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The Effect of a Copper Smelter Emissions on the Stock and Decomposition of Coarse Woody Debris in Spruce and Fir Woodlands

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Abstract—We have studied the share of coarse woody debris (CWD) reserves at different decay classes in the spruce and fir woodland within the impact area of aerial pollution from the Middle Ural Copper Smelter (Revda, Sverdlovsk oblast). Control and impact areas slightly differ in total reserves and number of trunks of CWD (sum of standing and fallen dead wood). However, the number of CWD tends to grow in proximity to the plant. The mechanisms involved in CWD-reserve formation differ between impact and control sites. A larger number of relatively thin trunks prevail in CWD reserves of impact sites when compared to the lower number of thick trunks at control sites. The CWD share of 30% in the total number of dead and living trees did not differ across pollution loads. However, the share of CWD reserves in total stock is 1.9 times higher near the plant than at the control site. The share of logs at the initial stages of decomposition (first and second decay classes) is 3.2 times higher in terms of CWD number and 4.2 times higher in terms of CWD reserves than at the control sites. This points to the strong inhibition of CWD decomposition. The pattern of decay classes of all sizes of fallen trees significantly differs in volume across pollution zones.

Keywords: industrial pollution, copper smelter, heavy metal, coarse woody debris, spruce and fir woodland, timber destruction, snags, logs

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INTRODUCTION

Since the 1980s, the number of publications devoted to the study of coarse woody debris (CWD) has been steadily increasing worldwide (Sollins, 1982; Harmon et al., 1986; Sturtevant et al., 1997; Fridman and Walheim, 2000; Nilsson et al., 2002; Zell et al., 2009; Tuomi et al., 2011; Shorohova and Kapitsa, 2014; and others). In Russia, interest in this object arose somewhat later—in the 1990s—and also remains consistently high (Alekseev and Berdsi, 1994; Krankina and Harmon, 1995; Isaev and Korovin, 1997; Treifeld, 2001; Karelin and Utkin, 2006; Vorob'ev, 2006; Zamolodchikov, 2009; Klimchenko et al., 2011; Grabovskii and Zamolodchikov, 2012; Zamolodchikov et al., 2013; Bobkova et al., 2015; and others).

CWD is usually understood as the dead matter of tree trunks (snags, logs, and stumps) of all stages of decomposition, up until its transition to detritus. Interest in its study is not accidental and is primarily due to the importance of CWD characteristics in the analysis of carbon sequestration processes (Karjalainen and Kuuluvainen, 2002, Zamolodchikov, 2009), as well as the development of biodiversity conservation programs for forest ecosystems (Siitonen 2001, Stokland et al., 2012). For Russia, the study of CWD is especially important, because the extensive form of forest management leads to mass debris in plantations (Vorob'ev, 2006).

Despite the huge number of publications on CWD stocks, papers devoted to the analysis of the effect of industrial pollution on this indicator are few (Zalesov et al., 2002; Tsvetkov, V.F. and Tsvetkov, I.V., 2003; Bergman et al., 2015) and their results are contradictory: both an intensification of dead trees input as the level of pollution increases (Fimushin, 1979, Ivshin, 1993; Tsvetkov, V.F. and Tsvetkov, I.V., 2003; and others), and the absence of regular changes (Polyakov and Polyakova, 2005; Tarkhanov, 2011; Bergman et al., 2015) has been demonstrated.

The situation is similar for studies of the decomposition of wood substances under pollution conditions. We do not know any works in which the rate of decomposition of CWD near industrial plants has been estimated by the direct method (i.e., by the loss of mass or density of the exposed wood samples). This contrasts sharply with the situation in undisturbed areas, for which the regularities of the decomposition of this substrate have been studied in detail (Karelin and

Utkin, 2006; Mukhin and Voronin, 2007; Shorokhova et al., 2009; Mukhortova et al., 2009; Zell et al., 2009; and others). Under conditions of contamination, the decomposition of plant organic matter was studied using its rapidly decomposing fractions—leaf litter (Strojan, 1978; Zwolinski, 1994, Medvedeva et al., 2006) or pure cellulose (Vorobeichik, 1991, 1995, 2002, 2007; Vorobeichik and Pischulin, 2011), or indirectly—based on an analysis of the distribution of tree trunks in the decay classes, which are diagnosed visually (Zalesov et al., 2002, Stavishenko, 2010; Stavishenko and Kshnyasev, 2013; Bergman et al., 2015).

Thus, we can state a significant shortage of information on the impacts of industrial pollution on the formation of CWD stock and the rate of their decomposition. At the same time, this information is quite important, as it complements the picture of the transformation of forest ecosystems under the influence of pollution, which in turn is necessary for the development of the ecology of the impact regions (Vorobeichik and Kozlov, 2012). Such regions are formed near large industrial enterprises and are specific spatial structures consisting of areas with different pollution levels and correspondingly different degrees of ecosystem transformation. Works in this field are relevant not only because of the obvious applied aspects, but also from the point of view of fundamental ecology, since the impact region can be viewed as a result of a long-term field experiment with ecosystems that started at the time the enterprise was launched, which makes it possible to study the mechanisms of ecosystem resistance to strong external effects (Vorobeichik and Kozlov, 2012).

The purpose of this work is to analyze the changes in CWD stocks and the transformation of the CDW distribution on decomposition stages in spruce and fir forests of the southern taiga under the influence of industrial pollution from a large point source of pollutants (Middle Ural Copper Smelter, MUCS). In the course of the work, we tested several possible alternatives (decrease, increase, and absence of differences) with respect to the change in the following CWD parameters influenced by contamination: (1) the stock/number of CWD trunks (snags and logs) and (2) the proportion of logs of one of the five decay classes.

In the work we tested two hypotheses: (1) in the contaminated territories, the stock/number of CWD is higher than under similar background conditions (this increase may be due to either the intensification of dead trees input or inhibition of decomposition but it is not possible to separate these processes under this methodological scheme); (2) the distribution of CWD on the decay classes near the plant has been changed in comparison with undisturbed areas, primarily due to the increase in the share of weakly decomposed trunks. Hypotheses follow from well-documented facts of the oppression of woody plants (Fimushin, 1979; Mukhlbaier, 1987; Tsvetkov, V.F. and Tsvetkov, I.V., 2003; Usoltsev et al., 2012; etc.) and the inhibition of destructive processes (Vorobeichik, 1991, 1995, 2002, 2007; Volchatova et al., 2007; Vorobeichik and Pischulin, 2011) under the influence of industrial pollution.

This work is also important methodically. Earlier, we (Bergman et al., 2015) already analyzed the effect of MUCS on the intensity of tree stand mortality and the distribution of CWD on the decay classes. However, in that work, firstly, a somewhat different set of sites is considered; secondly, when considering CWD, the length of log fragments was not measured (respectively, CWD stock was calculated indirectly—by the diameter of a trunk at the time of tree death); thirdly, a rather coarse 3-point scale of the degree of decomposition was used. Accordingly, the results of this paper allow us to assess the extent to which the conclusions depend on the accuracy of the methods (the direct or indirect determination of CWD stocks and a coarse or more fractional scale for evaluating the decomposition of the logs) and the arrangement diagram of study plots.

It should be emphasized that CWD stocks and their distribution on the decay classes are parameters that can depend heavily on the effect of many “interfering” natural (windfalls and windbreaks) and anthropogenic (improvement cutting, removal of CWD from the stand, etc.) factors. That is why considerable attention is paid to correctly selecting the sites under investigation.

MATERIALS AND METHODS

The investigations were carried out in the area of operation of the Middle Ural Copper Smelter located on the outskirts of the city of Revda, Sverdlovsk oblast, 50 km to the west of Yekaterinburg. The plant has been operating since 1940 and is considered one of the largest sources of atmospheric pollution in Russia: the total volume of emissions in the late 1980s was more than 140000 t/year^{-1}; by the middle of the 2000s it had decreased to 25000 t/year^{-1}; and, after the cardinal reconstruction of the enterprise in 2010, it is estimated to be less than 5000 tons per year^{-1} (Vorobeichik et al, 2014). The emissions are mainly made up of SO_2 and dust particles with sorbed toxic elements (Cu, Pb, Cd, Zn, Fe, As, Hg, etc.). As a result of long-term exposure, zones with different degrees of damage to ecosystems have formed around the plant, the shape of which partly coincides with the predominant direction of winds in the area (from west to east). As the gradient of pollution in the eastern direction is more strongly stretched and overlaps with the impact zone from the urban agglomeration of Yekaterinburg, studies were conducted to the west of MUCS.

The territory belongs to the subzone of the southern taiga. The works were carried out in spruce and fir forests of different plant associations, which regularly change as they get closer to the plant (from nemoral—wood sorrel through wood sorrel—herbaceous to dead-cover and moss–horsetail). The soil cover of the investigated areas is represented by combinations of mountain–forest brown, soddy-podzolic, and gray forest soils transformed to different degrees by the action of technogenic factors. In this paper, parts of the gradient are combined into three contamination zones: impact zone—at a distance of 2 and 3 km from the source of emissions; buffer zone—4, 7, and 10 km; and background zone—20 and 30 km. When approaching the plant, the concentration of Cu in the forest litter increases more than 100 times, Pb 30–40 times, and Cd 10–20 times (Smorkalov and Vorobeichik, 2011). A detailed description of the nature of ecosystem changes is given in the works (Vorobeichik et al., 1994, 2014; Kaigorodova and Vorobeichik, 1996; Usol'tsev et al., 2012).

A total of 30 permanent study plots with dimensions of 25 × 25 m were laid in a gradient of contamination at different times, some of which we used for this work. If there were either stumps from cut or felled trees or traces of strong fires within the study plot, it was excluded from analysis. In total, according to these criteria, 13 study plots were excluded; accordingly, the work was performed on 17 study plots. To a certain extent, such an approach allowed us to minimize the influence of interfering factors related to forest management.

In August 2014, the total counting of living trees, as well as CWD, was performed on each study plot. The main tier included trees with a diameter no less than 5 cm at a height of 1.3 m. Forest-taxation indicators of the stand were calculated by standard formulas (Usol'tsev and Zalesov, 2005). The average diameter of the stand (D, cm) is calculated as $D = \sqrt{G(N \times (\pi/4))^{-1}}$, where G is the basal area in the study plot, cm^2; N is the number of trees in the study plot, pcs. Using an altimeter (Haglöf Electronic, Sweden), at each distance the height (with an accuracy of 10 cm) was measured in 22–24 living trees over the entire range of their diameter variation. According to these data, the dependence of the tree height on its diameter at a height of 1.3 m was constructed, described by a semilogarithmic function, which was subsequently used to determine the average height of the stand. The stock of wood substance of living trees is determined on the basis dependencies of the trunk volume on its diameter at an height of 1.3 m previously constructed for the area of study (Bergman, 2011). Age is determined from model trees in the entire range of variation of their diameters. The taxation characteristics of stands are given in Table 1.

CWD was subdivided into two categories: (1) snags—dead but not fallen trees with a trunk diameter at an height of 1.3 m no less than 5 cm; (2) logs—trees (or their fragments) decomposed to varying degrees located on the surface or partially buried with a diameter of the larger base of no less than 5 cm. The trunks of dead trees suspended in the crowns of neighboring trees are also referred to as logs. Since the logs in the last stages of decomposition is essentially a woodchip covered with mosses and lichens, it was impossible to determine its species identity. Therefore, in the earlier stages of decomposition the logs was not distinguished by species either.

When considering the snags, its diameter was measured (with an accuracy of 0.5 cm) and, according to the height-diameter relationship, the tree height was estimated at the time of death. The basis for determining the snags stock, as well as for living trees, is the dependence of the volume of the tree trunk on its diameter at an height of 1.3 m (Bergman, 2011). For snags and logs, the following size categories for the diameter at an height of 1.3 m were adopted: thin plants 5 cm $< d_{1.3} \leq$ 18 cm, medium plants 18 cm $< d_{1.3} \leq$ 28 cm, and large plants $d_{1.3} >$ 28 cm.

When considering the logs, the length (with an accuracy of 1 cm) and the diameter at an height of 1.3 m (with an accuracy of 0.5 cm) were measured; for partially preserved trunks, the diameters of the opposite ends of the fragment (with an accuracy of 0.5 cm) were measured. If the fallen trunk was outside the study plot but its stump was within its boundaries, it was included in the count.

To find the stock of the logs, a formula for the volume of a truncated cone is often used (Trefilova et al., 2009; Klimchenko et al., 2011), but its use in the case of well-preserved trunks due to high taperingness in the butt-log portion (Bergman, 2016) can lead to an overestimation of their volumes. Therefore, the volume of logs, depending on the degree of their preservation, was determined by us in three different ways (Fig. 1). The volume of slightly decomposed trunks with a preserved or slightly decomposed top (diameter of its base less than 3 cm) (Fig. 1a) was calculated as the volume of the trunk at the time of the fall using the dependence of the volume on the diameter at a height of 1.3 m (Bergman, 2011). The volume of the trunk with a strongly decomposed top (diameter of its base more than 3 cm), but with well-preserved lower and middle parts, was calculated as the difference in the volume of the trunk at the time of the fall and the volume of the missing (decomposed) part (Fig. 1b). The volume of strongly decomposed trunks was calculated from the formula for the volume of a truncated cone (Fig. 1c).

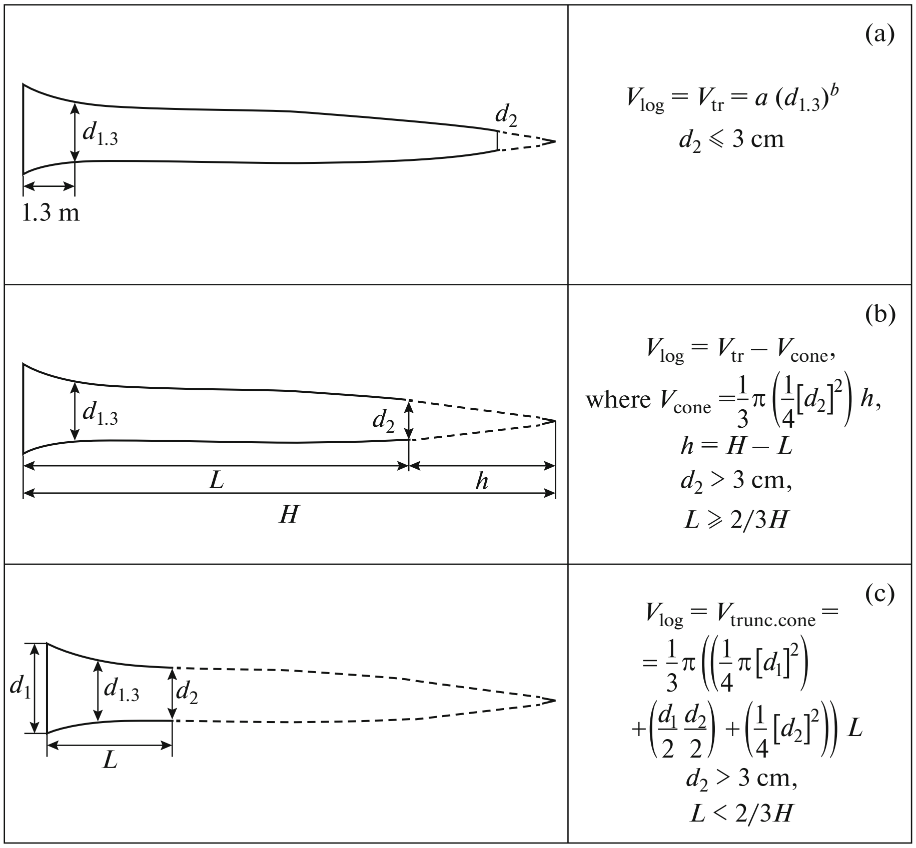
In the further analysis, log fragments were divided by volume into three size categories according to the principle of equal representation—154 samples in each category: small (fragment volume of 0.010–0.055 m^3), medium (0.056–0.159 m^3), and large (more than 0.160 m^3).

The decay classes of the logs were diagnosed according to the scale used in the work of P.V. Gordienko (1979), which is close to the scale of R. Fogel et al. (1973) widely used abroad. The comparative characteristics of the two scales are presented in Table 2. Statisti-

Table 1. Taxation characteristics of the investigated spruce and fir stands

Pollution zone	Distance from the plant, km	Number of the study plot	Stand composition	Average age, years*	Average height, m	Average diameter, cm	Density, pcs./ha	Basal area, m^2/ha	Stock, m^3/ha
Background		1	5Fr3S1As1P + B	100 (64–134) [14]	21.3	22.3	1244	48.4	487.6
	30	2	5Fr2S2As1B		20.9	21.6	1177	43.2	412.8
		3	6S4Fr ind. B		22.2	23.9	1110	49.6	465.2
	20	4	4Fr3S2B1As ind. P		21.2	24.7	1070	51.4	522.5
Buffer		1	3S3Fr3B1Ln + As	99 (37–64) [28]	15.9	18.4	1520	40.4	391.4
	10	2	5S4Fr1B + Ln		16.7	20.0	1055	33.2	304.1
		3	4B3S3Fr + Ln		17.3	21.3	1014	36.1	360.4
		4	4S4Fr2B + Ln + As		22.4	24.0	1062	48.2	472.4
	7	5	7Fr3B ind. As		21.8	23.1	888	37.1	362.9
		6	5Fr3S2B		21.0	21.5	1049	38.2	367.5
		7	9S1Fr ind. B		21.5	24.2	802	36.9	354.5
	4	8	6Fr3S1B ind. As		15.4	14.3	2345	37.6	336.3
Impact		1	3S3Fr2P2B	77 (44–130) [24]	14.9	15.8	1616	31.5	241.5
	3	2	5Fr4S1B + P		13.7	13.9	2006	30.4	200.4
		3	5S3P1B1Fr ind. Wl		15.1	16.9	1033	23.1	181.0
	2	4	5S3Fr1B1Wl + P		12.8	13.5	1207	17.3	112.6
		5	5S4Fr1B + P		14.5	16.0	1238	24.9	166.3

* Average age is indicated; the minimum and maximum age (estimated by model trees (Bergman, 2011)) is given in parentheses and the number of trees is in square brackets.



(a)

$$V_{\log} = V_{\mathrm{tr}} = a\,(d_{1.3})^b$$
$$d_2 \leqslant 3\ \mathrm{cm}$$

(b)

$$V_{\log} = V_{\mathrm{tr}} - V_{\mathrm{cone}},$$
$$\text{where } V_{\mathrm{cone}} = \frac{1}{3}\pi\left(\frac{1}{4}[d_2]^2\right)h,$$
$$h = H - L$$
$$d_2 > 3\ \mathrm{cm},$$
$$L \geqslant 2/3H$$

(c)

$$V_{\log} = V_{\mathrm{trunc.cone}} = \frac{1}{3}\pi\left(\left(\frac{1}{4}\pi[d_1]^2\right) + \left(\frac{d_1}{2}\frac{d_2}{2}\right) + \left(\frac{1}{4}[d_2]^2\right)\right)L$$
$$d_2 > 3\ \mathrm{cm},$$
$$L < 2/3H$$

Fig. 1. Schematic representation of logs of different states of preservation and corresponding formulas for volume calculation. The dashed line shows the missing (decomposed) top. $V_{\log}$ is the volume of the log, cm^3; V_{tr} is the volume of the tree trunk at the time of fall, cm^3; V_{cone} is the volume of the cone (decomposed top), cm^3; $V_{\mathrm{trunc.cone}}$ is the volume of the truncated cone, cm^3; a and b are the constants of the equation; $d_{1.3}$ is the diameter at an height of 1.3 m, cm; d_2 is the diameter of the base of the decomposed top, cm; h is the height of the decomposed top, m; H is the height of the trunk at the time of fall, cm; L is the length of the log, cm; d_1 is diameter of the log base, cm.

cal analysis of the data is carried out in the STATISTICA v.8.0. and AtteStat (version of February 24, 2013) programs. To compare the averages, the Mann–Whitney test was used (the accounting unit is the study plot). The CWD distribution over the decomposition stages was analyzed using contingency tables; Pearson's χ^2 criterion was used to estimate the differences. If there is a potential problem of approximating χ^2 (frequency in cells is less than five), the Freeman–Holton criterion was applied.

RESULTS AND DISCUSSION

Number and Stock of CWD

The greatest total stock of CWD (i.e., total snags and logs) is observed in the buffer zone, which is slightly higher than the values in the background zone (1.5 times) and significantly ($p < 0.05$) higher than in the impact zone (1.9 times). This is associated with the larger log stock (4.2 times higher than in the background zone and 2.9 times higher than in the impact zone), while the snags stock in the buffer zone is the smallest (2.3 times lower than in the background zone and 1.2 times lower than in the impact zone) (Table 3).

A different picture is observed when considering the number of CWD trunks. The total number of CWD is slightly higher (1.3 times) near the plant in comparison with background stands, whereas for the snags the opposite ratio is recorded (1.1 times); however, these differences are not statistically significant ($p > 0.05$). The number of logs is significantly higher ($p < 0.05$) in the impact and buffer zones than in the background zone (2.4 and 2.3 times, respectively) (Table 3).

The distribution of the number of CWD (summarized snags and logs) on size categories is statistically nonuniform ($\chi^2(4) = 35.6, p < 0.001$) and is associated with the contamination zone (Fig. 2). Significant differences are established between the impact and buffer zones ($\chi^2(2) = 28.4$, $p < 0.001$), as well as buffer and background ($\chi^2(2) = 14.3$; $p < 0.001$) zones, whereas

Table 2. Scales for the diagnosis of the stages of decomposition of the logs

Characteristic	Decay class				
	I	II	III	IV	V
Scale used by P.V. Gordienko (1979)					
Bark	Dense, unchanged	Dense, mostly undamaged	The largest part fell away	Absent	Absent
Condition of wood substance	Dense build, no signs of rotting	Dense build, visible signs of rotting	Top layer is soft, pronounced rotting	Rot penetrates to a considerable depth, layers of wood substance are soft	Only the shape of the trunk remains
Epiphytes	No	No	No	Synusiae of mosses and lichens start to develop	Synusiae mosses and lichens are well developed
Scale of R. Fogel et al. (1973)					
Bark	Undamaged	Undamaged	Partially preserved, exfoliates	Absent	Absent
Structure of wood substance	Undamaged	Mainly preserved, partially soft	Hard, splits into large pieces	Soft, splits into small pieces	Soft and powdery
Epiphytes	No	No	Sprouts of conifers	Moss, sprouts of conifers	Moss, sprouts of conifers
Presence of small branches ($d < 3$ cm)	Present	Absent	Absent	Absent	Absent
Wood substance color	Original	Original	Original or red-brown	From light brown to reddish	From red-brown to dark-brown

Table 3. Change in the number of trunks and CWD stock in the pollution gradient

Pollution zone	Number of study plot	Number of trunks, pcs. per ha^{-1}			Stock, m^3 per ha^{-1}		
		logs	snags	total CWD	logs	snags	total CWD
Background	1	154	385	539	18.6	53.5	72.2
	2	92	445	536	9.3	50.3	59.5
	3	175	453	628	24.3	54.6	78.9
	4	149	119	267	19.7	31.6	51.3
Mean ± *SE*		**142 ± 18 a**	**350 ± 79 a**	**493 ± 78 a**	**18.0 ± 3.2 a**	**47.5 ± 5.4 a**	**65.5 ± 6.2 ab**
Buffer	1	384	64	448	55.8	2.5	58.3
	2	256	90	347	53.6	3.2	56.8
	3	241	32	274	49.9	5.3	55.2
	4	341	249	590	61.4	34.6	96.1
	5	425	396	820	114.4	49.4	163.8
	6	318	276	594	81.3	59.6	141.0
	7	335	44	379	81.0	0.8	81.8
	8	316	72	388	101.6	7.6	109.2
Mean ± *SE*		**327 ± 21 b**	**153 ± 48 b**	**480 ± 63 a**	**74.9 ± 8.4 b**	**20.4 ± 8.4 ab**	**95.3 ± 14.4 a**
Impact	1	235	188	424	17.5	23.8	41.3
	2	172	345	517	18.9	35.9	54.8
	3	339	308	648	24.1	23.1	47.2
	4	515	467	982	34.1	22.7	56.8
	5	441	305	746	33.3	17.2	50.5
Mean ± *SE*		**341 ± 63 b**	**323 ± 45 a**	**663 ± 97 a**	**25.6 ± 3.5 a**	**24.6 ± 3.1 b**	**50.1 ± 2.8 b**

SE is the error of the mean. The same letters mean the absence of significant differences between pollution zones by the Mann–Whitney criterion. The accounting unit is the study plot.

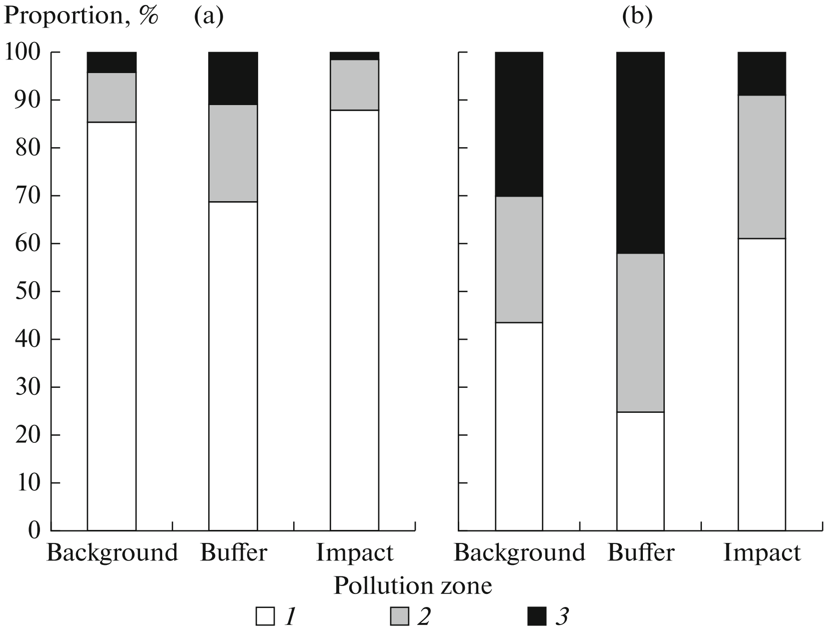


Fig. 2. Distribution of the number of trunks (a) and stock (at the time of tree death) (b) CWD by size categories (by diameter) in different pollution zones; (*1*) thin plants, (*2*) medium-sized plants, and (*3*) large plants.

the impact and background zones do not differ ($\chi^2(2) = 2.51$, $p = 0.29$). The revealed differences are associated with a larger proportion of the medium and large fragments upon moderate contamination—2.1–2.6 times in the number of trunks and 1.3–1.9 times in stocks in comparison with the stands of the background and impact zones, respectively (Fig. 2).

The share of the number of CWD trunks (summarized snags and logs) in the total set of living and dead trees is about 30% and, in the gradient of contamination, it does not differ significantly ($\chi^2(2) = 0.759$; $p = 0.32$) (Fig. 3a). At the same time, there are significant differences in the change in the proportion of CWD stock (Fig. 3b) between the background (12.2%) and impact (22.7%) zones, as well as the background (12.2%) and buffer (20.1%) zones (Mann–Whitney, $p < 0.05$).

The values of CWD stock (snags and logs) in the background zone (51.3–78.9 m^3 per ha^{-1}) that we obtained are slightly higher than those recorded in other regions, for example, in middle-aged and maturing coniferous stands of Leningrad oblast—26 m^3 per ha^{-1} (Treifeld, 2001) and forests of the southern taiga—39.4 m^3 per ha^{-1} (Shvidenko et al., 2009). At the same time, it was shown that, for the temperate and boreal zones, in the absence of strong natural disturbances, CWD stock can reach 150 m^3 per ha^{-1} (Norden et al., 2004; Rouvinen et al., 2002).

As we noted earlier, the results of studying the processes of tree mortality in the stands exposed to atmospheric pollution are not unambiguous. According to one of the materials (Fimushin, 1979, Ivshin, 1993, Tsvetkov, V.F. and Tsvetkov, I.V., 2003; etc.), with growing pollution, the magnitude of mortality increases; according to others (Polyakov and Polyakova, 2005, Tarkhanov, 2001), no regular changes in CWD stocks as they approach the source of emissions have been identified. The results of both the present study and our earlier one in the same region (Bergman et al., 2015) did not establish clear significant differences between the segments of the pollution gradient, either in terms of the number or of stock of CWD. Nevertheless, the total number of CWD (summarized snags and logs), as expected, is maximal in the impact zone, but the maximum stock is shifted to the buffer zone (Table 3). It is noteworthy that the total CWD stock is minimal in the impact zone. Thus, our first working hypothesis was confirmed only partially.

The inconsistency of the results can be related to the variety of situations near different emission sources, which differ in duration and intensity of the impact, but primarily with the dynamics of the mortality processes, since the result largely depends on the stage of development of the stand at a particular time. It is well known that "the magnitude of dead tree input has the nature of fluctuations, successively following the periods of increase and decrease in the intensity of mortality" (Kataev, 1990, p. 39). Despite the visual homogeneity of the stands under study, the ratio of the age groups composing them may differ (Table 1), which, in turn, leads to an uneven intensity of tree mortality in different parts of the pollution gradient.

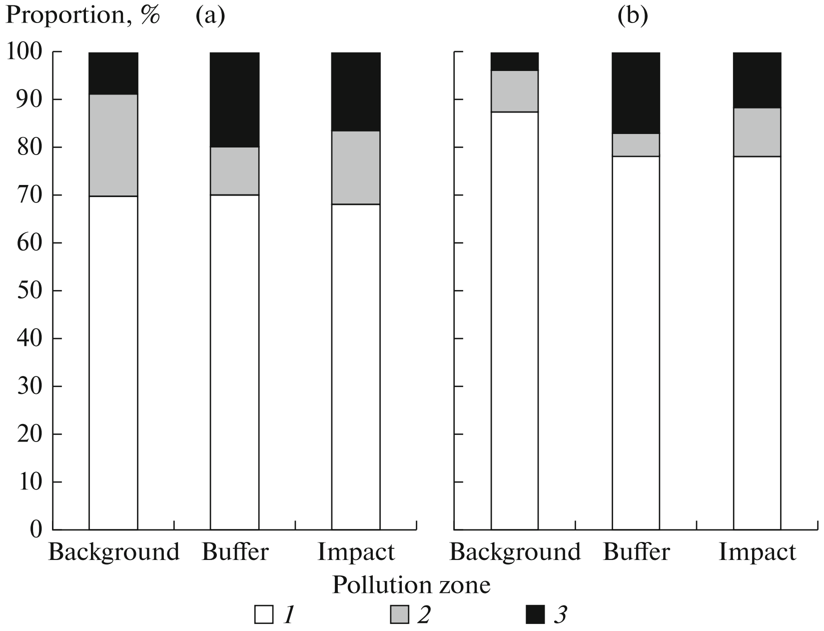


Fig. 3. Distribution of the number of trunks (a) and stock (b) of living trees (*1*), snags (*2*), and logs (*3*) in different pollution zones.

It has been repeatedly shown that the bulk of CWD in dark coniferous forests accounts for the fragments of low degrees of thickness (Dyrenkov, 1971; Gusev, 1977); the data obtained by us (Fig. 2a) also correlate with this not only for the background, but also for the impact zone. We did not find an increase in the fraction of thin trunks in the CWD (snags and logs) in the impact zone like we did before (Bergman et al., 2015). Most likely this is due to differences in the set of study plots in 2009 and 2014, as several objects were excluded from consideration due to the presence of various types of forest management there in recent years.

The different directions of changes of the number and stock of CWD in the gradient of the contamination may be associated with differences in the mechanisms of formation of the CWD pool in different load zones. In the impact zone, CWD is primarily formed due to the large number of trees with low degrees of thickness oppressed by contamination constantly accumulating on the soil surface, both due to the increased intensity of mortality and due to low decomposition. In the background zone, CWD stock is formed due to a smaller number, but larger, trees that do not experience negative pollution effects.

The almost twofold increase in the proportion of CWD in the total stock of living and dead trees as they approach the plant may indirectly indicate oppression and the continued decay of the stand near the plant. At the same time, the proportion of CWD on the number of trunks in the total set of living and dead trees does not differ much in the gradient of pollution (Fig. 3a). Moreover, we can note the positive dynamics of this parameter: in comparison with the results of 2009 (Bergman et al., 2015) (i.e., after 5 years) it decreased from 36 to 30% in the background zone and from 45 to 32% in the impact zone.

Distribution of the Logs on the Decay Classes

The distribution of the number of logs on the decay classes varies with the approach to the source of emissions ($\chi^2(6) = 113.43, p < 0.001$) (Fig. 4a). Pair contrasts between the most polluted area and less polluted areas are statistically significant ($p < 0.001$): impact/buffer, $\chi^2(3) = 106.4$; impact/background, $\chi^2(3) = 42.0$. The background and buffer zones do not differ ($\chi^2(3) = 2.2, p = 0.48$). The proportion (according to the number of trunks) of a slightly decomposed logs (i.e., the first and second decay classes) in the stand near the plant is 3.2 times higher than in the background territory. The distribution of the log stock on the decay classes is similar to the distribution according to the amount of logs (Fig. 4).

Statistically significant differences in the distribution of the number of logs on the decay classes between different contamination zones are noted not only as a whole, but also for each size category by volume—for small ($\chi^2(6) = 40.09, p < 0.001$), medium ($\chi^2(6) = 46.5, p < 0.001$), and large ($\chi^2(6) = 15.60, p < 0.03$) fragments (Fig. 5). Pair contrasts of impact/buffer and impact/background zones are also significant for each size category ($\chi^2(3) = 9.47–44.27; p < 0.025$). The exception is the large fragments of the impact and background zones, the difference in the distribution over the decay classes of which turned out to be statis-

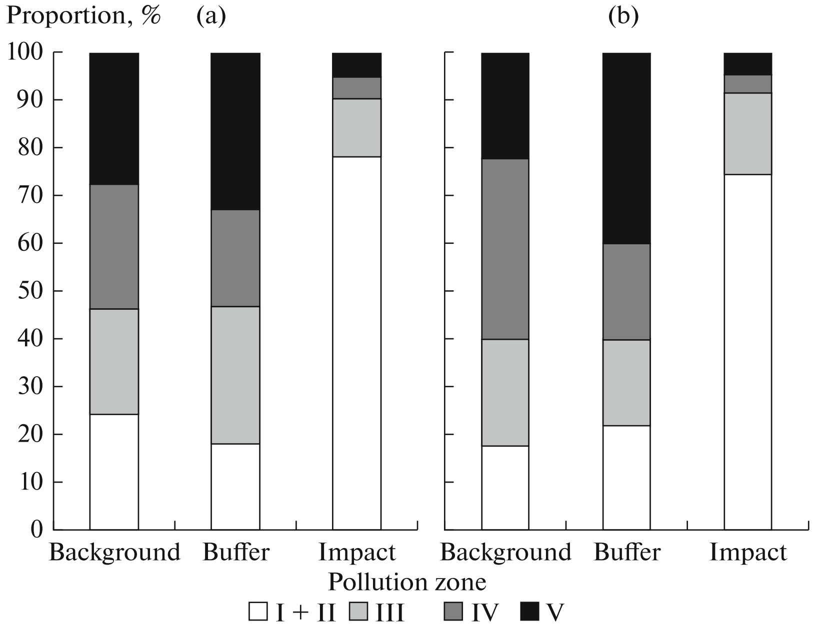


Fig. 4. Distribution of the number of trunks (a) and stock of the logs (b) according to the decay classes (I–V, see Table 2) in different pollution zones.

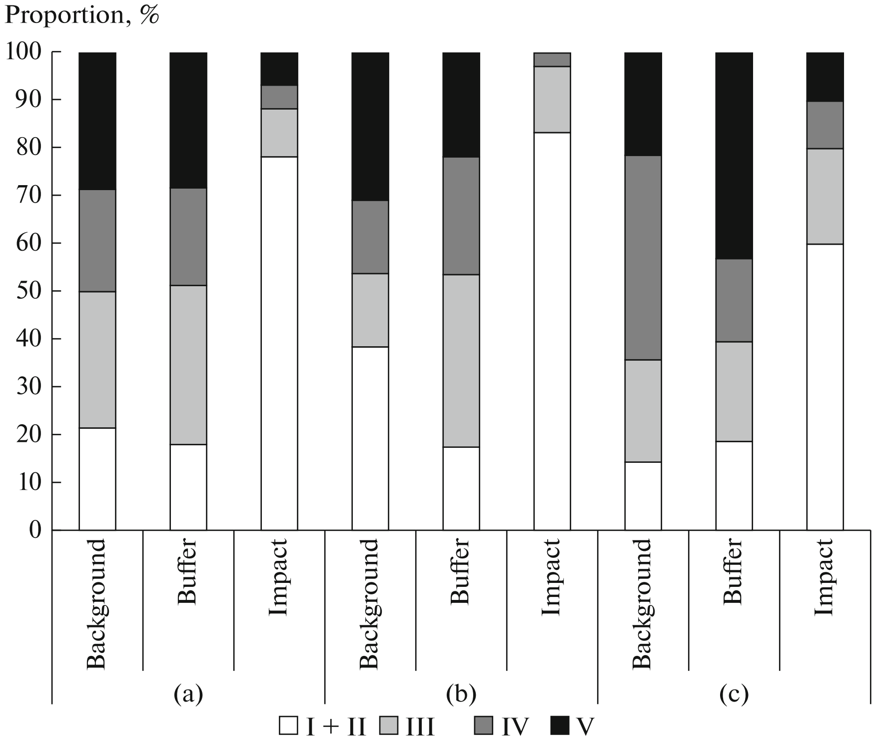


Fig. 5. Distribution of the number of logs on the decay classes (I–V, see Table 2) of different size categories (by volume) ((a) small, (b) medium, and (c) large) in three pollution zones.

tically insignificant ($\chi^2(3) = 6.28, p = 0.10$) due to their small number of trunks. The proportion (according to the number of trunks) of weakly decomposed (i.e., summarized first and second stages) small fragments of the logs in the impact zone is 3.7 times higher than in the background zone—of medium 2.2 times and of large 4.2 times. Like in total for the logs, significant differences between the background and buffer zones have not been established for any of the dimensional categories ($\chi^2(3) = 0.14–5.23$, $n = 0.16–0.22$).

According to our results, in the background forest stand (by volume), the proportion of logs at the initial stages of decomposition (first and second classes) was 18% and, at the last stages (fourth and fifth), 60%. These values fit into the range that V.G. Storozhenko (2012) gives for spruce stands in the southern taiga: according to his data, the logs volume of the first and second stages is 19–46% and that of the fourth and fifth stages is 32–70%.

As the source of contamination is approached, we recorded a pronounced shift in the logs distribution towards the initial (first and second) decay classes, especially noticeable for small fragments (Fig. 5). This fully confirms our second working hypothesis. The inhibition of the decomposition of plant organics under conditions of industrial pollution was demonstrated in many works (Strojan, 1978; Zwolinski, 1994; Volchatova et al., 2007), including those performed in the MUCS area (Vorobeichik et al., 1994; Vorobeichik, 1991, 1995, 2002, 2007; Vorobeichik and Pishchulin, 2011). However, in all cases, relatively decomposing materials (leaf litter and pure cellulose) were used in the experiments. As for those few works (Stavishenko, 2010, Stavishenko and Kshnyasev, 2013) in which the influence of pollution on the decomposition of CWD was assessed, they did not show an obvious dependence on the increase in the proportion of logs of initial stages of decomposition upon approaching the source of emissions. This contradiction is most likely due to differences in methodological approaches, which we discuss in the next section.

It is generally accepted that the decomposition of organic matter under natural conditions is determined by three groups of factors—substrate quality, biota activity, and physicochemical habitat conditions (*Biology*..., 1974, Swift et al., 1979). From this point of view, let us consider the possible reasons for the inhibition of the decomposition of CWD under the influence of emissions that we registered.

The quality of the substrate before the plant started operating was unlikely to differ greatly between the different zones (a close similarity of tree species composition in all areas suggests that at least there are no considerable differences in parameters such as wood density, nitrogen and lignin content, etc.). On the other hand, the long-term income of heavy metals and metalloids, including Cu and As, with atmospheric emissions at the time the material was collected formed considerable differences in the quality of the substrate between different contamination zones. It is known that preservatives based on copper, chromium, and arsenic compounds with strong fungicidal activity are widely used in economic activities to protect wood against fungal decay (Schultz et al., 2007). In other words, heavy-metal contamination from copper smelter emissions can be considered as a kind of analogue of antifungal treatment of wood with such preservatives. Most likely, it is this “treatment” that is the main reason for the decrease in the quality of the substrate and, accordingly, the inhibition of the decomposition of CWD near the plant.

As is known, the main agents of decomposition of dead wood substance in boreal forests are wood-destroying fungi (*Biology*..., 1974, Mukhin, 1993). Studies of the state of xylotrophic Basidiomycetes communities under atmospheric pollution conducted in Sverdlovsk oblast (Stavishenko, 2010) indicate a clear inhibition of basidium growth near emission sources when compared to background sites. Therefore, the abundance of fungi on birch and fir at the sites most closely approximated to the enterprises was reduced 3 times in comparison with the background level, on spruce almost 2 times, and on pine more than 5 times (Stavishenko, 2010). The results of the work carried out directly in the vicinity of MUCS (Bryndina, 2000) also saw the degradation of xylotrophic Basidiomycetes communities under the influence of pollution.

Finally, microclimatic conditions are usually more pessimal near emission sources (Kozlov, 2002; Vorobeichik and Pischulin, 2011; Vorobeichik et al., 2014) due to the increased fragmentation of habitats (Mukhacheva et al., 2012). According to our observations, the frequency of occurrence of open areas (“windows in a stand”) in the impact zone is much higher than in the background zone, which increases the amplitude of temperature and humidity fluctuations of CWD, which in turn can adversely affect the decomposition of organic matter (Uvarov et al., 2006). Indirectly in favor of this counts the more pronounced inhibition of decomposition in small trunks, in which the stability of the hydrothermal regime is clearly less than that of large ones.

In addition, larger trunks of trees in the background territory with a low proportion of crown participation in the general overground phytomass (Usol’tsev et al., 2010, Bergman, 2011) fall easily into their own branches and, therefore, immediately come into contact with the soil. In contrast, tree trunks in the impact zone (as a rule, of low levels of thickness) “hang” for a long time in their own crown, and this postpones the moment of their contact with the soil and thus inhibits the population of fungi. Thus, the inhibition of the decomposition of CWD may be due to all three factors. Most likely, the primary cause is the increase in toxicity of substrates, which decreases the activity of fungi, and the more pessimal microclimate enhances the effect of the first two factors.

Methodological Aspects of CWD study

The processes of formation of the CWD pool is influenced by a variety of factors, both natural (winds, fires, and damage by diseases and insect pests) and anthropogenic (improvement cutting, cleaning from felling residues, logs harvesting, etc.). Proceeding from this, the correct selection of study plots is of primary importance for unbiased results, because otherwise the possible influence of pollution on the processes of formation and transformation of CWD will be "camouflaged" by the action of interfering factors.

The above discrepancy between our conclusion about the inhibition of the decomposition of CWD near the enterprise and the results of other authors (Stavishenko, 2010, Stavishenko and Kshnyasev, 2013), which did not find this fact in the same area, can serve as a confirmation of this thesis. Firstly, in the cited papers, due to the specific nature of the route method used by the authors, usually large and medium-sized fragments of logs were included in the enumeration, which clearly underestimated the fraction of weakly decomposed CWD elements in the impact zone. Secondly, the routing records did not imply the exclusion of sites subject to natural and anthropogenic factors from the analysis. The lack of standardization of conditions (accounting transect with a length of about 100 m, as a rule, covers a wide variety of situations in the stand) could lead to the "obscuring" of the influence of pollution as such. Thirdly, the authors used a "shortened" pollution gradient: the study plots most remote from the plant were located at a distance of only 7 km. As background sites, the territory of the Visimsky reserve, located several hundred kilometers away from the MUCS, was used, and it experienced massive windthrow in the recent past. Our methodology (total counting of CWD fragments in study plots without visible signs of forest management) also cannot guarantee the complete elimination of the influence of interfering factors; however, a careful selection of study plots, in our view, allows at least a minimization of their effect.

Compared with our previous research (Bergman et al., 2015), more accurate (but more labor-intensive) approaches were used in this paper for both estimating CWD stock and characterizing the distribution of trees at the decay classes. Thus, the stock of logs fragments is determined by the direct method, not by the indirect method (at the time of the fall); the diameter is measured with an accuracy of 0.5 cm, not in steps of a thickness of 4 cm; the degree of decomposition of the substrate is determined on a five-point scale instead of the three-point scale used previously. In general, as the results of this work have shown, at a qualitative level our conclusions proved to be completely reproducible under different methodological schemes and a different set of study plots. However, the determination of the volume of CWD by a direct method allowed, firstly, to obtain a more accurate estimate of their stock; secondly, to conclude that the large trees contribute significantly to CWD stock; and, thirdly, to reveal statistically significant differences between pollution zones in the distribution according to the decay classes not only of small (Bergman et al., 2015), but also of medium and large log fragments.

CONCLUSIONS

In contrast to the expectations, it is established that the background and impact areas differ slightly in total stock/number of BWW trunks, although there is an increase in the number of CWD on the trend level as the copper smelter is approached. The mechanisms of formation of CWD stock are not the same in different zones of pollution: in the impact zone, CWD stock is primarily formed due to the greater number of trunks of low thickness levels and, in the background zone, due to a fewer number but larger fragments.

In the gradient of contamination, the distribution of trees on the decay classes changes significantly. Near the plant, the fraction of fragments at the initial stages of the decomposition increased sharply: 3.2 times in number and 4.2 times in stock, which indicates the strong inhibition of the decomposition of CWD. Such inhibition is most pronounced for small fragments.

Comparing the materials of this work with those obtained earlier (Bergman et al., 2015), it can be stated that, at a qualitative level, the results were reproducible under different methodological schemes and different sets of sites. To some extent this can serve as a guarantee of the reliability of our findings.

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