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The Humus Index: A Promising Tool for Environmental Monitoring

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Abstract—The European morpho-functional classification of humus forms, based on the detailed description of the morphology of organogenic soil horizons, has been applied to the assessment of soil biological properties in the zone of impact from a copper smelter in the southern taiga of the Middle Urals. It has been shown that, as the distance from the polluter decreases, zoogenic mull-type humus forms are replaced by nonzoogenic mor-type forms. The shift in the spectrum of humus forms along the pollution gradient is closely connected with increase in the thickness (stock) of forest litter and reduction in the abundance of large soil saprophages. The high information value and low labor intensity of measurements, compared to other methods, allow us to recommend the humus index (the ordinal number of a humus form in their ordered total list) as a tool for environmental monitoring and assessment.

Keywords: organic matter decomposition, humus forms, soil, forest litter, soil fauna, earthworms, industrial pollution, heavy metals, copper smelter, the Middle Urals

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The concept of three humus types—mull, moder, and mor—dates from the studies by P.E. Müller (the late 19th century), who distinguished them by the morphology of organogenic horizons reflecting the activity of different groups of soil biota. In Russia, classification efforts have been focused on forest litters, which are only part of the forest humus system. The resulting classifications are based on different criteria, e.g., morphological (Sapozhnikov, 1984) or morphogenetic (Bogatyrev et al., 2004), but the scope of their application is limited because of insufficient operationality of diagnostic characters and the absence of a unified general scheme. It should be noted that the term *humus* in the Russian special literature is generally used in a relatively narrow sense, referring to the complex of corresponding organic substances analyzed by chemical methods. Morphological humus types comprising both humus substances themselves and plant remains at different stages of decomposition are considered less frequently (Chertov et al., 2007).

The diagnosis of humus types has long remained poorly formalized, with different national research schools disagreeing on terminology and classification principles. The old idea gained new impetus with the development of European morpho-functional classification of humus forms (Zanella et al., 2011a) based on a detailed description of the morphology of organogenic soil horizons. The classification system has two levels: at the first, humus forms are classified with respect to parameters of soil hydromorphism; at the second, to parameters characterizing their biological activity.

The basic humus types in the series mull → moder → mor are arranged in order of decrease in the activity of soil invertebrates in transformation of plant remains, the average rate of litter decomposition, and the stock of nutrients in the soil; the zone of predominant carbon accumulation in this series shifts from organomineral soil horizons to the litter. The main role in the formation of mull-type humus is played by endogeic and epigeic earthworms; of moder-type humus, by epigeic earthworms, enchytraeids, microarthropods, and fungi; and of mor-type humus, by soil fungi, without the involvement of large saprophages. The humus forms can be diagnosed by the fragmentation pattern of plant debris, changes in its color, the presence of invertebrate droppings, their size and shape, structuring of organogenic horizons, and other characteristics.

The humus index has been proposed for the practical use of the above classification. This index is the ordinal number of a given humus form in the ordered list of these forms and allows the descriptive (qualitative) information about them forms to be converted into a quantitative scale (Ponge and Chevalier, 2006). Studies on forest recovery after cutting have shown that the humus index is indicative of soil morphological properties (the depth and color of the humus horizon), chemical properties (acidity, exchangeable bases, organic carbon, total nitrogen), and also the productivity and diversity of vegetation (Ponge et al., 2002; Ponge, 2003; Ponge and Chevalier, 2006).

Therefore, it has been proposed to use this index for relatively rapid assessment of the state of ecosystems.

Pollution by emissions from the metal industry often has dramatic consequences for the soil and its biota, and it is likely that the humus index also changes strongly and consistently under such conditions. If so, this index can be an effective tool for ecological monitoring.

It is well known that heavy metal pollution and/or acid precipitation retard the organic matter decomposition (Freedman and Hutchinson, 1980; Vorobeichik, 1991; Vorobeichik and Pishchulin, 2011), with consequent increase in the thickness of forest litter (Strojan, 1978; Coughtrey et al., 1979; Vorobeichik, 1995). However, information on the change of humus forms under pollution is fragmentary and contradictory: some authors have reported that no change in humus forms take place (Belotti and Babel, 1993), even after the disappearance of earthworms (Dijkstra, 1998), while others have observed such changes (Gillet and Ponge, 2002; Filzek et al., 2004). Thus, there is the need to accumulate more data on the effect of pollution on humus forms.

The humus index can be effectively tested and "calibrated" in an impact region with a distinct gradient of pollution from a point polluter (Vorobeichik, and Kozlov, 2012). In particular, this concerns the territory around the Middle Ural Copper Smelter (MUCS), where pollution is very strong (heavy metal concentrations exceed the background level by an order of magnitude, the soil is acidified by one pH unit), and reactions of soil biota are highly contrasting, with several key groups of organisms disappearing as the pollution source is approached (Table 2). In addition, ample information is available on the responses to pollution observed in the soil (Kaigorodova and Vorobeichik, 1996; Meshcheryakov and Prokopovich, 2003), forest litter (Vorobeichik, 1995), soil fauna (Vorobeichik et al., 2007, 2012; Kuznetsova, 2009), and microflora (Vorobeichik, 1991; Vorobeichik and Pishchulin, 2011; Smorkalov and Vorobeichik, 2016; Mikryukov et al., 2015).

The purpose of this study was to analyze the change of humus forms in the pollution gradient near the MUCS in order to test the hypothesis that humus forms of mull type are converted into mor type as the polluter is approached. Prospects are also discussed for using the humus index as an integrated indicator of the activity of soil biota in polluted areas, in comparison with other indicators. Although the European classification has successfully passed testing in a wide range of environmental conditions characteristic of Europe (Zanella et al., 2011a), special tests are needed to confirm its validity in every new region, but, to our knowledge, the humus index has not been previously used in Russia.

MATERIAL AND METHODS

The region of impact from the MUCS (the city of Revda, 50 km west of Yekaterinburg) lies in the southern taiga subzone. Until recently, the MUCS was one of the largest sources of airborne emissions in Russia. Their total amount in the 1980s reached 150–225 × 10^3 t/year, with SO_2 and heavy metals (Cu, Pb, Zn, Cd, Hg, etc.) being the main pollutants. Although emissions have since been radically reduced, the vegetation near the plant is still suppressed (Vorobeichik et al., 2014), and the same is true of the soil fauna (Vorobeichik and Nesterkova, 2015).

Studies were performed in spruce–fir forests growing west of the MUCS at distances of 1 and 2 km (impact zone), 4 and 7 km (buffer zone), and 30 km (background zone), in areas with silt loam soddy podzolic soils and podzolized brown soils. Soil pits to a depth of about 20 cm were made at each distance from the polluter, in 3–8 replicates at intervals of about 100–200 m (a total of 28). Pits were distributed in a random pattern but avoiding tree-base areas and sites with pedoturbation.

Diagnosis of humus forms was made in the field according to the European Reference Base (Zanella et al., 2011b). The main diagnostic characters were as follows: (1) stratification into horizons with respect to the proportion of recognizable plant remains (organic horizons OL, OF, and OH forming the forest litter) or the total content of organic matter (marks the lower boundary of the litter); (2) type of litter transformation (zoogenic or nonzoogenic); (3) the size of the transition zone between the litter and organo-mineral horizon); (4) the structure of organo-mineral horizons (with regard to the size of granular and subangular blocky structures, aggregated soil horizons were classified as biomacrostructured, biomesostructured, or biomicrostructured; nonaggregated horizons were classified as loose or massive nonzoogenic). The indices assigned to the humus forms were as follows: Eumull – 1, Mesomull – 2, Oligomull – 3, Dysmull – 4, Hemimoder – 5, Eumoder – 6, Dysmoder – 7, Hemimor – 8, Humimor – 9, Eumor – 10, Hydromor (a hydromorphic analog of Eumor) – 10.

Comparisons between the pollution zones were made by Kruskal-Wallis test. The effect size (the difference between the impact and background zone) was estimated by calculating Cliff's Delta. All values of this measure are in the closed interval [–1, +1] and characterize the degree of overlap between two frequency distributions: +1 or –1 indicates the absence of overlap, and 0, complete overlap. For comparisons with other parameters (based on data from original publications), the effect size initially calculated as Cohen's *d* was converted into Cliff's Delta (Rogmann, 2013).

RESULTS AND DISCUSSION

Humus forms change from mull type (Mesomull) to mor type (Eumor) along the pollution gradient; i.e., the entire spectrum of variants in the series of soil biological activity is represented there, except for the most

Table 1. Forms of humus in forest soils from zones with different pollution levels

Distance from polluter, km	Sequence of soil horizons (depth, cm)		O/A, mm	Humus form (index)
	organic	organo-mineral		
Background zone				
30	OL(1)	meA(9)	3–5	Mesomull (2)
30	OL(1–2)/OFzo(disc)	meA(6)	<3	Oligomull (3)
30	OL(2)/OFzo(disc)	meA(8)	<3	Oligomull (3)
30	OL(0.5)/OFzo(1.5)	meA(8)	3–5	Dysmull (4)
30	OL(0.5–1)/OH(1–2)	meA(8)	>5	Hemimoder (5)
30	OL(2)/OH(2)	meA(6–8)	>5	Hemimoder (5)
Buffer zone				
7	OL(0.5)/OFzo(1)	miA(1.5)/meA(6)	3–5	Dysmull (4)
7	OL(0.5)/OFzo(1)/OH(1.5)	miA(1)/meA(8)	3–5	Dysmoder (7)
7	OL(1)/**OFnzo(disc)**/OFzo(1)/OH(disc–2)	miA(6–8)	>5	Dysmoder (7)
7	OL(1)/OFnzo(1)/OFzo(1)	miA(1)/**meA**(6)	3–5	Hemimor (8)
7	OL(1)/OFnzo(2)/OFzo(disc)	miA(1)/**meA**(8)	<3	Humimor (9)
4	OL(0.5–1)/OFnzo(4)/OFzo(disc)	**meA**(6) + msA	<3	Humimor (9)
4	OL(2)/OFnzo(2)/OFzo(1)	**meA**(6) + msA	<3	Humimor (9)
4	OL(2)/OFnzo(2)/OFzo(2–disc)	**meA**(3) + msA	<3	Humimor (9)
4	OL(1)/OFnzo(4)/OFzo(1)	msA(5) + meA	<3	Humimor (9)
4	OL(1)/OFnzo(2)/OFzo(1)/OH(1)	**meA**(6**)** + msA	<3	Humimor (9)
4	OL(1)/OFnzo(2.5–3)/OH(0.5–1)	**meA**(6) + miA	**>5**	Humimor (9)
4	OL(2)/OFnzo(2)/OFzo(1)/OHdisc	**meA(7)**	<3	Humimor (9)
4	OL(1)/OFnzo(2)/OFzo(1)	**meA**(7)	<3	Humimor (9)
Impact zone				
2	OL(4)/OFnzo(0.5–2)/OH(0.5)	**meA(5) +** msAg	<3	Humimor (9)
2	OL(0.5)/OFnzo(2.5)/OFzo(disc)/OH(1)	**meA(6)**	<3	Humimor (9)
2	[OL(7)]	miA(6) + msA	<3	Eumor (10)
2	[OL(13)]/[OFnzo(1)]	**meA**(disc**)/**msAg(6)	<3	Eumor (10)
2	OL(1)/OFnzo(1)/OHg(1)	msAg(6)	<3	Eumor (10)
2	OL(1)/OFnzo(3)	**meAg(2)** + msA	<3	Eumor (10)
1	OFnzo(2)	msAg(4)	<3	Eumor (10)
1	OL(1)/OFnzo(3.5)/OHg(1)	msAg(3) + miA	**3–5**	Hydromor (10)
1	OL(0.5)/OFnzo(2.5)/OHg(2)	msAg(8) + miA	<3	Hydromor (10)

Designations: (O/A) the size of transition zone between (O) organic and (A) organo-mineral horizons; (zo) signs of zoogenic transformation of plant remains, (nzo) no such signs; (disc) discontinuous layer, (me) biomesostructured layer, (mi) biomicrostructured layer, (ms) massive layer, [ ] layer buried under moss carpet; (+) combination of different structures within the same horizon (the structure occupying greater volume is in the first place); (g) signs of hydromorphism (in horizon A, gleying). Boldface indicates characteristics that do not correspond to the specified form of humus.

zoogenic Eumull form (Table 1). The spectra of forms found in the impact and background zones do not overlap, differences in the indices between them are statistically significant (H (2, n = 28) = 21.3, p < 0.0001).

Humus forms prevailing in the background zone are of mull type: they are characterized rapid litter decomposition with the involvement of large saprophages and input of partly humified organic matter into soil aggregates of the organomineral horizon, which has a distinct zoogenic structure. The Hemimoder form (close to the mull type) occurs in better moistened locations. Humus forms in the buffer zone at 7 km from the MUCS are highly diverse, ranging from zoogenic mull type to low-active mor-type forms. Mull- and moder-type forms disappear as the polluter is approached. At a distance of 4 km, only the mor-type Humimor form remains, where signs of zoogenic transformation can be found only in the lower part of the litter.

Humus forms in the impact zone are also of mor type, with the extreme Eumor variant being prevalent. It is characterized by the accumulation of slightly

Table 2. Parameters of soil biota and some properties of soils under spruce–fir forests in zones with different pollution levels

Parameter (year)	Zone (distance from polluter, km)				Effect size				Information source
	background (20–30)	buffer (6–7)	buffer (4–5)	impact (1–3)	*N*	*D*	CI_L	CI_U	
Litter Cu concentration, μg/g (2004)	44.6	561.4	1153.9	2808.6	4/4	1.00	0.82	1.00	Vorobeichik et al., 2012
Litter pH_{water} (2004)	5.6	5.2	4.9	4.6	4/4	–1.00	–1.00	–0.78	Vorobeichik et al., 2012
Humus index (2015)	3	7	9	10	6/9	1.00	0.12	1.00	This study
Abundance, ind./m^2:									
earthworms (2004)	261	212	39	0	5/5	–0.96	–1.00	–0.45	Vorobeichik et al., 2007
enchytraeids (2004)	168	125	30	0	5/5	–0.99	–1.00	–0.64	Vorobeichik et al., 2007
springtails (2002–2004)	35 333	41177	59624	12376	9/9	–0.94	–1.00	–0.63	Kuznetsova, 2009
Trophic activity of saprophages, %/15 days (bait-lamina test) (2006)	42.5	–	11.2	6.7	15/15	–1.00	–1.00	–0.99	Vorobeichik et al., 2007
Litter thickness, cm (1990)	2.0	2.9	5.3	5.2	5/12	1.00	0.98	1.00	Vorobeichik, 1995
Litter stock, kg/m^2 (2003)	1.4	–	3.6	7.2	10/10	1.00	0.98	1.00	Vorobeichik and Pishchulin, 2009
Cellulose decomposition rate, %/day (2005)	0.53	–	0.37	0.25	15/15	–0.83	–0.96	–0.54	Vorobeichik and Pishchulin, 2011
Litter specific respiration rate, mg CO_2/g per hour (2011–2013)	0.20	0.10	0.14	0.05	9/9	–0.90	–0.99	–0.52	Smorkalov and Vorobeichik, 2016

Values of the humus index are medians (for the background zone, the left median); for other parameters, arithmetic means are shown; (–) no data; *N* is the number of replicates (test plots) in the background/impact zones; *D* is Cliff's delta; CI_L and CI_U are the lower and upper limits of 95% confidence interval for *D*.

decomposed plant remains in the absence of their zoogenic transformation and any signs of zoogenic structure in the organo-mineral horizon. Moreover, there also occur humus hydromorphs (Hydromor) characteristic of overmoistened soils, which could not be expected in the area because of its topographic features. In other words, differences between the impact and buffer zones are so great that they manifest themselves even at the first level of classification based on the signs of hydromorphism. Probable causes of disturbances in hydrological regime that activated soil gleying have been discussed previously (Kaigorodova and Vorobeichik, 1996).

Although the transition from one humus form to another implies the replacement of the entire complex of decomposers, the key role in the differentiation of forms is played by large saprophages. An abrupt drop in the abundance of earthworms and enchytraeids at 4 km from the polluter (Vorobeichik et al., 2007, 2012) coincides with the disappearance of mull and moder types from this zone, and elimination of these animals in the impact zone, with peak values of the humus index, which indicate that soil biological activity is extremely low (Table 2). The increase in its values at closer distances from the polluter is concurrent with increase in the thickness and stock of forest litter and decrease in the trophic activity of soil saprophages and functional parameters of soil microflora (cellulose decomposition rate and specific respiratory activity of the litter). Thus, it may be concluded that changes in the humus index and in other parameters characterizing the saprotrophic complex of soil biota are closely correlated with each other.

Several cases of incongruity between soil characters in contiguous horizons were revealed in the buffer and impact zones (at 4 and 2 km from the polluter) (Table 2). In particular, the structure of organic horizons was indicative of the Humimor form, while the size of soil aggregates in the organo-mineral horizon characterized it as a biomesostructured variant, which is not typical of the mor type. In such cases, diagnosis was based mainly on the characters of organic horizons and the pattern of transition between the litter and organomineral horizon. In our opinion, identification of diagnostic characters of different humus forms in the same profile may be explained by differences in the timing of formation and obliteration of their properties after change in ambient conditions. The litter is relatively rapidly transformed under pollution, whereas soil aggregates in the organo-mineral horizon are relatively stable and retain their shape for a long time, attesting to the former activity of the soil fauna. Soil transformation in the impact zone is more profound: the organo-mineral horizon becomes unstructured, which is in complete correspondence with the mor type.

As estimated from effect size, the information value of the humus index is not inferior, but sometimes even superior to that of other methods for assessing soil biological activity (see Table 2; in all cases confidence interval for Cliff's Delta doesn't include 0)). Compared to these methods, the approach based on diagnosis of humus forms is more cost-effective, since it can be used without expensive special equipment (unlike measurements of soil respiration) and expendable materials (unlike measurements of decomposition rates of trophic activity of saprophages). The required labor input (no more than 30–40 min per pit in the field and, when necessary, laboratory measurements of pH and organic carbon) is incomparably lower than that required, e.g., for manually breaking up soil monoliths to estimate the abundance of soil macrofauna. The humus index is "automatically" averaged over time and, hence, is a much more reliable estimator than the abundance of soil invertebrates (estimated instantaneously) or the thickness of forest litter, which is exposed to extraneous influences.

A possible complication is that the humus index is measured on an ordinal scale, but it can be easily overcome by selecting appropriate methods of analysis. Thus, it is the median (rather than arithmetic mean) that should be used to characterize the central tendency; the range (rather than mean deviation), to evaluate variation; the Kendall coefficient (rather than Pearson coefficient), to analyze correlation; etc.

CONCLUSIONS

The classification of humus forms developed for Western Europe is readily applicable to the forest soils of the geographically distant Middle Urals and, hence, can be used on a much wider scale. The results of this study confirm our initial hypothesis: pollution with heavy metals has a strong impact on soil organic matter, displacing the spectrum of humus forms from the zoogenic mull type to the nonzoogenic mor type. This displacement is due primarily to significant decrease in the role of large soil saprophages (in the first place, earthworms) in transformation of plant remains.

The approach based on humus index obviously needs further testing in different situations (in terms of biotope, soil, spatial scale, pollution type, etc.). Nevertheless, its high information value and labor efficiency already allow the humus index to be recommended as a tool for evaluating the status of soil biota under conditions of industrial pollution.

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