ISSN 1064-2293, Eurasian Soil Science, 2023, Vol. 56, No. 10, pp. 1407–1419. © The Author(s), 2023. This article is an open access publication.
Russian Text © The Author(s), 2023, published in Pochvovedenie, 2023, No. 10, pp. 1244–1258.

SOIL CHEMISTRY

Seasonal Activity of Soil Peroxidase in Drained Swamp Pine Forests of Western Siberia: Systemic-Ecological Analysis

T. T. Efremova[a, *], **S. P. Efremov**[a], **and A. F. Avrova**[a]

[a] *Sukachev Institute of Forest, Krasnoyarsk Research Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*

**e-mail: efr2@ksc.krasn.ru*

Received March 16, 2023; revised May 30, 2023; accepted May 31, 2023

Abstract—We studied a mesotrophic swamp drained 25 years ago in the northern part of the Ob' River basin (56°23′710″ N, 84°34′043″ E). In peat soils (0–30 cm layer), the weighted average of peroxidase activity for the season (base level) constituted 14.4, 21.9, and 70 units (mL I/g abs. dry soil per 2 min) in the areas subjected to weak, moderate, and intensive drainage, respectively. Second-order parabola is the most adequate function of the main trend of development of seasonal fluctuations in peroxidase activity. Numerical values and signs of the parabolic trend parameters showed that the average peroxidase activity decreased from June to October weekly by 4.4, 7.6 and 15.2 units with weekly average acceleration by 0.31, 0.59 and 1.54 units in the mode of weak, moderate, and intensive drainage, respectively. The seasonal wave of peroxidase activity relative to the baseline level was characterized by a June increase in growth rates with a maximum in the layer of 0–10 cm. In July, there was a decrease in the growth rate according to the depth of reclamation: in the modes of weak and moderate drainage, the process embraced the entire soil profile in August; in case of intensive drainage, in October. The enzyme activity significantly and positively correlated with the soil volumetric water content and pH, negatively correlated with redox potential, and displayed multidirectional relationship with the soil temperature. Environmental conditions acted as mutually replacing parameters when assessing their contribution to the seasonal dynamics of peroxidase, creating the effect of interchangeability of environmental gradients. Canonical determination indices approximated the cumulative impact of the discussed set by 52–74%, depending on the depth of reclamation. Canonical weights showed that the hydrothermal regime was the main factor, regulating the seasonal activity of peroxidase: according to canonical correlations, temperature was the main factor under the conditions of weak drainage, moisture was the main factor under the conditions of intensive drainage, and both moisture and temperature were important factors under the conditions of moderate drainage. The peroxidase activity and the depth of humification in peat soils of different degrees of drainage were interrelated in 87% of cases.

Keywords: drained peat soils, oxidoreductases, seasonal fluctuations trend, seasonality index, redox potential, hydrothermal conditions, pH value, interdependent effect

DOI: 10.1134/S1064229323601452

INTRODUCTION

Efficient and rational use of drained peat mires, together with other aspects, depends on assessment of the processes of organic matter transformation, which largely form the functioning of bogs as integral ecological system. Organic matter transformation proceeds dynamically and depends on several factors, including enzyme activity as catalyst of soil metabolism and regulator of biochemical homeostasis, and indicator of the ecological state of soil [8, 15, 27, 29, 36–38, 40, 42]. Enzymes in complex perform the key ecosystem functions: lignin degradation, humification, carbon mineralization via different biochemical reactions of decomposition and resynthesis, oxidation and reduction of soil organic matter [15, 44, 46]. The reactions are of great interest of biogenesis of specific humus substances with participation of phenol oxidases: polyphenoloxidase and peroxidase. They catalyze oxidation of polyphenols to quinones in the presence of air oxygen or due to oxygen of hydrogen peroxide formed in the result of life activity of biota. Under respective conditions, quinones form primary molecules of humic acids as the result of condensation with amino acids and peptides [14, 15, 19]. Secretion of extracellular enzymes by living plant roots and microorganisms and postmortal input of intracellular enzymes are the main sources of phenol oxidases entering the soil [1].

Bibliography on enzyme activity in peat soils over 1958–2001, including researches in Belarus, Armenia, Latvia, and Ukraine, accounts for about 150 sources [9]. According to literature data, peat soils are characterized by greater enzyme activity than the mineral ones, and it decreases down the profile. The most favorable water-air conditions are formed in the layer 0–20 cm, the zone of maximal development of root systems and active microbiological processes. The relationship was demonstrated between enzyme activity and botanical composition, ash content, and peat decay degree. It was found that enzyme activity in waterlogged soils is maximal in spring and in the first half of summer. The insufficiency of data was noted on the activity of oxidoreductases (except for catalase).

The studies were published in current decade on enzyme processes, including oxidases, within the whole profile of peatbogs [2, 10, 11, 16, 22–24]. The peculiarities of biochemical processes development by stratigraphic columns (100–325 cm) were studied by the authors relative to botanical composition of peat by rather large strokes spaced at intervals of 25–50 cm and more. The conclusion was made that biochemical processes, dynamics of which depends on weather conditions of the year and months of the growing period, run actively in both aerobic and anaerobic zones of peat. Maximal activities of peroxidase and polyphenoloxidase were observed in the lower layers of peat deposits. Performed researches are important first of all for understanding the development of biochemical processes through geological time, and the change of natural conditions in the course of peat genesis.

However, some works of current time, as well as those of the past years, discussed somewhat other direction of enzyme reactions in the profile of peat deposits. Enzyme activity decreased several times from the surface to lower horizons, and the upper layer to the depth of 10 cm was mostly biologically active [18]. It was found that potential activity of enzymes in ombrotrophic bog decreased along the depth of peat deposit and corresponded to the change of microbial biomass from acrotelm to catotelm, but significant seasonal influence on temperature dependence of enzyme was not observed [45]. The results obtained, using linear models, demonstrated that phenol oxidases activity decreased significantly, as the depth of peat deposit increased, and reflected significant variations during the growing period with minimum in spring and maximum in summer and autumn [43]. Limitation of phenol oxidase activity with the depth of the peat deposit promoted the formation of conditions inhibiting decomposition of plant residues and had significant consequences: preservation of archaeological organic materials, absorption of atmospheric CO_2, and elimination of water contamination [39].

Recent processes of soil formation characterize surface horizons of peat deposits, which studies by morphological-genetic approach in seasonal dynamics, permits to assess with an unbiased eye the influence of different anthropogenic factors and climate change recorded. So, it is essential to understand and assess, how environmental factors (temperature, moisture, humus content, pH, biogeneity, cation composition, etc.) affect enzyme activity and regulate synthesis and secretion of soil extracellular enzymes. However, high spatial-temporal variability of enzymes made it more difficult to analyze interactions with the factors of soil environment [27, 44]. From this, the necessity follows of systemic strategy of research, when interaction between enzyme soil activity and environmental factors in their spatial-temporal expression is assessed with the methods of multivariate and multiple factor analysis [27]. Based on the strategy of system-ecological analysis, we substantiated the significance of differentiation over the 20–25-year period of hydrotechnical amelioration of peat soils under bog pine forests according to the degree of drainage. Oxidoreductases made maximal contribution to discrimination (difference) of peat soils together with water-physical and chemical parameters [6, 7].

Seasonal dynamics of activities of phenol oxidases and particularities of their distribution in the profile allow assessing the specificity of organic matter humification relative to soil-environmental factors [33]. This is important for understanding recent soil-formation processes and substantiating the rational use of bogs relative to physico-geographical and environmental conditions. However, the question over how biotic and abiotic factors interact with spatial variations of activity of soil oxidases remains to be undecided [41].

The task of our work is to determine the regularities of peroxidase activity in forest soils with different depth of drainage in their spatial-temporal interaction with environmental conditions. We solved the following tasks, using the methods of mathematical statistics:

a) revealing the main tendency (trend) of peroxidase activity, intensity of seasonal variations (seasonality index), and determination the course of seasonal wave in soils of different degree of drainage;

b) assessing the relationships between peroxidase activity and the conditions of soil environment: level of occurrence of temporary perched water, temperature, moisture, redox potential, soil reaction (pH), group composition of humus acids;

c) determining the dependence on one another effect of ecological parameters and revealing dominant environmental factors, which regulate peroxidase activity in peat soils of different degree of drainage.

OBJECTS AND METHODS

We studied mesotrophic bog (Elovochnoe) of the area 280 ha in the northern part of the Ob' and Tom' rivers interfluve, drained to the moment of study 25 years ago with the network of small shallow channels (geographical coordinates 56°23′710″ N, 84°34′043″ E). The bog is covered by pine forests (*Pinus sylvestris* L.) of natural origin. Mostly distributed types of pine forests were isolated within the area of hydro-reclamation system. These were: sedge-sphagnum, situated in the inter-channel stripe 47 m,

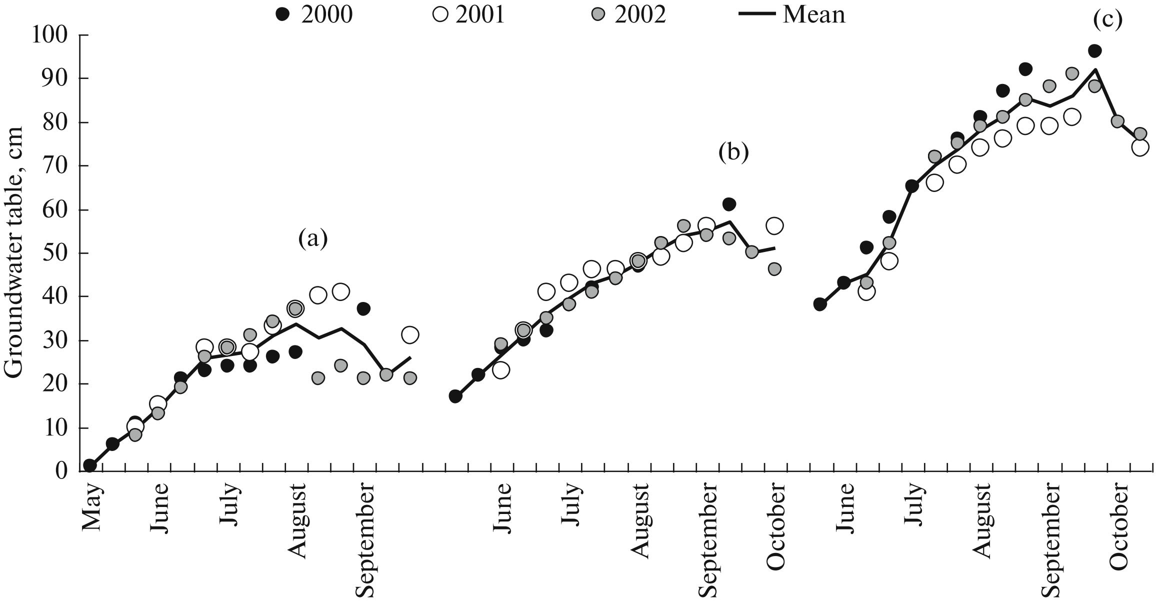

Fig. 1. Groundwater table depths over periods of observation in swampy pine forests with different intensity of drainage. Hereinafter: (a) weak; (b) moderate; and (c) intense drainage.

weakly drained. reed grass in the inter-channel stripe 93 m, moderately drained, herbaceous-bluegrass pine forests at the junction of the main and intercepting channels, intensely drained. Average depth of the table of bog water over three years of study accounted for 23.2 ± 9.9 cm in the case of weak drainage, 41.5 ± 11.2 cm in moderately drained pine forest, and 70.2 ± 16.0 cm in the intensely drained forest. The reliability of discrimination of the objects was proved by the multivariate statistical methods by a set of water-chemical properties of peat soils and enzyme activity [6].

According to classification [4, 17, 25, 26], the studied soils were qualified for reclaimed soils of transitional (mesotrophic) type on thick sedge-sphagnum peat deposit (more than 3 m), underlain by sandy loams. We studied recent morphologically weakly differentiated soils by the horizons 0–5, 5–10, 10–20, and 20–30 cm, which differed by the intensity of penetration of sucking roots and to lesser extent by the color and density of peat layers. Soils were characterized by normal ash content, decreasing with depth: weakly drained, 8.9–5.2%; moderately drained, 10.6–5.8%; and intensely drained, 15.6–6.9%. Bulk density of peat substrate changed in the soil profiles in agreement with the ash content and constituted 0.106–0.010, 0.134–0.115, and 0.146–0.087 g/cm^3, respectively.

Seasonal activity of soil oxidoreductases (peroxidases, catalases, and dehydrogenases) in each of three objects was studied during one year from June to October, interval of observation was 5–8 days (in average one week), i.e., that the study was carried out altogether during 3 years. Soil samples were taken in the layers: 0–5, 5–10, 10–20, and 20–30 cm in freshly dug pit in triplicate, and composite sample was formed of these samples. The samples were placed into a refrigerator, and were taken for analysis next morning. We discuss in this paper the active soil peroxidase of samples with naturally moisture content. The determination was carried out in two weighed portions with iodometric method of K.A. Kozlov and expressed in mL iodine per 1 g of absolutely dry weighed portion over 2 min [28]. Group composition of organic matter of peat soils was determined according to the method [21].

In seasonal dynamics, we studied soil conditions together with enzyme activity in every object during three years. Redox potential and soil reaction (pH) were measured with the help of portable pH meter—millivoltmeter PPM-03M I in the horizons of freshly dug pit, soil temperature with plug-in thermometer, bulk density with cutting ring method. All measurements were carried out in 3–4 replications. Moisture of soil samples was determined with thermostatic-gravimetric method with subsequent recalculation per weight by volume (volumetric water content). The depth of bog water table (temporary perched water) was recorded at each date. The levels of temporary perched water over (May) June–October in the plots of different degree of drainage varied in a predictable manner ambivalently (Fig. 1). The peculiar course of seasonal variations of groundwater level in every object during 3 years was characterized by obvious simultaneousness. This circumstance allowed performing the comparative analysis of seasonal peroxi-

Table 1. Statistical parameters of peroxidase activity in forest peat soils with different drainage intensity over June–October, mL iodine per 1 g of dry weighed portion over 2 min

Statistical parameters	Depth of soil horizons, cm				
	0–5	5–10	10–20	20–30	0–30
Weakly drained					
Weighted mean	12.5	17.7	15.4	11.9	14.4
Median	11.8	13.6	13.2	8.7	12.3
Minimum–maximum	1.9–33.9	4.4–66.2	3.6–50.2	3.5–24.4	3.7–39.7
Variation coefficient, %	60	88	83	60	63
Moderately drained					
Weighted mean	32.2	27.5	16.6	16.4	21.9
Median	27.3	29.6	13.3	18.8	22.7
Minimum–maximum	6.2–92.9	6.3–69.2	3.7–57.5	3.5–48.1	5.7–61.8
Variation coefficient, %	66	60	79	69	59
Intensely drained					
Weighted mean	80.8	73	66.5	59.3	69.9
Median	90	58.9	6.3	56.9	68.9
Minimum–maximum	37.1–140	40.8–312	24.5–214	29.3–133	39–200
Variation coefficient, %	36	80	62	46	48

dase activity on the basis of locations of objects in the area of drainage network.

Statistical analysis of experimental data was carried out according to the manual [31]. Statistical characteristics of distribution series of seasonal peroxidase activity was carried out according the guide [32].

RESULTS AND DISCUSSION

Peroxidase activity in recent (0–30 cm) peat soil of different degree of drainage was characterized by high variability, *Cv* 48–66% (Table 1). Soils with weak hydro- reclamation had minimal activity, 14.4 units (weighted arithmetic mean over the observation period). Peroxidase activity increased 1.5 times in moderately reclaimed soils, and reached 70 units (mL iodine/g of dry weighed portion over 2 min) in intensely reclaimed soils. Peroxidase activity decreased 1.5–2 times down the profile. Maximal activity was observed in the upper 0–10 cm horizons maximally penetrated with roots. The effect of sharp decrease in forest soils of enzyme activity with the depth was also reported in the work [35].

Graphic-analytical schemes of seasonal peroxidase activity presented in Fig. 2, made it more difficult assessing the studied phenomenon. Reliable conclusions were substantiated with the help of regression equation of the trend—time-varying function, which substitutes factual levels of temporal series by theoretical evened out level. Second-order parabolic curve is the most adequate function of seasonal trend of peroxidase activity in the horizons of peat soils. Confidence level of selected trend equation was maximal in 10–20 cm horizon of weakly reclaimed soils ($R^2 = 0.84$) and 20–30 cm horizon of moderately reclaimed soils ($R^2 = 0.86$).

Let us characterize in details the main trend of the studied phenomenon development by the example of the whole profile of recent soils (0–30 cm). Related close distribution of peroxidase activity and time factor manifested themselves in weakly and moderately drained soils: $R^2 = 0.8$ (Figs. 2a and 2b). Seasonal variations of enzyme in the case of intense reclamation as function of time were agreed upon certainly weak, $R^2 = 0.2$ (Fig. 2c). In parabolic function of the trend ($y = b_2x^2 - b_1x + a$), negative sign of parameter $b1$ and positive sigh of parameter $b2$ represent the descend of dressed ranks with acceleration equal to $2b_2$ [32]. On the basis of this interpretation, weekly decrease of peroxidase activity averaged in weakly reclaimed soils 4.4 units with weekly average acceleration 0.31 units. It accounted for 7.6 in moderately reclaimed soils with acceleration 0.59, and accounted for 15.2 with acceleration 1.54 units in the mode of intense reclamation. In actual fact, trend equations reflect only the main trend of the development of peroxidase potential and bear no direct relation to the dynamics of seasonal activity in time [32].

Time (date) in studied period is the clustering factor in the statistical study of seasonal variations. The period of seasonal variations equals to a month in the case of week interval of observations [32]. Hence, time series in increments 5–8 days arranged to summarized average data (weighted mean) by months in every horizon and in soil profile (0–30 cm) in the whole (Table 2). We used relative analytical parameters to obtain more clear and clean-cut characteristics of the studied phenomenon: growth rate (seasonality index) and rate of increment [32]. Calculation of these parameters was based on comparing the levels y_i of temporal series with some comparison base y_t, which was taken as weighted arithmetic mean over the observation period in the layer 0–30 cm of the corresponding soil. Seasonality index: $I_s = y_i/y_t$ 100% characterizes the relative rate of the change of levels in temporal series and demonstrates, what part of time mean it represents. The influence of the main tendency in the development of seasonal variations (trend) is eliminated in individual seasonality indices [32]. Rate of increment (RI) of peroxidase activity was calculated on the basis of growth rate R: RI, % = (R – 100). Rate of increment demonstrates, by what percent the level of particular date of observation is greater of smaller than the basic level: positive value of increment means the increase and negative increment means the decrease.

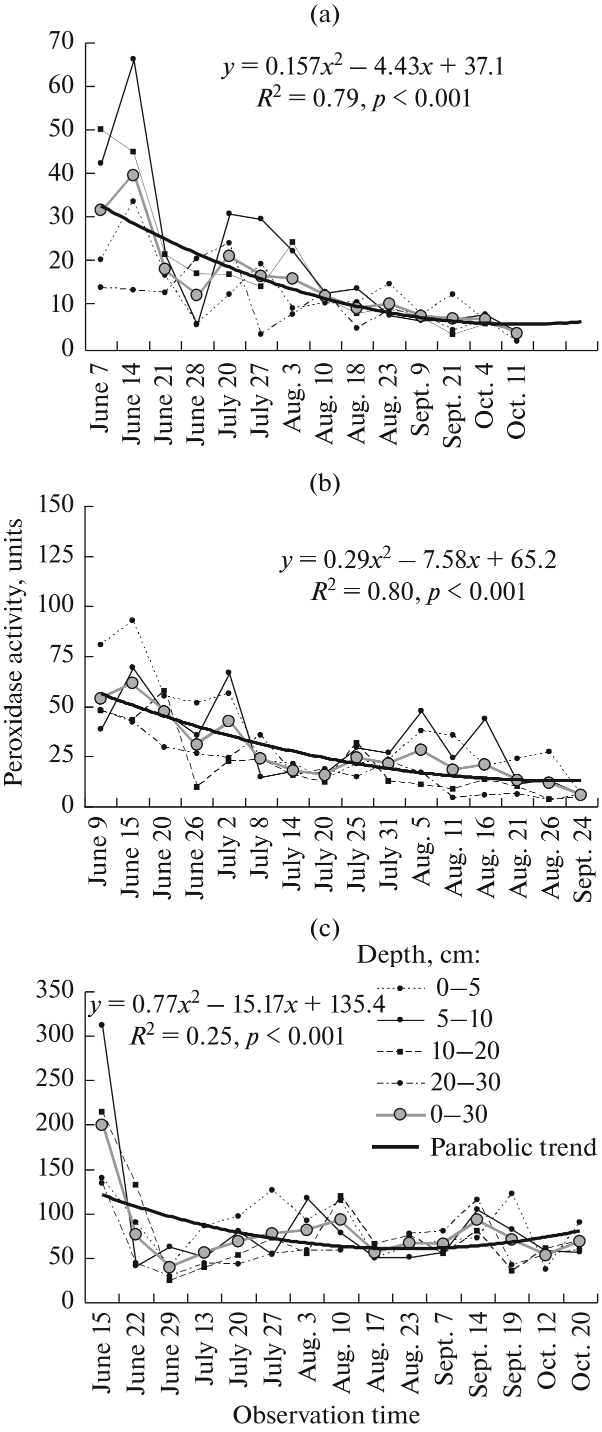

Fig. 2. Dynamics of peroxidase activity (June–October) and the main tendency of seasonal variations in forest peat soils of different intensity of drainage, mL I/g dry soil per 2 min.

Seasonal increment of peroxidase activity is characterized in drained peaty soil (0–30 cm) by June maximum less pronounced in the mode of intense reclamation (Fig. 3). The decrease of increment rate advances in August in the cases of weak and moderate drainage and intensifies in autumn period. Weak decrease of increment under the regime of deep drainage was observed in July and October. The course of seasonal dynamics of peroxidase had some particular features in the horizons of the soil profile. An increment of peroxidase activity in weakly drained soils was observed in June all over the profile with maximum in the layer 5–20 cm (Fig. 3a). Some decrease of the increment rate in the lower analyzed horizon began in July, expanded practically over the whole profile in August, and went down to 56–70% of basic level by October. Similar dynamics of seasonal wave was observed in moderately drained soils (Fig. 3b). However, June maximum of enzyme activity became displaced to the surface 0–5 cm and smoothly decreased approximately two times, as the depth of every horizon increased. The decrease of increment rate in July was recorded in the lower part of soil layer and grew down to 71–78% all over the profile in September. June increment of peroxidase activity in intensely drained soils was the least pronounced and restricted by 0–20 cm with its maximum in 5–10 cm horizon (Fig. 3c). In July, almost all soil layers demonstrated the decrease of increment rate by 11–32%, rising with depth. Weak increase of increment rate 6–26% restarted in August or in September, alternating in the horizons of the soil profile. Increment rate of peroxidase activity decreased everywhere in October, but was characterized by significantly lower intensity: decrease by 6–19%. Seasonal wave of such level can be classified as relatively leveled-off type according to the classification [32]. So, June increment of peroxidase activity with maximum in the layer 0–10 cm was observed in forest peat soils irrespective of the degree of their drainage. The decrease in the increment rate in July corresponded to the depth of drainage reclamation. The less was the soil waterlogged, the closer to the surface was the hori-

Table 2. Grouping by months and growth rate of seasonal activity of peroxidase in the horizons of drained peat soils

Month	0–5 cm		5–10 cm		10–20 cm		20–30 cm		0–30 cm	
	Un.*	*R*	Un.	*R*	Un.	*R*	Un.	*R*	Un.	*R*
Weakly drained										
June	19.4	134	34.0	236	33.6	233	15.4	107	25.6	178
July	16.2	112	30.5	212	15.8	110	14.0	97	19.1	133
August	11.5	80	14.4	100	13.6	94	8.8	61	12.1	84
September	10.4	72	7.0	48	5.5	38	6.5	45	7.3	51
October	4.4	30	6.3	44	5.1	35	5.4	38	5.3	37
Moderately drained										
June	70.1	320	47.7	218	39.4	180	36.5	143	48.4	221
July	26.5	121	28.8	132	19.8	90	21.8	86	24.2	111
August	28.9	132	28.1	128	9.3	42	7.3	29	18.4	84
September	6.2	28	6.3	29	4.8	22	5.5	22	5.7	26
Intensely drained										
June	76.0	109	138.4	198	123.6	177	68.9	99	101.7	146
July	102.9	147	62.0	89	55.0	79	47.5	68	66.9	96
August	80.0	115	74.2	106	78.6	113	64.9	93	74.4	107
September	88.0	126	81.3	116	56.8	81	79.1	113	76.3	109
October	63.5	91	57.6	83	65.4	94	56.6	81	60.8	87

* Un.—unit of measurement, mL iodine per 1 g of dry weighed portion over 2 min, *R*—rate of growth relative to the mean weighted value in the layer 0–30 cm (Table 1) over the period of observation, %.

zon, from which the decrease of enzyme activity began. It was 5–10 cm in intensely drained soils, 10–20 in moderately drained, and 20–30 cm in weakly drained soils.

Formation and dynamics of enzyme potential is environmentally dependent. We assessed the influence of bulk volume of water, which directly participates in many biochemical processes, determines the conditions of enzyme reactions, and determines population density and physiological activity of microorganisms and life activity of sucking roots as the sources of enzyme. It was demonstrated that the upper 10 cm in drained peat soils under pine stands accumulated 87% of absolutely dry matter of roots, which did not exceed 1% in 20–30 cm horizon relative the rhizosphere zone 0–30 cm [3]. The non-spore-forming fluorescent bacteria and mold fungi formed (in the region of our study) the most widespread group of microorganisms in the upper 10 cm of peat in mesotrophic bogs [13]. The number of microbes decreased down the profile, was subjected to seasonal variations, and increased after drainage construction.

Positive correlation between peroxidase activity and moisture content was statistically significantly determined in forest peat soils by ascending arm of parabola of the second order (Fig. 4). The values R^2 suggested, that peroxidase activity was determined in weakly drained soils by 48% by moisture content with the range 45.9–82.2%, by 51% (18.4–59.4%) in moderately drained soils, and by 58% in the range of bulk volume of water 13.1–51.3% in intensely drained soils. As follows from figures, maximum of peroxidase activity was in the range 50–80% of moisture content, and correlation between discussed parameters became negative below 20–25% (critical points were calculated by parabola equations). Approximately the same level of moisture, 60–80%, is presented as maximal for cultivated peat soils of Belarus [34]. The influence of moisture on soil enzyme activity varied in accordance with temperature fluctuations. Maximal peroxidase activity was observed in forest drained soils, when combination of moisture and temperature accounted for 81% and 8.2°C in the case of weak drainage, 56% and 9.5°C under moderate drainage, and 51% and 15.4°C under intense drainage (maximums of parabola arms). Consequently, temperature optimum of peroxidase activity increased, as soil moisture decreased. Similar trend characterized seasonal dynamics of enzyme activity in chernozems of the Cis-Ural region [27, 29].

Soil temperature determined the energy level of enzyme reactions. Peroxidase activity demonstrated significant positive correlation (analogy with parabola) with temperature of peat soils 1.8–15.4°C in the case of intense drainage at the level $R^2 = 0.2$ and weak drainage $R^2 = 0.5$ (Figs. 4a2 and 4c2). The strength of relationship between discussed phenomena increased to $R^2 = 0.7$ and became negative in higher thermal inter-

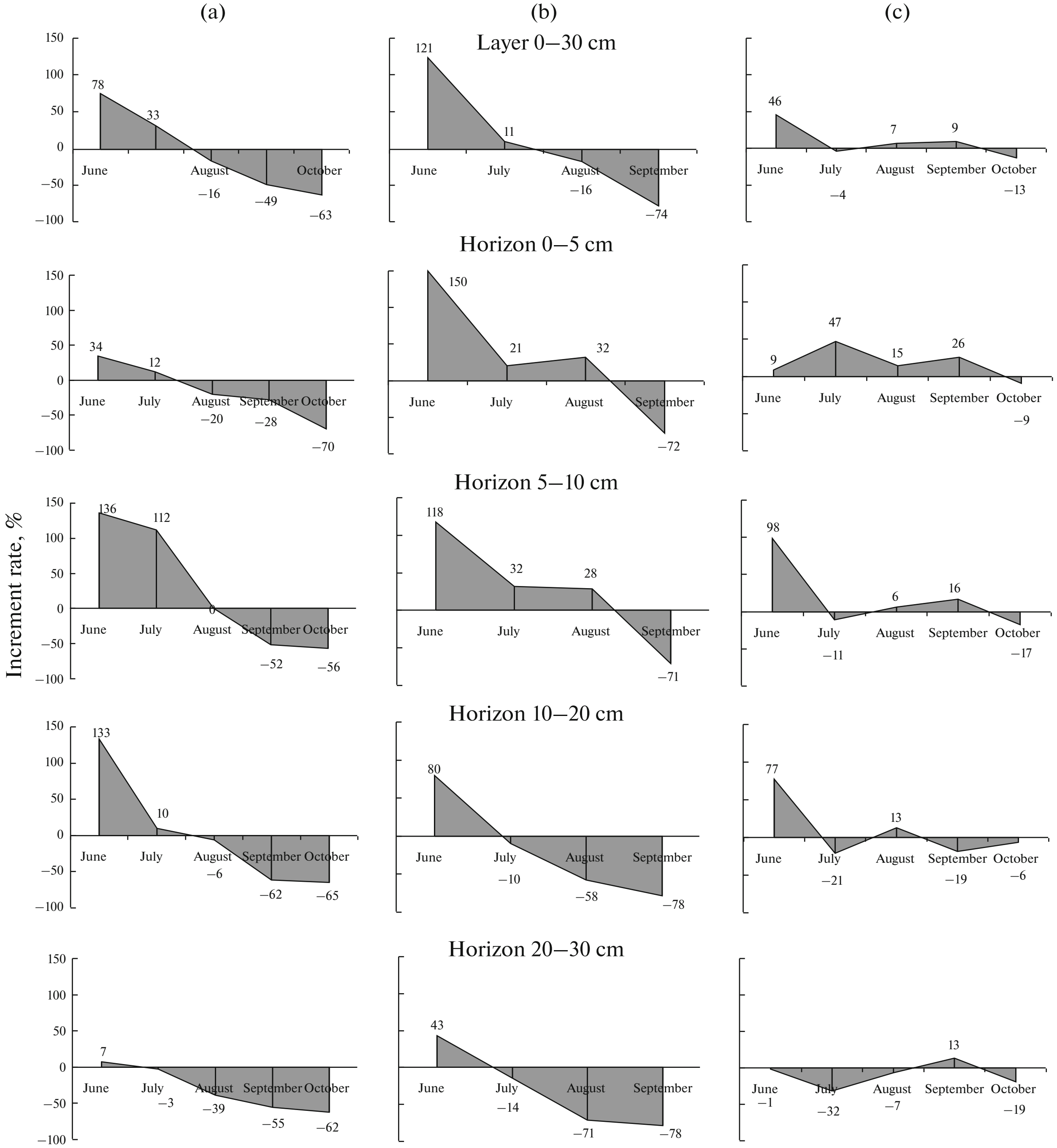

Fig. 3. Rates of increment of seasonal peroxidase activity in drained peat soils, %.

val 8.4–16.8°C of moderately drained soils (Fig. 4b2). We assume the priority influence of redox potential (ROP), which actively responded to the change of environmental situation. In the result of positive correlation between redox potential and temperature $R^2 = 0.61$ (Fig. 5b2), ROP reached in warmer soils the values >600 mV, which characterize according to [12] the development of intense oxidation processes. It is likely that the influence of thermal factors became weaker under such level of oxidative medium, and the significance increased of ROP, adversely affected the peroxidase activity (Fig. 4b3). Increased role of ROP under the regime of moderate drainage is supposed indirectly by maximum canonical correlation coefficient ($r = 0.45$) with discussed totality of soil factors in the following synthetic generalization (Table 3). So, the influence of thermal factor on peroxidase activity in forest peat soils of mesotrophic type was related to

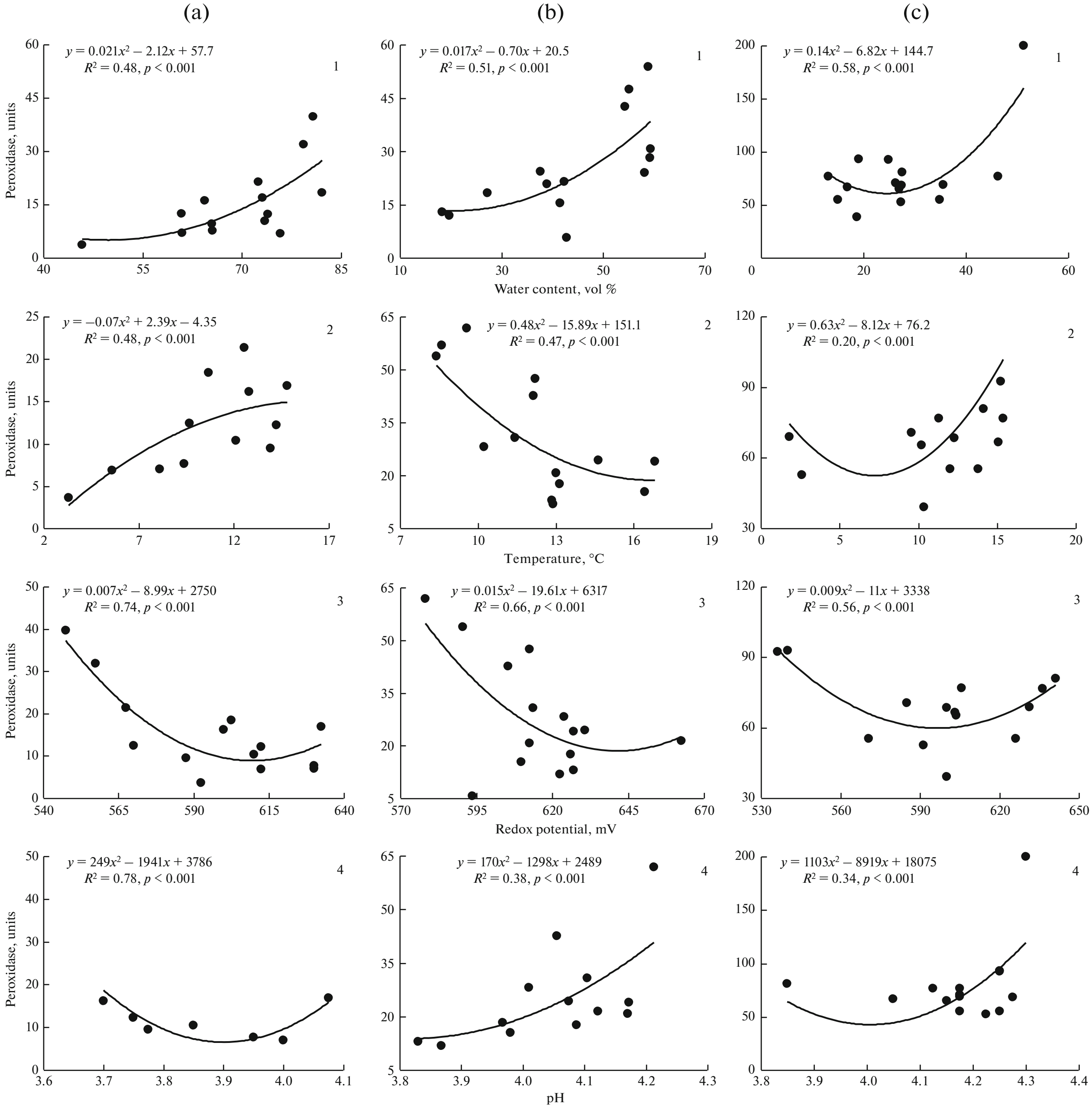

Fig. 4. Regression relationships between peroxidase activity in differently drained peat soils (0–30 cm) and environmental factors: (1) volumetric water content, %; (2) soil temperature, °C; (3) redox potential, mV; and (4) pH.

the depth of drainage reclamation. Peroxidase activity in weakly drained soils demonstrated the trend towards the decrease under soil temperature above 16°C and towards the increase under the conditions of moderate drainage (critical points of cuspidal function). Under the regime of intense drainage, 6°C characterized the extremum, and the increase of soil temperature was accompanied by the increase of peroxidase activity. It can be assumed that not of the temperature dependence of catalytic process activity on the hydrothermal environmental conditions was determined by the form of peroxidase occurrence, in free or bound state, but by the change of amount and/or composition of microflora. For example, sharp decrease of peroxidase activity, when temperature increased from 0.5 to 2.5°C, in drained eutrophic soils of forest-steppe zone of Krasnoyarsk krai correlated with the dynamics of microbiological associations, which can develop under cool media [5].

The profile of recent drained soils over the studied period (June–October) should be classified as the type of redox regime with absolute domination of oxi-

Table 3. Results of canonical analysis of relationship between seasonal peroxidase activity and parameters of soil medium

Parameter	Intensity of peat soils drainage, estimate of canonical variable (radical)					
	weak $R^2 = 0.74$, $\chi^2 = 4.0$, $p = 0.045$, $\lambda = 0.26$		moderate $R^2 = 0.52$, $\chi^2 = 2.9$, $p = 0.054$, $\lambda = 0.48$		intense $R^2 = 0.64$, $\chi^2 = 9.2$, $p = 0.051$, $\lambda = 0.36$	
	canonical weights	factor structure	canonical weights	factor structure	canonical weights	factor structure
Temperature	–1.58	**–0.86**	0.58	**0.80**	–0.67	–0.41
Moisture	0.61	–0.52	–0.52	**–0.81**	–0.83	**–0.74**
pH	0.57	0.16	–0.11	0.08	–0.37	–0.32
ROP	0.12	0.12	0.29	0.45	–0.32	0.04

R^2, canonical index of determination; χ^2, criterion; *p,* confidence level; λ, Wilks criterion: ROP, redox potential.

dation processes according to estimates [12]. The influence of ROP on peroxidase activity under these conditions had a negative trend and was approximated by the parabola of the second order (Fig. 4). Interdependence of parameters in weakly drained soils was high: 74% (within ROP range 547–632 mV). It was medium in intensely and moderately drained soils: 56% (536–641 mV) and 66% (590–662 mV) respectively. Redox maximum reached 540–590 mV with the extremum (point of inflexion) of 600 mV.

Close correlation is known between soil enzyme activity and soil acidity. The pH value determines the ionization rate of reactional groups in substrate and mobility and stability of active center of enzyme. Seasonal activity of peroxidase in forest peat soils and pH value 3.7–4.3 correlated positively by the type of parabola of the second order by 78% in weakly drained soils and by 34 and 38% in intensely and moderately drained soils. Optimum of pH was 4.3. Critical point, below which enzyme activity was inhibited, was pH 3.8. According to literature data, activities of phenol oxidase and peroxidase usually increased in all ecosystems, as soil pH increased [41, 44].

Subsequent synthetic generalization of relationships between enzyme activity and environmental factors is the main prerequisite of system strategy of the study [27]. Canonical analysis was used to assess the interdependent effect and to determine the dominant factors regulating the peroxidase activity of the soil. The method represents the generalization of multivariable correlation as a measure of correlation between one random variable and the totality of other random variables. Canonical indices of determination (R^2) demonstrated that enzyme activity was determined by discussed totality by 74% in weakly drained soil, by 52% in moderately drained, and by 64% in intensely drained soils. According to canonical weights, maximal contribution to the resulting effect was made by hydrothermal factors. Coefficients of factor structure, reflecting the correlation between corresponding variable and radical (weighted sum), are interpreted similar to correlation coefficients: the greater are values, the closer is correlation. Maximal canonical correlation with radical demonstrated temperature in weakly drained soils, moisture in intensely drained, and temperature and moisture in moderately drained soils.

Strong influence of ROP and pH on peroxidase activity, determined with the help of pair regression analysis, substantially decreased or practically was excluded in combination with hydrothermal parameters. Soil properties, as it is known, are closely connected with each other and can be regulated by the same ecological parameters. In this case, hydrothermal regime should be considered as factorial feature, and other characteristics should be regarded as resulting. It was found that redox potential of forest peat soils was negatively agreed upon moisture in the case of intense and weak drainage by 70 and in the case of moderate drainage by 44%, and positively agreed upon temperature by 49–60% with minimum under the conditions of intense drainage. Soil reaction (pH) correlated positively with c bulk volume of water and soil temperature. The closest correlation was found with moisture under the regime of weak drainage by 96% and moderate drainage by 67%, less close correlation was found with temperature by 41–46% (Fig. 5). So, it was found in systemic research of seasonal activity of peroxidase that hydrothermal regime, redox potential, and soil acidity act as duplicated each other parameters. The effect of interchangeability of soil factors was a result of interaction of ecological gradients.

Humus had a direct effect on enzyme activity of soil: molecules of enzymes, being bound with humus acids, formed the enzyme-humus complexes [30]. Close correlation was found between the organic matter content and activities of soil peroxidase and polyphenoloxidase, which participate in the synthesis of humus compounds [1, 44, 46]. Group composition of humus is the most significant relative index of biochemical processes intensity in the soil [20]. Peroxidase activity in studied peat soils correlated with the contents of humic and fulvic acids: decreased with the depth and characterized maximums of indices under the regime of intense drainage (Table 4). To assess the

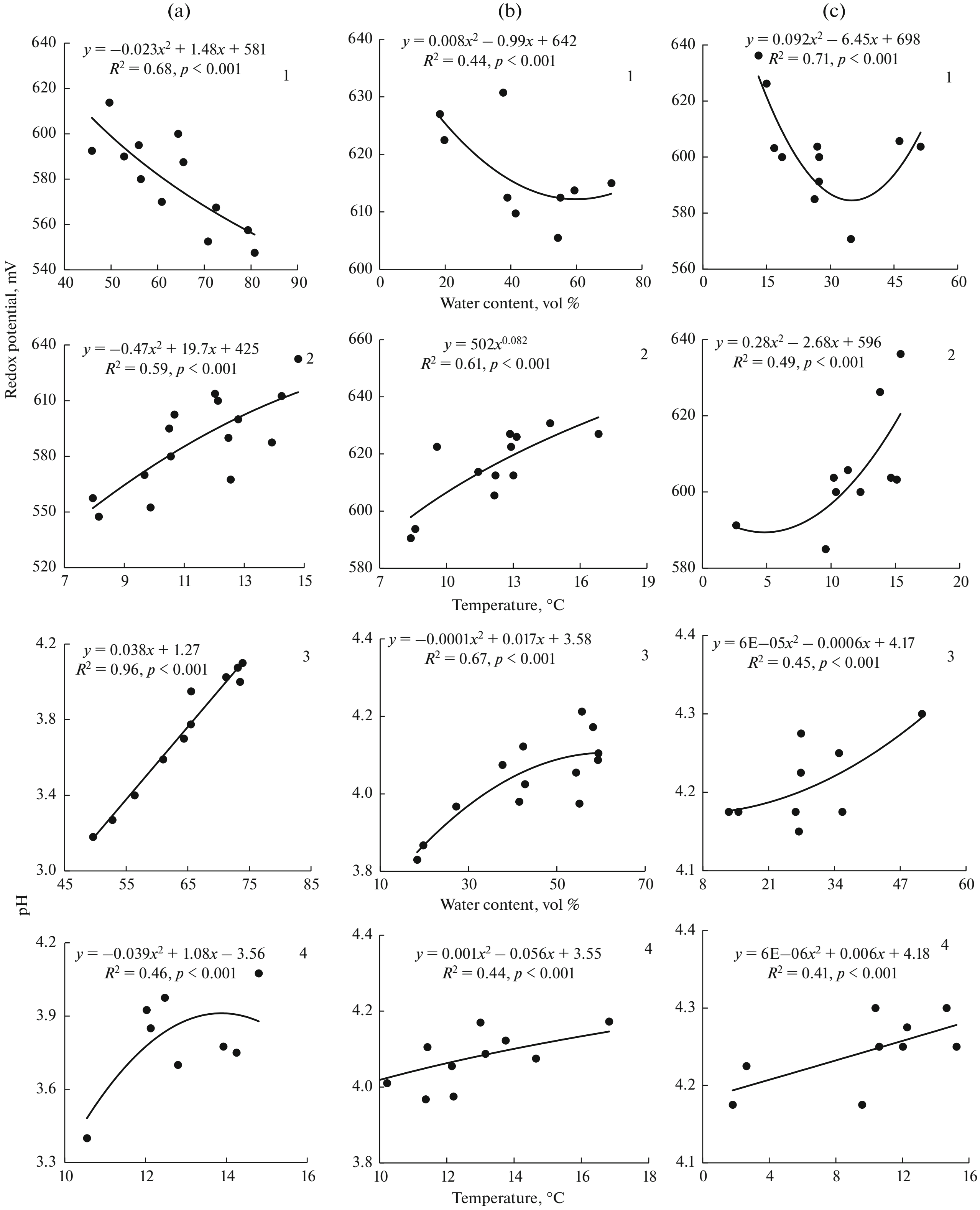

Fig. 5. Regression relationships between redox potential and pH of forest peat soils and hydrothermal environmental conditions: (1 and 3) water content, vol %; (2 and 4) temperature, °C.

Table 4. Group composition of humus acids in drained peat soils, % of C_{tot}

Depth, cm	Weakly drained			Moderately drained			Intensely drained		
	HA	FA	(HA + FA)	HA	FA	(HA + FA)	HA	FA	(HA + FA)
0–5	17.7	19.4	37.1	27.9	23.9	51.8	29.3	26.1	55.4
5–10	17.4	16.4	33.8	28.4	17.8	46.2	31.9	23.2	55.1
10–20	19.3	14.1	33.4	29.1	15.3	44.4	29.9	21.0	50.9
20–30	16.0	13.3	29.3	28.1	14.3	42.4	31.1	20.6	51.7

HA, humic acids, FA, fulvic acids, (HA + FA), humification degree.

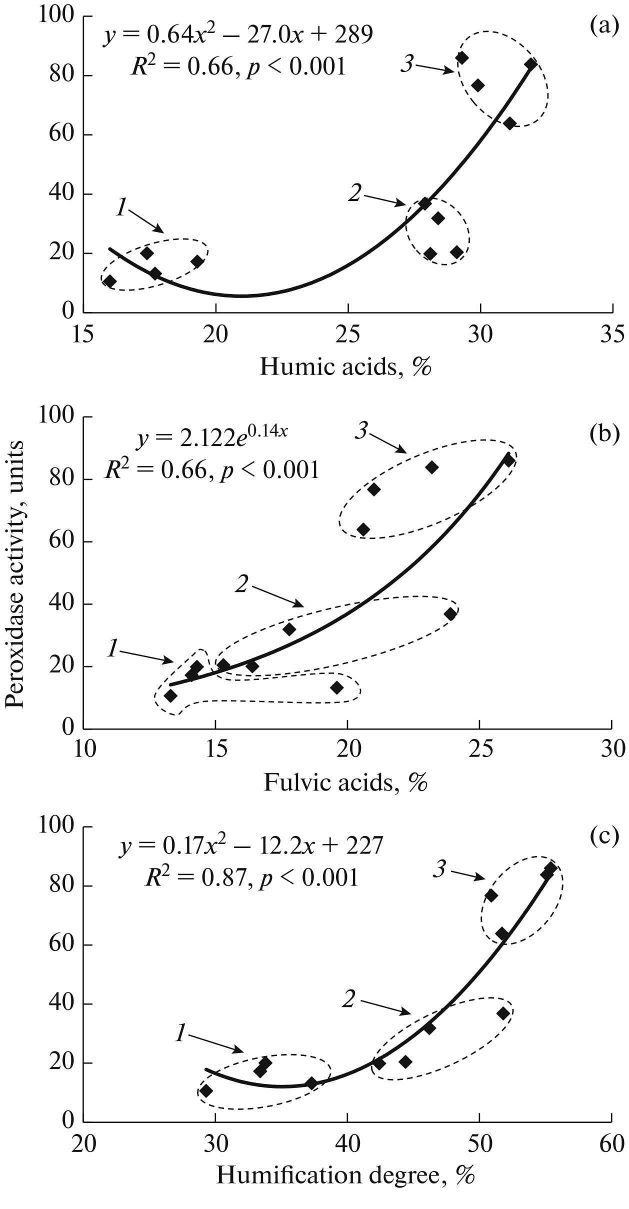

Fig. 6. Regression relationships between peroxidase activity and indices of the humus state of drained peat soils: (a) humic acids, (b) fulvic acids, (c) humification degree. (*1*), (*2*), (*3*) are weakly, moderately, and intensely drained peat soils, respectively.

strength of relationship, the data on peroxidase activity in soils of different depth of drainage were combined into one totality, and this increased the number of observations and variation of characteristics. It was found that peroxidase activity was with certainty positively approximated by nonlinear functions by 66% by humic and fulvic acids and by 87% by degree of humification (Fig. 6). Mathematical functions characterize objectively the differentiated contribution of peroxidase to the formation of humus state of peaty soils with different degree of drainage.

CONCLUSIONS

(1) Weighted mean activity of peroxidase in recent peat soils (0–30 cm) of swampy pine forests accounted for over the period June–October (base level) in the mode of weak hydro-reclamation 14.4 units, moderate—21.9, and in intense hydro-reclamation 70 units (mL I/g of abs. dry sample per 2 min). The upper 10 cm were characterized by maximal potential of enzyme.

(2) Parabola of the second order was the most adequate function of the main trend in the variations in peroxidase activity. Numeric values and signs of parameters of parabolic trend demonstrated that mean peroxidase activity decreased every week by 4.4, 7.6, and 15.2 units under the regime of weak, moderate, and intense drainage with weekly average acceleration by 0.31, 0.59, and 1.54 units,, respectively.

(3) Seasonal wave of peroxidase activity irrespectively of soil drainage intensity was characterized by June increment with maximum in the 0–10 cm layer relative to the base level. The decrease of the increment rate in July correlated with the depth of drainage. The less was soil waterlogged, the close to the surface was the horizon, from which the decrease of enzyme activity began. These were 5–10 cm in intensely drained soils, 10–20 cm in moderately drained, and 20–30 cm in weakly drained soils. The decrease of increment rate came over the whole layer of weakly and moderately drained soils from August and sharply increased in autumn. Stable weak decrease of increment rate began only in October under the regime of deep drainage.

(4) The results of pair regression analysis with certainty approximated the nonlinear positive correlation

between peroxidase activity and bulk volume of water and pH, negative correlation with redox potential, and bidirectional correlation with temperature depending on the regime of hydro-reclamation.

(5) Peroxidase activity according to the canonical indices of determination depended on the combined influence of discussed factors by 74% in weakly drained soils, by 52% in moderately drained, and by 64% in intensely drained soils. The data of canonical weights reflected maximal fraction of hydrothermal parameters in weighted sum. Canonical correlation characterized the leading role of temperature in weakly drained soils, moisture in intensely drained soils, and equally temperature and moisture under the regime of moderate drainage.

(6) Enzyme activity was with certainty positively approximated by nonlinear functions with humic acids, fulvic acids, and humification degree and attested to the differentiated contribution of peroxidase to the formation of humus state of peat soils with different degree of drainage.

FUNDING

The study was carried out within the framework of the base project of the Sukachev Institute of Forest, Krasnoyarsk Research Center, Siberian Branch, Russian Academy of Sciences *Functional Dynamic Indication of Biodiversity of Siberia Forests* (no. 0287-2021-0009).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

OPEN ACCESS

REFERENCES

1. A. E. Gul'ko and F. Kh. Khaziev, "Soil phenol oxidases: production, immobilization, activity," Pochvovedenie, No. 11, 55–68 (1992).
2. V. A. Dyrin, "Activity of peroxidase and polyphenol oxidase in peat of virgin and recultivated areas of lowland bog ecosystem," Vestn. Tomsk. Gos. Pedagog. Univ., No. 2, 164–169 (2015).
3. S. P. Efremov and T. T. Efremova, "The effect of drainage on the loading of peat soil with the roots of woody and herbaceous plants," in *Complex Estimation of Swamps and Swampy Forests in Connection with Their Reclamation* (Nauka, Novosibirsk, 1973), pp. 113–127 [in Russian].
4. T. T. Efremova, "Soil formation and diagnostics of peat soils in bog ecosystems," Pochvovedenie, No. 12, 25–35 (1992).
5. T. T. Efremova, S. P. Efremov, and P. T. Voronkov, "Regression analysis of the enzymatic activity of drained peat soils," in *Peculiarities of Forest-Marsh Ecosystems of Western Siberia* (Krasnoyarsk, 1978), pp. 111–131.
6. T. T. Efremova, T. M. Ovchinnikova, and V. G. Sukhovol'skii, "Multiparametric analysis of soil properties in the drained forest bogs of Western Siberia," Eurasian Soil Sci. **39** (6), 588–596 (2006).
7. T. T. Efremova and T. M. Ovchinnikova, "Oxidoreductase activity of peat soils as an indicator of the degree of biochemical transformation of drained and forested bogs in West Siberia," Biol. Bull. (Moscow) **34** (3), 297–302 (2007).
8. D. A. Zvyagintsev, "Problems of soil biochemistry," Vestn. Mosk. Univ., Ser. 17: Pochvoved., No. 1, 74–84 (1977).
9. L. I. Inisheva, S. N. Ivleva, and T. A. Shcherbakova, *Guidelines for Determining the Enzymatic Activity of Peat Soils and Peat* (Izd. Tomsk. Univ., Tomsk, 2003) [in Russian].
10. L. I. Inisheva, L. Szajdak, and M. A. Sergeeva, "Dynamics of biochemical processes and redox conditions in geochemically linked landscapes of oligotrophic bogs," Eurasian Soil Sci. **49** (4), 466–474 (2016).
11. L. I. Inisheva, S. G. Maslov, and K. E. Shchukina, "Biochemical activity of peat in the Ob region," Solid Fuel Chem. **52** (6), 373–381 (2018).
12. I. S. Kaurichev and D. S. Orlov, *Redox Processes and Their Role in the Genesis and Fertility of Soils* (Kolos, Moscow, 1982) [in Russian].
13. L. S. Kozlovskaya, V. M. Medvedeva, and N. I. P'yavchenko, *Dynamics of Organic Matter in the Process of Peat Formation* (Nauka, Leningrad, 1978) [in Russian].
14. M. M. Kononova, *Soil Organic Matter* (Izd. Akad. Nauk SSSR, Moscow, 1963) [in Russian].
15. V. F. Kuprevich and T. A. Shcherbakova, *Soil Enzymology* (Nauka i Tekhnika, Minsk, 1966) [in Russian].
16. G. V. Larina, L. I. Inisheva, and E. V. Porokhina, "Enzymatic activity of the swamps of the Altai Mountains," Vestn. Altai. Gos. Agrar. Univ., No. 10, 60–68 (2016).
17. R. M. Morozova, "To the question of classification of swampy and drained soils," in *Change in Forest-Bog Biogeocenoses under the Influence of Drainage* (Petrozavodsk, 1986), pp. 108–124 [in Russian].
18. G. V. Naumova, N. A. Zhmakova, N. L. Makfrova, N. F. Rassokha, and T. F. Ovchinnikova, "Enzymatic activity of peat from natural and developed peat deposit," Prirodopol'zovanie, No. 1, 208–216 (2018).

19. D. S. Orlov, *Soil Humic Acids and the General Theory of Humification* (Mosk. Univ., Moscow, 1990) [in Russian].
20. D. S. Orlov and O. N. Biryukova, “On some indicators of the biological activity of soils and the secondary transformation of humic acids,” in *Ecological Conditions and Enzymatic Activity of Soils* (Ufa, 1979), pp. 78–98 [in Russian].
21. V. V. Ponomareva and T. A. Nikolaeva, “Methods for studying organic matter in peat-bog soils,” Pochvovedenie, No. 5, 88–95 (1961).
22. E. V. Porokhina and O. A. Golubina, “Enzymatic activity in peat deposits of the Tagan bog,” Vestn. Tomsk. Gos. Pedagog. Univ. **122** (7), 171–176 (2012).
23. E. V. Porokhina, L. I. Inisheva, and V. A. Dyrin, “Biological activity and seasonal changes of CO_2 and CH_4 in peat deposits of the eutrophic bog,” Vestn. Tomsk. Gos. Univ. Biol., No. 3 (31), 157–176 (2015).
24. E. V. Porokhina and M. A. Sergeeva, “Chemical composition and biological activity of the peat deposit of the oligotrophic bog,” Samar. Nauchn. Vestn. **7** (3), 82–87 (2018).
25. N. I. P’yavchenko, “On the diagnostics of types of peat soils and deposits in the course of surveys and design of forest drainage reclamation,” in *Research on Forest Swamp Science and Land Reclamation* (Petrozavodsk, 1978), pp. 5–24 [in Russian].
26. I. N. Skrynnikova, “Classification of virgin bog and ameliorative peat soils of the USSR,” Pochvovedenie, No. 5, 14–27 (1964).
27. F. Kh. Khaziev, *System-Ecological Analysis of the Enzymatic Activity of Soils* (Nauka, Moscow, 1982) [in Russian].
28. F. Kh. Khaziev, *Methods of Soil Enzymology* (Nauka, Moscow, 1990) [in Russian].
29. F. Kh. Khaziev, “Ecological connections of soil enzymatic activity,” Ekobiotekh **1** (2), 80–92 (2018). http://ecobiotech-journal.ru.
30. F. Kh. Khaziev, “On the kinetics of enzymatic processes in soils,” Izv. Ufim. Nauchn. Tsentra Ross. Akad. Nauk, No. 3, 45–51 (2018).
31. A. A. Khalafyan, *Statistica 6. Statistical Data Analysis* (OOO Binom-Press, Moscow, 2007) [in Russian].
32. E. V. Chekotovskii, *Graphical Analysis of Statistical Data in Microsoft Excel 2000* (Izd. Dom Vil’yams, Moscow, 2002) [in Russian].
33. T. A. Shcherbakova, “The role of enzymes in the processes of transformation of organic matter entering the soil,” in *Ecological Conditions and Enzymatic Activity of Soils* (Ufa, 1979), pp. 59–78.
34. T. A. Shcherbakova, *Enzymatic Activity of Soils and Transformation of Organic Matter (in Natural Artificial Phytocenoses)* (Nauka i Tekhnika, Minsk, 1983) [in Russian].
35. P. Baldrian and M. Stursova, “Enzymes in forest soils,” in *Soil Enzymology* (Springer-Verlag, Berlin, 2011), pp. 61–73.
36. R. G. Burns, J. L. DeForest, J. Marxsen, R. L. Sinsabaugh, M. E. Stromberger, M. D. Wallenstein, M. N. Weintraub, and A. Zoppini, “Soil enzymes in a changing environment: Current knowledge and future directions,” Soil Biol. Biochem. **58**, 216–234 (2013).
37. B. A. Caldwel, “Enzyme activities as a component of soil biodiversity: a review,” Pedobiologia, **49** (6), 637–644 (2005).
38. E. N. Esimbekovaa, I. G. Torgashinaa, V. P. Kalyabinaa, and V. A. Kratasyaka, “Enzymatic biotesting: scientific basis and application,” Contemp. Probl. Ecol. **14**, 209–304 (2021).
39. C. Freeman, N. J. Ostle, N. Fenner, and H. Kang, “A regulator role for phenol oxidase during decomposition in peatlands,” Soil Biol. Biochem. **36** (10), 1663–1667 (2004).
40. A. Karaca, S. C. Cetin, O. S. Turgay, and R. Kizilkaya, “Soil enzymes as indication of soil quality,” in *Soil Enzymology* (Springer-Verlag, Berlin, 2011), pp. 119–148.
41. Q. Lia, W. Jiab, Q. Zhangc, and X. Cheng, “Localized plant-soil-microbe interactions regulate spatial variations of soil oxidase activities within afforested systems in a subtropical area,” Geoderma **406** (4), (2022). EDN: TPMGTL https://doi.org/10.1016/j.geoderma.2021.115499
42. J. H. Makoi and P. A. Ndakidemi, “Selected soil enzymes: examples of their potential roles in the ecosystem,” Afr. J. Biotech. **7** (3), 181–191 (2008).
43. A. J. Pinsonneault, T. R. Moore, and N. T. Roulet, “Temperature the dominant control on the enzyme-latch across a range of temperate peatland types,” Soil Biol. Biochem. **97**, 121–130 (2016).
44. R. L. Sinsabaugh, “Phenol oxidase, peroxidase and organic matter dynamics of soil,” Soil Biol. Biochem. **42**, 391–404 (2010).
45. M. J. Steinweg, J. E. Kostka, P. J. Hanson, and C. W. Schadt, “Temperature sensitivity of extracellular enzymes differs with peat depth but not with season in an ombrotrophic bog,” Soil Biol. Biochem. **125**, 244–250 (2018).
46. A. G. Zavarzina, “Heterophase synthesis of humic acids in soils by immobilized phenol oxidases,” in *Soil Enzymology* (Springer-Verlag, Berlin, 2011), pp. 187–205.

Translated by T. Chicheva