeister, 1843; endogeic *Apporectodea caliginosa* (Savigny, 1826), *Apporectodea rosea* (Savigny, 1826) and *Octolasion lacteum* (Örley, 1881), as well as two species with limited range (epi-endogeic *Eisenia nordenskioldi nordenskioldi* (Eisen, 1879)) with the range in the eastern regions of the European part of Russia and Ukraine, Siberia, the Far East and the East Asian species *Eisenia nordenskioldi pallida* Malevič 1956. The Moniligastridae family includes one species *Drawida ghilarovi* Gates, 1969 (endemic to the southern Far East), which is represented by two functional groups and various colour morphs: epi-endogeic (black morph) and anecic (grey, brown and greenish-blue morphs) (Ganin & Atopkin, 2018).

The largest species diversity of earthworms was found in the valley fir-cedar-broad-leaved forest in the Kedrovaya Pad Reserve (FS1) which is home to six species of Lumbricidae and two forms of *D. ghilarovi* species (Moniligastridae), i.e. epi-endogeic – black morph and anecic – brown morph. The composition of the functional groups of earthworms is full. However, the biomass and abundance of earthworms are significantly lower here than in the forests of the Ussuri Reserve (FS 2 and 4) (Table 1; Fig. 4). That said, we have not conducted surveys of additional earthworm habitats other than soil excavations in this area, therefore, the potential taxonomic diversity may be higher.

The largest abundance and biomass of earthworms were identified in this study and the entire spectrum of functional groups was represented in the valley elm-ash-cedar forest of the Anikin river valley (FS 4). The functional structure is dominated by the endogeic species group

(Fig. 4). The polymorphic species *D. ghilarovi* is represented by two forms, i.e. epi-endogeic and anecic, while earthworms of three colour morphs are found amongst anecic forms: grey, brownish and bluish-green. During the survey of Maximovich poplar dead wood (decomposition stage 3) and Korean pine (decomposition stage 2), *D. octaedra, D. r. tenuis* and a black morph of *D. ghilarovi* were found. The complex phytocenotic structure of this valley forest, with a diverse composition of forest-forming species, also supports the abundance and unique diversity of xylobiont beetles and other insects included in the Red List of Russia and neighbouring countries (China, The Republic of Korea): *Callipogon relictus* Semenov, 1899; *Rosalia coelestis* Semenov, 1911; *Osmoderma davidis* Fairmaire, 1887; *Carabus* (*Acoptolabrus*) *constricticollis* Kraatz, 1886 (Coleoptera); *Apis cerana* Fabricius, 1793; and *Liometopum orientale* Karavaiev, 1927 (Hymenoptera) (Kuprin, 2012; Kuprin, 2016; Kuprin & Drumont, 2016; Kuprin & Yi, 2019; Lee et al., 2018). Therefore, this polydominant valley forest can be considered as the most promising one for complex ecological studies of the most preserved forest ecosystems of Southern Primorye and for studying the relationships between different biota components.

The least diversity, abundance and biomass of earthworms (Table 1; Fig. 4) were identified in valley cedar-broad-leaved forest in Komsomolsky Reserve (FS 5): only epigeic and epi-endogeic earthworms were found here. The anecic group and soil group, as such, were lacking. In total, four earthworm species were identified when soil samples and the dead wood survey were taken into account.

Incomplete composition of the earthworm groups was also found in the hillside forests: cedar-broad-leaved forest (FS 2) and fir-hornbeam forest (FS 3). No epigeic or endogeic species were found here. Epi-endogeic *E. n. nordenskioldi* and *E. n. pallida* predominate in terms of abundance and biomass which are the typical species for polydominant forests of southern Far East (Perel, 1979; Vsevolodova-Perel & Leirikh, 2014).

The available data on the earthworm population of Southern Primorye, obtained mainly from the survey of black fir forests in the Ussuri Reserve and the mixed forests of the Kedrovaya Pad Reserve (Gilyarov & Perel, 1973; Perel, 1979) show that, generally, we have identified no potential species diversity of earthworms, either within local forest territories (for which a number of cosmopolitan species of the Lumbricidae fam. was also listed) or in the south of the Russian Far East in general, for which at least 16 earthworms species of four families have been specified (Ganin, 2011). At the same time, the results on the earthworms' abundance and biomass obtained by us are quite high, especially in the valley elm-ash-cedar forest with fern - tall-herb cover (FS 4). According to literature, these indicators are usually 2–3 times lower in mixed forests (Gilyarov & Perel, 1973; Vsevolodova-Perel & Leirikh, 2014). Unusually high quantitative indicators of the abundance and biomass of earthworms in this forest type are due to moist (often waterlogged) soils; it is also evidenced by the prevalence of *O. lacteum* species which is an indicator of waterlogged biotopes (Perel, 1979) and good trophic conditions with mixed litter fall and easily decomposable fractions of linden, poplar, ash, maple leaves etc. However, despite similar moisture conditions, as well as other comparable trophic and topological conditions (soil type, mixed litter fall, pH), the valley cedar-broad-leaved forest of the Gorin river valley (FS 5) showed the lowest abundance, biomass and diversity of earthworms. These differences are most likely caused by other factors impacting on soil biota, i.e. more frequent fires in Komsomolsky Reserve and the economic activity (logging) mode, including before the creation of the Nature Reserve in 1963 (Kuberskaya & Novomodnyi, 2019), the consequences of which do not allow soil fauna to restore and sustainably to develop.

Table 1. Abundance* (ind./m^2) and total biomass (g/m^2) of earthworms in intact polydominant forests of the Far East of Russia

Family of earthworms	Species	Functional group	Kedrovaya Pad Nature Reserve	Ussuri Nature Reserve			Komsomolsky Nature Reserve
			FS 1 "Pikhtovaya" (Fir) valley fir-cedar-broad-leaved forest with fern-dead cover	FS 2 "Turov" cedar-broad-leaved forest with sedge-small-herb cover	FS 3 "Grabovaya" (Hornbeam) Fir-hornbeam forest with dead-small-herb cover	FS 4 "Anikin" valley elm-ash-cedar forest with fern-tall-herb cover	FS 5 "Gorin" valley cedar-broad-leaved forest with fern-small-herb cover
Lumbricidae	*Dendrobaena octaedra*	epigeic	3.7±1.7	0	0	7.4±2.7	7.0±2.2
	Dendrodrilus rubidus tenuis		0	0	0	+ (found in dead wood only)	+ (found in dead wood only)
	Eisenia nordenskioldi nordenskioldi	Epi-endogeic	0	34.8±8.8	33.3±6.6	37.0±6.8	0
	Eisenia nordenskioldi pallida		8.9±2.1	27.4±5.4	17.0±5.3	0	12.6±3.1
	Lumbricus rubellus		3.7±2.2	0	0	3.7±1.3	0
	Apporectodea caliginosa	Endogeic	24.4±6.6	0	0	0	0
	Aporrectodea rosea		5.1±2.4	0	0	0	0
	Octolasion lacteum		20.7±5.8	0	0	129.5±11.3	0
	Apporectodea juv. sp.		13.3±6.4	0	0	0	0
	Eisenia juv. sp.	Epi-endogeic	14.4±4.5	52.5±6.5	20.0±2.9	0	0
Moniligastridae	*Drawida ghilarovi*	Polymorphic species	12.2±3.3 epi-endogeic and anecic form	18.5±6.3 anecic form	14.8±3.5 anecic form	22.2±5.4 epi-endogeic and anecic form	+ (found only in dead wood) epigeic form
Total abundance			106.4±10.8**	133.2±12.5**	85.1±15.2	199.8±25.4**	19.6±6.6
Total biomass			48.5±8.4	80.2±10.8**	50.3±16.3	142.6±15.5**	15.5±6.1

Note: * – the abundance values are given in the table cells for species

** – indicators are significantly higher as compared to the samples of other forest types (Kruskal-Wallis test, $p < 0.05$)

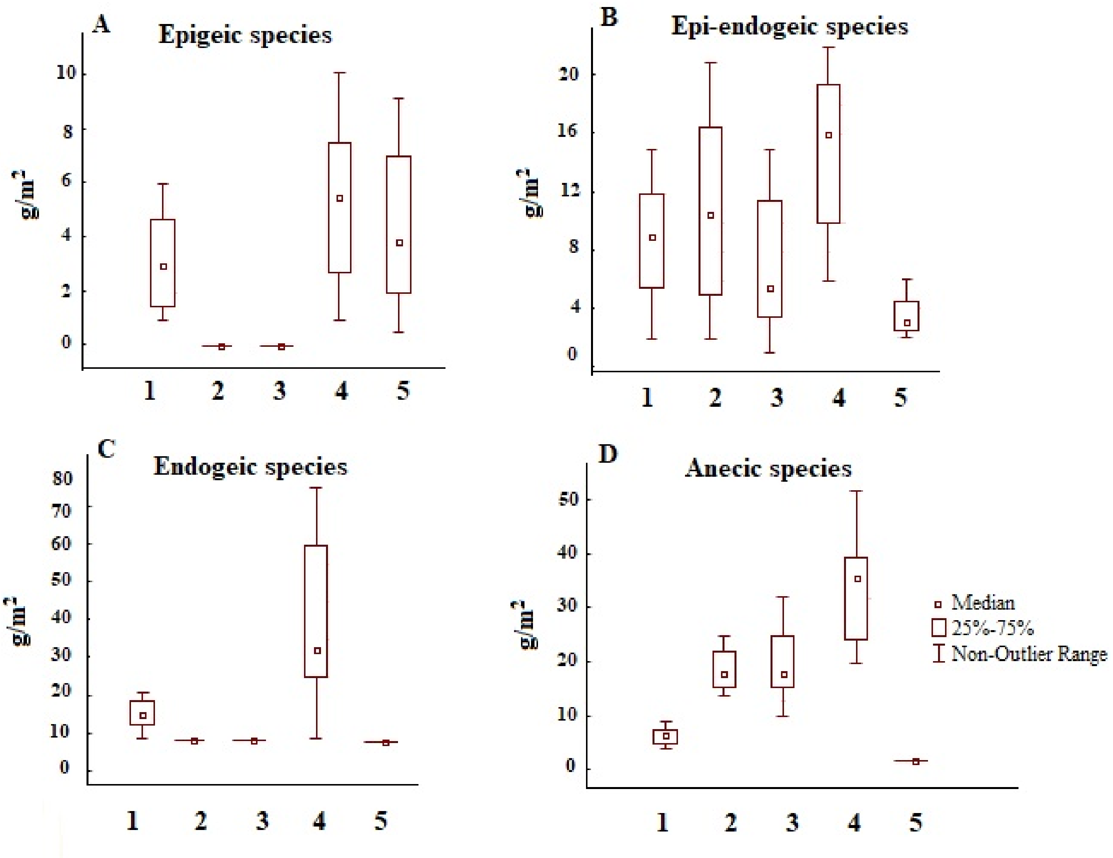

Figure 4. Biomass of functional groups of earthworms in polydominant forests of Southern Primorye (1–5 are numbers of test plots as in Table 1)

4.2. Patterns of spatial distribution of earthworms

Spatial distribution of earthworms is partially described by species occurrence rate within the study area. Epigeic and anecic species show the lowest occurrence in samples of all the studied communities (under 15% of samples); at the same time, these species were not detected in a number of communities. Plant communities with the occurrence of other functional groups of earthworms (epi-endogeic and endogeic) reaching 80–100% may be identified. In this regard, the horizontal spatial distribution types were analysed for these two groups: the distribution of epi-endogeic species was studied within three test plots (FS 2, 3 and 4) and the distribution of endogeic species was studied within two test plots (FS 1 and 4).

Casey index values for epi-endogeic species on 0.25 m^2 sites was close to zero (+0.5 to -0.5) and, on 1 m^2 to 100 m^2 sites, it was below zero (0 to -1.6) (Fig. 5). This type of distribution is a sign of absence of aggregations and is defined as "covering" (Saraeva et al., 2015) or regular distribution without aggregation (Whalen, 2004).

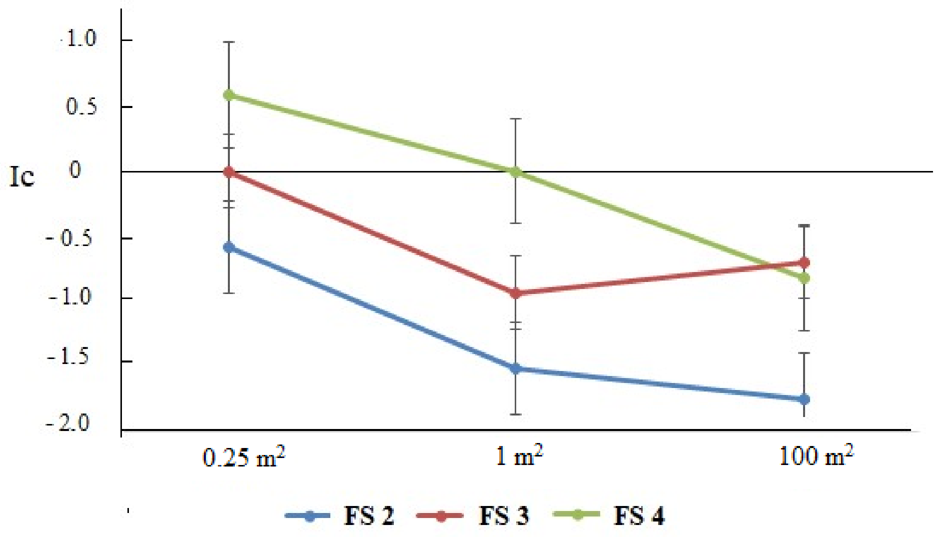

Figure 5. Casey index values for the epi-endogeic species group distribution

Casey index values for endogeic species on 0.25 m^2 to 100 m^2 sites are positive (from 0.5 to 2.5), i.e. the distribution of these species tends to form aggregations (Fig. 6). Since there are three levels of aggregation of these species, this type of spatial distribution is defined as "spotty" (Saraeva et al., 2015) or aggregated distribution (Whalen, 2004). The largest clusters may be identified within 0.25 m^2 and 1 m^2 plots, whereas the smallest ones were found on 100 m^2 plots.

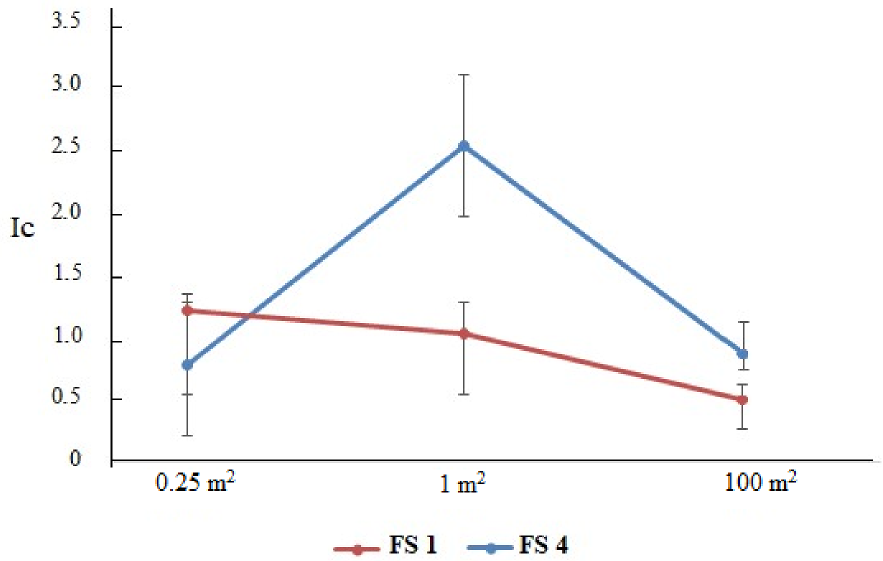

Figure 6. Casey index values for the endogeic species group distribution

There are few studies of the horizontal spatial distribution of earthworms in world literature (Pauli et al., 2010; Gutierrez-Lopez et al., 2010; Jimenez et al., 2014) and the available data show that the groups' distribution is usually unstable, season-dependent and is very often determined by the level of soil moisture and the distribution of trophic resources (Pauli et al., 2010). In our conditions, in the studied forest types, the distribution was evaluated on levelled sites with a uniform litter horizon and evenly moistened soil, so this distribution pattern can probably be explained by the peculiarities of the habitat and travelling of functional groups. Epi-endogeic species feed in the litter horizon and travel over the soil surface more actively, so their distribution type tends more to "covering" or regular distribution without aggregation; endogeic species are more dependent on the mineral horizons of the soil, their migration over large areas is limited, individual samples often containing a mature individual and several juvenile earthworms of different sizes (and age) who live together with mature earthworms and are probably unable to travel for long distances over a long period.

5. Conclusions

One of important criteria for the assessment of earthworm population is the functional diversity of the heterogeneous composition of the functional group of these saprophages. The most complete set of functional groups of earthworms was only found in two valley forests amongst the studied polydominant forests: Kedrovaya Pad Reserve and in the valley of the Anikin River (Ussuri Reserve). These forests are home to epigeic, epi-endogeic, endogeic and anecic species. Epigeic and endogeic species were not found in hillside forests of the Ussuri Reserve (Turov Hill, Grabovaya Hill).

No endogeic or anecic species were found in the valley section of the Komsomolsky Reserve (Gorin river valley), despite a detailed survey of different habitats (dead wood, micro-depressions etc.), which is a sign of serious disturbances of these ecosystems that occurred in the past. The main reasons are most probably associated with considerable anthropogenic impact on these forests and their poorer preservation as compared to other studied territories, because, in general, the floral diversity of the main forest-forming species, mixed litter fall, the intensity of soil horizons, good moisture (including in summer seasons) and the presence of dead wood, form potentially favourable habitats for different groups of earthworms.

Horizontal spatial distribution was analysed for the dominating groups of earthworms in terms of biomass and occurrence, i.e. epi-endogeic and endogeic. Plots of different sizes have shown the "covering" type of distribution for the epi-endogeic species, i.e. these species do not show a tendency to form aggregations in homogeneous conditions, but are spread evenly. On the contrary, the endogeic species have shown the "spotty" type of distribution, i.e. these species have a tendency to form aggregations.

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