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GENESIS AND GEOGRAPHY OF SOILS

Structural and Functional Organization of Litter in the Forests of Mari Zavolzhye

L. G. Bogatyrev[a,]*, Yu. P. Demakov[b,], A. V. Isaev[b,]***, R. N. Sharafutdinov[c,]****, A. I. Benediktova[a,]*****, and F. I. Zemskov[a,]***

[a] *Department of Soil Science, Moscow State University, Moscow, 119991 Russia*
[b] *Bolshaya Kokshaga State Nature Reserve, Yoshkar-Ola, 424038 Russia*
[c] *Naberezhnye Chelny Institute, Kazan Federal University, Naberezhnye Chelny, 423812 Russia*
**e-mail: bogatyrev.l.g@yandex.ru*
***e-mail: YPDemakov@yandex.ru*
****e-mail: avsacha@yandex.ru*
*****e-mail: sharafrn@yandex.ru*
******e-mail: beneanna@yandex.ru*

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Abstract—A detailed study of the vegetative–detrital cover (VDC) of pine ecosystems of the Mari Zavolzhye demonstrated that, depending on its origin, a specific hydrothermal soil regime is formed in each type of forest. It has been established that the VDC has the highest moisture capacity in lichen–mossy pine forests in comparison to lichen–pine forests. For the first time, based on the VDC parameters, a scale has been proposed to estimate the rate of the biological cycle. It is established that the most important indicators are the thickness of the VDC, ash content, and hydrolytic acidity.

Keywords: forest biogeocenoses, ground cover, forest litter variability, forest litter ecology, vegetative–detrital cover, biological cycle

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INTRODUCTION

According to L.O. Karpachevskii, forest litter refers to a specific mesostratum; it is a product of vital activity and a sensitive indicator of the state of the biogeocenosis [4, 16]. It fulfills important ecological functions, determining the hydrothermal regime of soils and regulating the flow of biocenotic and biochemical processes [12]. Removal of the litter leads to drying of soil to a significant depth and a decrease in the content of mobile forms of phosphorus, potassium, and exchangeable bases [8]; artificial turnover accelerates its decay and enhances the development of the assimilation apparatus of trees and their growth rates [17]. Reproduction and productivity of the stand depend on the thickness, structure, and decomposition specificity of the litter [18, 19]; so, it is no accident that one of the major problems of biogeocenology is comprehensive study of its properties and specification of its role in forest ecosystem functioning [5]. According to Fokin [20], elements in the detritus can be directly utilized by living plants.

In recent years, the range of problems in the field of forest pedology has significantly expanded. For example, in terms of theory, the concept of carbon saturation was proposed within the framework of the humus problem [22]. Special studies are devoted to the role of leaf litter in the transformation of organic matter [21]. One line of research includes the traditional study of decomposition processes, e.g., the transformation of the litter and its chemical composition [24], including determination of the decay rate, e.g., in forests of the United States [25]. More sophisticated methods include the use of nitrogen and carbon isotopes to study their cycle in litter and soils [23].

In pine ecosystems with sandy sediments, there are some peculiarities when litter with the classical 01–02–03 structure forms on areas with dead cover. At the same time, the prevailing spatial distribution is characteristic of a litter with the following specifics: litter accumulates between lichen thalli or moss shoots. The concept of organic matter mass concentrated in dead detritus can be based purely on the sequential separation of living plants from fine earth and root residues.

Litter with such a structure pertains to the destructive type and belongs to encrusted groups since in this case, detrital litter is located among the living vegetation cover. Such a litter can be studied in two ways. The first involves its division into appropriate fractions, and the second is based on the study of the vegetative–detrital cover (VDC) as a whole. The latter approach has been substantiated as follows. First, in functional terms, including the impact on the water–air soil regime, this cover acts as an integral whole. Second, as was noted by B.R. Striganov [18], when considering the destruction of plant residues, it is necessary to take into account detritus and living organisms as a unified whole. These arguments form the basis of a methodological approach to studying the VDC parameters in pine biogeocenoses when the entire thickness of the ground cover, including detritus, is analyzed.

MATERIALS AND METHODS

The study was conducted on 45 test plots in stands of different ages and composition growing on sandy soils in different types of forest in the Bolshaya Kokshaga reserve, which adjoins the Starozhilskii forestry and Mariy Chodra national park. On each test plot, plant communities and soils were described in detail based on profiles and trenches, the thickness of the VDC was measured, and samples for standard analyzes were taken. To assess the influence of the VDC on the soil microclimate, five 3 × 3 m sites were established on two permanent test plots in the lichen–pine forest and lichen–mossy pine forest in the reserve by clearing the surface of mosses, lichens, and litter to the mineral horizon. At each of these sites, three times per season, the soil temperature was measured at different depths with an electronic thermometer and samples were taken to assess moisture by weighing. Similar measurements were made near sites with undisturbed ground cover. Due to the unity of vegetation (lichens and mosses) and the detritus concentrated between them, analysis was carried out for the entire horizon of the VDC without dividing it into detritus and living parts of mosses or lichens. Mobile phosphorus compounds were determined by the Kirsanov's method modified by the Central Institute of Agrochemical Maintenance of Agriculture (GOST 26207) in an extract of 0.2 mol/dm^3 HCl; exchangeable Ca and Mg were determined in an extract of 1 mol/dm^3 NaCl. Experimental digital material was processed by standard mathematical statistics methods using the Statistica-6 program.

RESULTS AND DISCUSSION

One of the main VDC parameters is its thickness [4], which depends on the composition and productivity of the plant community, as well as the rate of litter decomposition. The mean value of this parameter in forest biogeocenoses on sandy soils within the study area is 3.7 ± 0.3 cm, ranging from 1 to 15 cm with significant variability within each biogeocenosis (V = 22–43%), which depends on a pattern of vegetation development. The relationship between these parameters, as shown earlier [11], is rather close, but specific to each biotope, and is determined by the component composition of this cover, the degree of its development, and the decay rate. The least developed VDC is in linden pine forests, where the litter rapidly decomposes under the influence of various biota, which reaches the greatest abundance here. The litter in such biogeocenoses pertains to the destructive type. A significantly higher accumulation of organic matter in the VDC is observed in cowberry pine forests, where it is represented by dry peat densely penetrated by plant roots. According to [7], this detritus is classified as peaty. Since the soil is moistened, there is a gradual accumulation of detritus up to the formation of its peat types, and the of peat deposits in wetland ecotopes. The age and normality of the stand do not substantially influence the thickness of the VDC, since it depends on all of the previous development of biogeocenoses, as well as the occurrence frequency of forest fires there. The total stock of organic matter concentrated in the VDC varies from 16.2 to 80.7 t/ha; on average, 52% of it is ash, 25% carbon, and 23% nitrogen, oxygen, and hydrogen. The sizes of these parameters are within the range identified by other researchers in pine biogeocenoses but significantly exceed similar indicators for deciduous forests of the Volga Region [16]. As studies have shown, the VDC has high thermal insulation properties that prevent the soil from heating up in summer and promote heat preservation in winter. Thus, in lichen–mossy pine forests, the soil temperature throughout the growing season is lower than in the lichen–pine forest, where the thickness of the cover is almost twice as small. The differences between these biotopes clearly appear up to a depth of 80 cm, reaching 2.5–3.1°C in the upper soil horizons in June–July [10]. At a depth of 20 cm, the differences in temperature are 1.9°C, and at a depth of 40 cm, 1.2°C. Removal of the VDC leads to a significant rise in temperature in the upper soil horizons. With depth, the difference in soil temperature between the experimental variants decreases exponentially: 0.5–1.5°C at a depth of 60–80 cm and remaining constant during June–July.

An assessment of the VDC water capacity showed that its highest value, as well as possible interception of precipitation, is noted in the lichen–mossy pine forest (Table 1), and the lowest, in the cowberry pine forest. At the same time, VDC removal is not a significant factor determining the moisture of the soil profile. Thus, the observations of 2015–2016 showed that for two types of forest (lichen–pine forests and lichen–mossy pine forests), the differences in the value of this indicator of soils with undisturbed and remote VDC are not significant. We can only speak about a weak

Table 1. Water capacity of vegetative–detrital cover in pine forests of reserve and its possible interception of precipitation

Biotope	Stock, t/ha	Water capacity, %	Possible interception of precipitation	
			t/ha	mm
Lichen–pine forest	45.8 ± 5.2	424 ± 20	194.1 ± 30.5	19.4 ± 3.0
Lichen–mossy pine forest	50.1 ± 2.6	445 ± 20	222.9 ± 27.9	22.3 ± 2.8
Cowberry pine forest	80.7 ± 7.8	229 ± 24	184.8 ± 31.1	18.5 ± 3.1

Table 2. Dynamics of water stock in upper 80 cm soil horizon for different ecotopes

Ecotope	Water stock in different terms (above line) and its change (under line), t/ha				
	June 16, 2015	Sept. 23, 2015	May 12, 2016	July 15, 2016	Sept. 14, 2016
Lichen–pine forest	349.8	449.6	453.0	314.7	449.6
		99.8	3.4	–138.3	134.9
Lichen–mossy pine forest	351.5	487.5	487.2	312.7	487.5
		136.0	–0.3	–174.5	174.8

tendency of increased moisture in the upper horizons of the lichen–mossy pine forest (4.7%) compared with the lichen–pine forest (3.7%). For the compared soils of pine forests, it is common to have a regular decrease in humidity down the profile and a tendency to its increase in autumn. Note that the total moisture stock and the nature of its changes depend both on the season and on the amount of rainfall (Table 2).

Hence, the role of the VDC in pine biogeocenoses on sandy soils is far from unambiguous. On the one hand, it hinders the entry of precipitation into the soil and causes it to evaporate during vital activity; on the other hand, it contributes to the preservation of moisture during hot periods. The thickness and structure of the VDC indirectly reflect the characteristics of the biological cycle in forest ecosystems, determines the rate of forest renewal, and the fire hazard of stands [18]. The study has shown that an increase in the fraction of moss in the VDC compared to lichen leads to increased acidity; this difference remains the same within the entire soil profile (Fig. 1) and negatively affects the development of soil biota, fermentation activity, mobility of chemical elements, and their accessibility to plants [3, 15].

Other VDC indicators carry important information about the state of forest ecosystems and the behavior of biological cycles, and the content of exchangeable magnesium is the one with the highest variability (Table 3). The values of hydrolytic acidity, exchangeable calcium, total exchangeable bases, calcium/magnesium ratio, and mobile potassium/phosphorus ratio vary to a lesser degree. The values of active and exchangeable acidity, as well as their ratio, change least of all.

The coefficient of variation of other VDC parameters ranges from 26.5 to 5.3%. Some of the parameters correlate with each other, indicating the same informational importance in analyzing VDC formation processes. For example, a strong positive correlation was found between hygroscopy and ash content in the VDC with a determination coefficient of 0.7, making it possible to assess the latter parameter by the hygroscopy value using the corresponding regression equation. It has also been established that the ash content is inversely proportional to the total VDC stock [11]. This is likely due to the high content of mineral impurities. The values of active, exchangeable and hydrolytic acidity are rather closely related. A positive correlation is observed between the values of exchangeable and active forms with a determination coefficient of 0.9 [6, 15]. The values of other VDC parameters are weakly related, which indicates their independent informative significance. For example, low values of hygroscopy, ash content and exchangeable acidity of

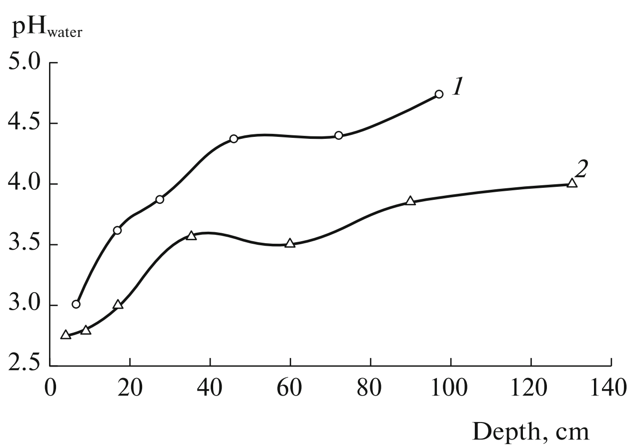

Fig. 1. Changes in soil pH in (*1*) lichen–pine forest and (*2*) lichen–mossy pine forest of reserve based on depth gradient.

Table 3. Statistical indicators of vegetative–detrital cover parameters in pine biogeocenoses (n = 79)

Parameter	$M_x \pm m_x$	min	max	S_x	V	p
Hygroscopic moisture, %	5.9 ± 0.9	1.3	11.5	2.4	40.1	4.8
Ash content, %	52.3 ± 1.9	15.6	88.4	16.6	31.7	3.6
Active acidity (pH_{water})	5.14 ± 0.06	3.66	6.12	0.48	9.4	1.1
Exchangeable acidity (pH_{KCl})	4.24 ± 0.08	3.10	5.85	0.66	15.5	1.9
pH_{water}/pH_{KCl} ratio	1.23 ± 0.02	1.00	1.72	0.13	10.3	1.2
Hydrolytic acidity, mg-equiv./100 g	42.1 ± 3.8	9.6	149.9	33.5	79.5	8.9
Content of exchangeable Ca^{2+}, mg-equiv./100 g	20.8 ± 1.5	6.4	68.0	12.5	60.3	7.2
Content of exchangeable Mg^{2+}, mg-equiv./100 g	13.4 ± 1.8	1.4	86.5	14.9	111.4	13.3
Ca/Mg ratio	2.5 ± 0.2	0.4	9.7	1.7	68.0	8.1
Total Ca^{2+} and Mg^{2+}, mg-equiv./100 g	35.6 ± 2.8	9.4	120.5	24.8	69.7	7.8
Degree of base saturation, %	47.3 ± 1.4	18.4	75.9	12.5	26.5	3.0
P_2O_5 content, mg-equiv./100 g	19.9 ± 1.1	5.5	52.3	9.4	47.5	5.7
K_2O content, mg-equiv./100 g	110.2 ± 7.3	11.8	268.2	60.9	55.3	6.6
K_2O/P_2O_5 ratio	6.6 ± 0.6	2.1	24.9	5.0	75.5	9.0

M_x is arithmetic mean of parameter; m_x is error of mean; min and max are minimum and maximum values respectively; S_x is root-mean-square (standard) deviation of parameter; V is coefficient of variation, %; p is experimental error, %.

Table 4. VDC parameters in different types of pine forest in reserve

Forest type	pH_{KCl}	Hydrolytic acidity, mg-equiv./100 g	Degree of base saturation, %	Ash, %	CaO	MgO	P_2O_5	K_2O
					mg-equiv/100 g of litter			
Lichen	3.30	81.8	21.5	16.3	12.0	10.4	14.5	65.0
Lichen–mossy	3.10	64.4	39.1	14.1	8.8	4.8	15.3	81.6
Cowberry	3.02	81.8	38.9	9.7	19.2	32.8	20.3	75.7
Bilberry	3.47	86.9	25.6	11.9	20.4	23.9	56.6	100.5
Sphagnum	2.68	133.9	16.2	4.3	9.3	14.7	21.5	175.5
Linden	4.15	72.5	49.7	12.2	22.8	8.6	19.4	89.6

the litter correspond to its weak decomposition and inhibition of the biological cycle. This is also borne out by the high values of the hydrolytic acidity of the litter and the total exchangeable bases there, as well as mobile phosphorus and potassium compounds, which are poorly taken up by plants in acidic conditions [3, 15]. In a neutral environment, which corresponds to hydrolytic acidity values of <10 mg-equiv./100 g of soil, the mobility of many elements again decreases, leading to a reduction in the rate of the biological cycle in ecosystems.

Studies have shown that the VDC has specific parameter values in each type of forest due to the characteristics of the ground cover composition and the microclimate (Table 4). The highest values of exchangeable and hydrolytic acidity are observed in sphagnum pine forests, which have a low ash content and the lowest saturation of exchangeable bases. The low acidity in combination with a high degree of base saturation has been established in linden pine forests. The values of the other VDC parameters of these stands hardly differ at all from each other.

Commonly, the rate of the cycle is assessed by the value of the litter coefficient [2]. However, there are a number of indirect attributes possibly characterizing the intensity of this process. For example, in terms of exchangeable acidity of the VDC, its ash content, and the content of mobile phosphorus and potassium, the rate of the biological cycle in almost all types of pine forests can be assessed as low or very low. Only in the

Table 5. Litter parameters in mixed cultures in coulisses under different wood species.

Wood species	pH_{KCl}	Hydrolytic acidity, mg-equiv./100 g	Degree of base saturation, %	Ash, %	CaO	MgO	P_2O_5	K_2O
					mg-equiv./100 g of litter			
Pine	4.25	32.2	39.6	59.3	14.6	5.76	14.3	77.0
Birch	4.43	22.6	45.2	57.2	12.9	5.94	18.0	77.2

Table 6. VDC parameters in different parcels and types if pine forests in reserve.

Forest type	Parcel	Stock, t/ha	pH_{KCl}	Hydrolytic acidity, mg-equiv./100 g	Degree of base saturation, %	Ash, %	CaO	MgO	P_2O_5	K_2O
							mg-equiv./100 g of litter			
LMPF-1	LM	33.8	3.48	133.6	50.3	33.1	34.0	84.6	12.7	218.2
	M–B	33.3	3.34	129.1	30.7	36.2	40.2	24.3	14.3	238.8
LMPF-2	L	17.5	4.30	74.0	49.4	46.2	34.7	49.8	10.3	197.9
	M–B	14.9	3.94	88.4	45.2	46.8	37.4	40.7	48.4	213.8
LMPF-3	L	17.9	3.74	66.9	39.7	53.2	33.7	29.8	8.1	204.1
	M–B	20.3	3.58	78.7	48.7	46.6	41.3	40.2	15.0	234.8
CBF	M–C	59.9	3.52	90.4	37.5	41.2	27.5	32.0	53.3	272.8
	M–B	58.2	3.72	70.9	37.8	41.6	30.1	14.8	23.5	227.2

LMPF is lichen–mossy pine forest; CBF is cowberry birch forest; LM is lichen–mossy parcel; L is lichen parcel; M–B is mossy–bracken parcel; L–C is lichen–cowberry parcel; M–C is mossy–cowberry parcel.

linden pine forest is it intermediate. From the values of VDC hydrolytic acidity, it is possible to conceivably estimate the rate of the cycle as intermediate. In 25-year-old pine cultures, prepared in fresh pinewood conditions, the VDC has higher values of exchangeable and hydrolytic acidity than in analogous cultures of *Betula pendula* (Table 5). The litter parameters, especially its acidity, are dissimilar not only in different forest types, but also in parcels inside each ecotope (Table 6). The available material, as well as analysis of literature sources [9, 16], allowed to group the VDC parameter values into gradations and suggest a scale to assess the rate of the biological cycle in forest ecosystems of the Middle Volga Region (Table 7).

Thus, the obtained materials attest the close relationship between the VDC properties and the stand, the productivity and composition of which depend on the type of forest growth conditions determined by soil trophicity and moisture. The VDC parameters, depending on the temperature and humidity of the environment, change cyclically due to seasonal and interannual climate dynamics. The parameters deter-

Table 7. Assessment scale of biological cycle rate in forest ecosystems by values of physicochemical parameters of VDC

Parameter	Very low	Low	Intermediate	High	Very high
Thickness, cm	>15	8–15	3–8	1–3	<1
Stock, t/ha	>90	45–90	15–45	5–15	<5
Hygroscopic moisture, %	<1.5	1.5–4.5	4.5–7.5	7.5–10.5	>10.5
pH_{KCl}	<3.5	3.5–4.0	4.0–4.5	4.5–5.0	>5.0
Hydrolytic acidity, mg-equiv./100 g	>120	120–90	90–60	60–30	<30
Total exchangeable bases, mg-equiv./100 g	>100	100–80	80–50	50–20	<20
P_2O_5 content, mg-equiv./100 g	>70	70–50	50–30	30–10	<10
K_2O content, mg-equiv./100 g	>180	180–130	130–80	80–30	<30

mined by biota have a clear relationship with the dynamics of their activity and developmental cycles. Plant residues, differing in chemical element content, produce a certain acidity in the VDC in particular moisture conditions, which affects chemical and microbiological processes. An important role here is played by the temperature of the subsurface environment [1, 10, 12–14], an increase in which leads to intensification of dead organic matter oxidation, the acceleration of water movement in the soil, and an increase in the concentration of soluble salts. All of this is reflected in the rate of the biological cycle in ecosystems and the properties of the VDC, which is distinctly associated with the types of forest growth conditions.

CONCLUSIONS

The litters of pine forests on sandy soils pertain to the encrusted group, since this is a well-formed lichen or moss–lichen cover. According to the classification, such litters pertain to the destructive or enzymatic type. This combination of a hardly separable mixture of dead organic matter, mineral particles, and living moss shoots, lichen thalli, and plant roots is called the vegetative–detritus cover (VDC). In each type of forest, it has its own parameters stemming from the characteristics of the ground cover composition, vegetation, and microclimate. The highest values of exchangeable and hydrolytic acidity are observed in the VDC of sphagnum pine forests with a typical low ash content and the lowest saturation of exchangeable bases. The lowest acidity and the highest saturation of bases observed for the VDC of linden pine forests. According to the values of other parameters, the VDC of various stands is differs quite weakly. The VDC parameters, especially its acidity, change not only for different types of forests, but also in different parcels inside one ecotope.

Thus, the most informative indicators of the state of the VDC in pine biogeocenoses on sandy soils that reflect the rate of the biological cycle in forest ecosystems are its thickness, ash content, and hydrolytic acidity. Other indicators yield supplemental information.

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