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TREE LITTER PRODUCTION AND DECOMPOSITION IN FOREST ECOSYSTEMS UNDER BACKGROUND CONDITIONS AND INDUSTRIAL AIR POLLUTION

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The paper provides an overview of Russian and foreign articles devoted to the study of the tree litter production and decomposition in forest ecosystems subjected to natural and anthropogenic factors. The spatial variability (below crown and between crown spaces) and the seasonal features of the tree litter production, its chemical composition, and decomposition processes are poorly studied. In addition, most of the works, both in Russia and foreign countries science, highlight the influence of natural factors on the litter production and the processes of its decomposition, while the impact of local sources of industrial air pollution is rarely considered. The study of the variability of the size, fractional and chemical composition and processes of decomposition of tree litter under conditions of industrial air pollution is important for predicting the dynamics of forest ecosystems subjected to the combined action of natural and anthropogenic factors and reducing the negative impact of production processes on forests.

Keywords: *forest ecosystems, tree litter, industrial air pollution, fractional composition, chemical composition, litter decomposition, litter production and decomposition seasonal variability, litter production and decomposition spatial variability*

Tree litter in forest ecosystems acts as a link between plants of the upper tiers and the soil, as a source of soil organic matter and nutrients for biota and is one of the key components of biogeochemical cycles in forest biogeocenoses. Due to its chemical composition, tree litter participates in the formation of phytogenic zones of influence of trees, suppresses or accelerates the growth of herbaceous plants, affects microbial activity, soil composition (Aponte et al, 2013; Chavez-Vergara et al., 2014; Ufimtsev, Egorova, 2016; Kolmogorova, Ufimtsev, 2018; Pomogaibin E., Pomogaibin A., 2018), contributes to changes in the composition and abundance of soil microorganisms and invertebrates during the decomposition (Rakhleeva et al., 2011). Removal of leaf litter reduces the biological activity of the upper soil horizons, depletes the forest ecosystem of mineral nutrients, slows tree growth, and reduces soil respiration (Sayer, 2005; Xu et al., 2013; Ivanova et al., 2015), whereas addition of leaf litter reduces the temperature amplitude in the soil, increases nitrogen and aluminium availability (Loydi et al., 2014) and promotes higher methane production rates (Yavitt, Williams, 2015). The adding of litter in tropical forests increased the input of nitrogen and phosphorus into the soil (Wood et al., 2009), increased the concentration of nitrates and the stocks of inorganic nitrogen in the soil (Sayer, Tanner, 2010). The forest floor formed from undecomposed plant litter acts as a physical barrier to the emergence of shoots in species with small seeds, promotes the emergence and establishment of large-seeded species, maintains a microclimate favourable for herbivores and pathogens, acting as their habitat (Sayer, 2005; Dupuy, Chazdon, 2008).

Quantitative and qualitative characteristics of tree litter are of practical interest for assessing the level of radiation pollution (Bondareva, Rubailo, 2016; Komissarov, Ogura, 2017), fire danger based on the accumulation of combustible materials (Arkhipov, 2014; Sobachkin et al., 2017), accumulation of heavy metals by tree plants in urbanized areas (Kopylova, 2012). The use of tree litter debris, mostly coniferous or foliar, as a source of cellulose (Danilova, Stepanova, 2017), sorption material (Alekseeva, Stepanova, 2015; Silaicheva, Stepanova, 2016; Shaimardanova et al., 2017; Sverguzova et al., 2017), calcium fertilizer (Petrochenko et al., 2015) is being actively investigated. In mathematical studies, data on the input and decomposition of plant litter are used to form models for estimating the participation of litter in the biological cycle, the relationship with atmospheric CO_2 and climate (Brovkin et al., 2012; Mironenko, 2017). In particular, data on the foliar litter dynamics of evergreen tropical forests in Panama, French Guiana, and Brazil were used to modify a global terrestrial ecosystem model to allow a more accurate estimate of gross primary productivity (De Weirdt et al., 2012). The elemental composition of tree litter is of interest for understanding the patterns of element cycles and soil formation (Meier et al., 2005; Wood et al., 2006; Wood et al., 2009; Vesterdal et al., 2012; Osipov, 2017).

The parameters of tree litter are studied mainly in background conditions, unaffected by industrial air pollution from large industrial plants or thermal power plants. Air pollution is known to cause degradation of forest ecosystems, changes in forest stand structure: death of conifers and their replacement by small-leaved species (Chernenkova et al., 2016), reduction of species diversity and adaptability of plant communities, death of mosses and lichens (Salemaa et al., 2004; Hale, Robertson, 2016). Acid-forming substances and heavy metals — components of emissions — cause damage to assimilating organs of coniferous woody plants (Lukina, Nikonov, 1998; Yarmishko, Lyanguzova, 2013), reduced life span of fir-needles (Lamppu, Huttunen, 2003), almost no seed production of trees and shrubs (Tsvetkov V., Tsvetkov I. 2012). At the same time, a decrease in the activity of soil microorganisms and changes in the number of micromycetes and soil invertebrates is observed in forest ecosystems, resulting in slower decomposition of organic matter and increased thickness of forest floor (Nieminen et al., 1999; Zenkova, 2000; Polyanskaya et al., 2001; Nikonov et al., 2001; Fomicheva et al., 2006; Lukina et al., 2008; Vorobeichik and Pishchulin, 2009, 2016). The accumulation of Cu and Ni in forest soils near metallurgical plants leads to a deficit of basic cations (exchangeable Ca, Mg, K) in the organic layer (Derome, Lindroos, 1998). Even when the technogenic load is reduced, the death of the stand continues (Vorobeichik et al., 2014), the value of radial growth of trees in the pollution zone remains significantly lower than the control and background values (Chernenkova et al., 2012). In the vicinity of the Severonickel Combine, coniferous forests remain in a critical condition despite a reduction in emissions (Chernenkova et al., 2011; Lyanguzova et al., 2018). In this regard, the study of the processes of formation and decomposition of tree litter, as one of the key links in biogeochemical cycles, is of particular interest for understanding the dynamics of the functioning of forest ecosystems under changing man-induced loads.

The aim of this paper is to review the current state of research on the formation and decomposition of tree litter in forest ecosystems.

METHODOLOGICAL APPROACHES TO THE STUDY OF THE CHARACTERISTICS OF TREE LITTER AND ITS DECOMPOSITION PROCESSES

International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) has developed a detailed toolkit for participants on tree litter sampling and analysis (Ukonmaanaho et al., 2016). The translated guidelines for integrated monitoring, including the methods of the ICP Forests programme, provide recommendations for both the selection of litter and the assessment of decomposition rate (Guide..., 2013). Major works analyse the methods and results of various experiments in boreal and low-disturbed forests (Berg, McClaugherty, 2008) and describe the most common and specific methods (ecological, chemical, microbiological, etc.) for studying plant litter decomposition processes comprehensively (Methods..., 2005). Study of the literature showed that field research methods vary considerably, depending on the climatic features of the area, the composition of the stand and the research objectives.

A number of modern papers present already known and proven methods for the sampling of tree litter. The most commonly used litter traps are box (preferably with a mesh bottom for water drainage) and collecting funnel located 1–1.5 m above the ground. For sampling the material directly from the ground surface, templates of different sizes are used (Table). In addition, litter is sometimes collected from the surface and without the use of a template from survey plots (Boldeskul et al., 2015; Ufimtsev, Egorova, 2016; Kolmogorova, Ufimtsev, 2018). Preston et al. (2006) simultaneously used different designs for collecting litter: plastic containers 27.3 cm in diameter and 30 cm high with a mesh bottom and 1 m2 square nets laid on the forest floor to capture the branches.

Table. Examples of the most commonly used types of tree litter collection equipment

Design	Size	Samples
Box	0.98 m^2	Bazilevich et al., 1978 Bryanin, Abramova, 2017 Abramova et al., 2018
	1 m^2	Rodin et al., 1967 Ermakova, 2009 Boev et al., 2018
	50 × 50 cm	Likhanova, 2014 Osipov, 2017 Yusupov et al., 1995
	80 × 80 cm	Kopáček et al., 2010
Funnel	0.2-0.5 m^2	Ukonmaanaho et al., 2008 Kouki, Hokkanen, 1992 Jonczak, Parzych, 2014 Berg et al., 1999 Stojnić et al., 2019 Ivanova, Lukina, 2017
Template	0.031 m^2	Reshetnikova, 2011 Vedrova, Reshetnikova, 2014
	100 × 100 cm	Bessonova et al., 2017
	0.25 m^2	Nakazato et al., 2021

The spatial variability of tree litter inflow to the soil surface is rarely considered. There are options for arranging the equipment in a non-random manner, but without specifying details (Ukonmaanaho et al., 2008); randomly (Dearden et al., 2006; Novák et al., 2014; Boev et al., 2018); evenly across the site (Yusupov et al., 1995; Stojnić et al, 2019); diagonally in sites (Albrektson, 1988); in a straight line 10 m apart (Michopoulos et al., 2020); in two lines (Meier et al., 2005; Ermakova, 2009); in a uniform grid on the site (Jonczak and Parzych, 2014); in different parts of the slope (Wood et al., 2006; Bessonova et al., 2017). A detailed study of the influence of stand structure is expressed in the distribution of equipment by parcel type (Lukina, Nikonov, 1996), below the crowns/between the crowns (Ivanova, Lukina, 2017). Tsandekova O. L. (2018), investigating the dynamics of ash accumulation in *Acer negundo* litter, conducted sampling at sampling sites in different conditions of crown density, taking into account the influence zones of trees: in sparse stands and in stands with crown closure of 50–60%, litter was collected in the subcrown and near-front zones, and in stands with crown density of 100% — in the near-trunk and intercrown zones. Similarly, in the study of the chemical composition of Scots pine litter, samples were taken in the under-crown, near-front (inter-crown), and outer zones on sampling sites in sparse (open stand), thin and dense forest stands (Kolmogorova and Ufimtsev, 2018).

The frequency of material sampling depends largely on the climatic zone in which the study is carried out, and can be done monthly/every 2 weeks during the warm period and once during the winter (Yusupov et al., 1995; Ukonmaanaho et al., 2008; Lenthonen et al., 2008; Ťupek et al., 2015; Bryanin and Abramova, 2017); monthly during the growing season without sampling for the winter period (Shpakovskaya and Rozhak, 2014); every two weeks (Wood et al., 2009); only in spring and autumn (Likhanova, 2014; Novák et al., 2014; Ivanova and Lukina, 2017); three times a year: in spring, late summer and autumn (Kopáček et al., 2010); or once in autumn (Boldeskul et al., 2015; Boev et al., 2018). In tropical forests, sampling periods counted in days (De Weirdt et al., 2012). In large-scale studies covering sites in different climates, sampling frequencies can vary from 3 to 12 times per year depending on site location (Berg et al., 1999; Berg, Meentemeyer, 2001).

In order to study the tree litter fraction composition, the plant material is sorted after sampling. Depending on the purpose of the study, only two parts could be distinguished in the litter: the fir-needles and a mixed fraction consisting of all other collected components (seeds, cones, bark etc.) (Berg et al., 1999; Berg, Meentemeyer, 2001). The litter was also divided into fractions: green needles, perennial needles and remaining fractions, while increasing the number of sampling periods (Ukonmaanaho et al., 2008). When sampling was from the ground surface, in addition to tree litter fractions (needles/leaves, bark, twigs and cones), dwarf shrub litter, moss litter, lichens, grasses could be identified (Yusupov et al., 1995; Preston et al., 2006; Reshetnikova, 2011; Hilli, 2013; Sobachkin et al., 2017; etc.). There are also papers describing an even more thorough accounting of the tree litter fractions, distinguishing fruit, buds, seeds and ament and other fractions (Ermakova, 2009; Shpakovskaya, Rozhak, 2014; Ivanova, Lukina, 2017). In terms of the study of tree litter as the L horizon of the forest floor, it is also possible to divide the plant material into active (leaves, needles, chaff, seeds) and inactive (cones, small branches, bark) fractions (Karpachevskii et al., 1980).

Studies of litter characteristics are most often devoted to a rather short observation period — up to 4-5 years, but there are also long-term studies. Ťupek et al. (2015) used data from the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) from 1996 to 2011 and studies by the Finnish Forest Research Institute (Metla) from 1960 to 2010. Lenthonen et al. (2008) studied time series for needle litter, tree growth, microstrobila (male pollinic cone) litter and daily weather data for 43 years from 1961 to 2004. In south-eastern Finland, Scots pine needle litter had been sampled over a period of 24 years (1962–1986) (Kouki and Hokkanen, 1992). Long-term observations of tree litter parameters are valuable for understanding the functioning of forest ecosystems in response to climate change.

Litter decomposition

The study of litter decomposition processes is mainly based on field experiments on incubating plant samples of active litter fractions (needles/leaves) directly in stands for periods ranging from 2-3 (Rakhleeva et al., 2011; Likhanova, 2014) to 4-6 years (Moore et al., 2006; Symonds et al., 2013). There are also studies covering just one season (Abramova et al., 2018). The frequency of sampling varies depending on the objectives of the study, climatic features of the area. When the initial decomposition stages were examined in more detail, the intervals ranged from a few days to a month (De Marco et al., 2007; Wood et al., 2009; Abramova et al., 2018). For the overall assessment of litter mass loss and changes in its chemical parameters, the periods ranged from a few months (Rakhleeva et al., 2011) and half a year (Aponte et al., 2013) to a year.

In the described incubation experiments litter samples were deposited for decomposition in mesh bags made of inert material: nylon (Rakhleeva et al., 2011), plastic (Wood et al, 2009), kapron (Likhanova, 2014), glass fibre (Ogden and Schmidt, 1997), polypropylene (Moore et al., 2006), terilene (polyethylene terephtalate) (Berg et al., 1993) with different hole sizes, which depended on the size of plant residues. For example, leaf litter from oak, birch, robinia, aspen and pine were placed in 1.5 × 1.5 mm mesh bags, while for douglas-fir litter the bags had 1 × 0.6 mm mesh size to avoid sample loss (Van Nevel et al., 2014). In studies of invertebrate participation in litter decomposition, it is possible to use a combined option where the lower part of the bag uses a mesh with smaller cells (0.5–1 mm) and the upper part with larger cells (0.2–1 cm) for biota access (Wood et al., 2009; Rakhleeva et al., 2011; Slade, Riutta, 2012). In addition to cloth bags, there are mentions of the use of 100 × 100 × 5 cm containers (De Marco et al., 2007).

The spatial patterns of litter decomposition and changes in its chemical composition are as little studied as its quantitative characteristics. An example of a study of tree influence zones can be found in the work of E. L. Vorobeichik and R. G. Pishchulin (2011), which studied the decomposition of pure cellulose in the near-trunk areas (at 0.2–0.4 m from the trunk), in the middle of crown projection (1.2–1.8 m), in the canopy gaps (3.8–5.3 m) and on the opposite side from the gap under a closed forest canopy (2–3 m from the trunk). The influence of the stand structure was also assessed when the samples were located below the crowns/between the crowns of spruce and pine forests (Lukina et al., 2017, Ivanova et al., 2019).

AMOUNT AND FRACTIONAL COMPOSITION OF TREE LITTER: NATURAL FACTORS AND INDUSTRIAL AIR POLLUTION

The quantity and quality of tree litter regulates carbon accumulation, element cycles in forests. Within the framework of the International Biological Program, work has been carried out to assess the weight and fractional composition of litter in taiga forests of European Russia (Kazimirov & Morozova 1973; Zaboeva 1975; Manakov & Nikonov 1981). Numerous long-term observations of plant litter volumes in the same years were carried out abroad (Bray and Gorham, 1964; Flower-Ellis, 1985; Kouki and Hokkanen, 1992).

Influence of natural factors on the formation of tree litter

Among the natural factors affecting tree litter formation, there is a dependence of coniferous litter mass on geographic latitude: among sites of similar fertility, the amount of coniferous litter is lower for sites located in the north (Albrektson, 1988; Berg et al., 1999). The size and composition of the litter depends on the composition of the forest stand (Shpakovskaya and Rozhak, 2014), the annual growth of trees, and their age (Pedersen and Bille-Hansen, 1999). In particular, litter mass (needles, cones and bark plus dead grass) in a mature pine forest exceeded its for a middle-aged plantation (Sobachkin et al., 2017). In recent decades, relationships between above-ground tree biomass and litter have been assessed based on long-term monitoring data (Lenthonen et al., 2008; Ukonmaanaho et al., 2008; Ilvesniemi et al., 2009; Novák et al., 2014). Thus, in the pine forests of northern Finland, the Scots pine needles litter depends on the production and mass development of needles, which occurs 4-6 years earlier (Lenthonen et al., 2008). The amount of litter may depend on weather conditions: unfavorable climatic factors, cooling, and lack of precipitation inhibit the development of plant leaf apparatus (Likhanova, 2014). A long-term study in south-eastern Finland showed a positive association of Scots pine needle litter with mean July temperature and high temperatures between March and April: the high temperature in July coincided with an increase in litter amount in the same year and the following year (Kouki and Hokkanen, 1992). In young oak stands, a positive relationship was found between annual litter and precipitation and a negative relationship with summer temperature (Novák et al., 2014). A high yield of pine seeds and cones is associated with the warm weather of previous years (Nekrasova, 1957).

Litter size exhibits species specificity, and an increase in species diversity leads to an increase in litter production (Scherer-Lorenzen et al., 2007). The average annual litter in the spruce forests of Finland was higher than that of pine forests (Ukonmaanaho et al., 2008); in the area with Siberian stone pine cultivation, there was almost three times more litter than in the spruce forest (Reshetnikova, 2011). Differences in the amount of litter fall of Hudson Bay pine (*Pinus banksiana*) and black spruce (*Picea mariana*) growing along the Boreal forest transect in northern Canada have been attributed to site conditions (soil structure and drainage) and forest floor thickness (Preston et al., 2006).

The fractional composition of tree litter, as well as its total mass, may depend on the age or species composition of the stand. In forb-green-moss pine forest of various ages in the forest-steppe zone cones and needles predominated in the fractional composition of litter. In the middle-aged stand, the needles accounted for most of the litter (52.2%), while in the mature stand the share of needles decreased to 36.7%. The participation of cones in litter is also explained by age differences in stands: in the litter of a mature stand, it is higher than in a mid-age stand (Sobachkin et al., 2017). In 40-year-old stands of the main forest-forming species of Siberia under cedar about 90% of the litter mass is needles, under pine, larch and spruce 40–50% are needles and 20–45% are branches (d ≤ 10 mm). In birch and aspen forests 70–74% of the litter mass is represented by leaves and 21–29% — by branches (Reshetnikova, 2011). High values of the mass of needle, bark, and branch litter can also be caused by the action of dangerous weather phenomena — strong winds and snowstorms (Report..., 2015).

Seasonal and spatial variability of tree litter formation

Tree litter formation processes (its mass and fractional composition) in seasonal dynamics and depending on forest canopy pattern structure are poorly studied. It is known that in spruce-beech and fir-spruce-beech forests of the Ukrainian Carpathians, most of the annual amount of litter occurs in October and November due to an increase in needles and leaves part in its composition. At the same time, the dynamics of needle supply has the form of a curve with two peaks at the beginning and at the end of the growing season and with a minimum at the beginning of autumn (Shpakovskaya and Rozhak, 2014). In a burnt forest and in control forest, the maximum inflow of litter occurs in October and the minimum — in July (Bryanin, Abramova, 2017). The bulk of the leaves of the flat-leaved birch in the forest stands of the Khamar-Daban ridge (Southern Baikal region) begins to fall at the end of the second decade of September, with a maximum rate during the third decade of September — the first pentad of October, and the bulk of the leaves of the Siberian mountain ash fall within 3–4 weeks — from the beginning of the second decade of September until the end of the first decade of October (Ermakova, 2009). In medium taiga spruce forests, the winter-spring period accounts for 52–58%, the summer period for 20–23%, and the autumn period for 22–25% of the total mass of litter (Likhanova, 2014). In 40-year-old coniferous stands of Siberia, the mass of litter in the summer-autumn period is higher than in winter (Reshetnikova, 2011). As part of a study of the role of litter in the formation of phytogenic tree fields in coal mine dumps, differences in the fractional composition of the litter horizon L were found in different zones: needles and cones dominated under the crowns, while in the outer zone the litter consisted almost entirely of meadow vegetation litter (Ufimtsev, Egorova, 2016).

Anthropogenic factors affecting the formation of litter

Fires as an anthropogenic factor lead to significant changes in the functioning of forest ecosystems. In the post-fire larch forest in the foothills of the Tukuringa Ridge (Upper Amur Region), the input of litter from the aboveground part of the vegetation was reduced by 2.8 times compared with the control forest. In addition, the fractional composition was also characterized by differences: in the control forest, there was a gradual decrease in the fractional composition of the total amount of litter in the series leaves — fir — needles — branches — grass — other fractions (33%, 26%, 21%, 11%, 9% respectively), whereas in the post-fire stand, grass litter was dominating and the fractional decrease occurred in reverse order: grass — other fractions — fir — needles — leaves — branches (28%, 23%, 22%, 20%, 7%, respectively) (Bryanin, Abramova, 2017). With a prolonged non-fire period, the branch/tree ratio in the litter increases due to reduced needle litter, resulting in a reduced decomposition rate (Dearden et al., 2006).

Air pollution with heavy metals and acid-forming substances leads to damage to the assimilating organs of coniferous woody plants and a decrease in the life span of needles — defoliation of trees is not only in phenological terms, contributing to an increase in the amount of litter (Nieminen, Helmisaari, 1996; Rautio et al., 1998; Lukina, Nikonov, 1998; Lamppu and Huttunen, 2004; Nikonov et al., 2004; Yarmishko and Lyanguzova, 2013). As pollution levels increase, the number of female cones per tree decreases (Stavrova, 1990), the proportion of large cones decreases, the number of damaged and diseased cones increases, cone diameter and average raw weight decrease (Tsvetkov V., Tsvetkov I., 2003). The proportion of epiphytic lichens in litter as an element of biogeocenosis sensitive to air pollution decreases in the area affected by Severonickel Combine emissions. At the same time, there are clear trends towards an increase in the total mass of litter due to pine needles and bark, despite a decrease in emissions over 20 years, which may be due to weakening of trees and premature die-off of individual organs (Ivanova, Lukina, 2017).

FEATURES OF THE CHEMICAL COMPOSITION OF TREE LITTER

The chemical composition of fresh tree litter determines its quality for the decomposing organisms and consequently influences the rate of decomposition and the change in the chemical composition of the plant residues during the mineralisation process. Thus, the work of N. V. Likhanova (2014) showed that birch leaves litter decomposition was the most intensive, where the C : N ratio was 35–38, while this ratio varied from 38 to 43 for spruce and pine needles, from 43 to 60 for tree branches, and from 105 to 142 for bark. The low content of nitrogen and phosphorus in the needles leads to an increase in the C : N ratio, which increases the chance of nitrogen immobilization during the early stages of decomposition (Symonds et al., 2013).

Natural factors determining the chemical composition of tree litter

Both the quantitative characteristics and the chemical composition of plant residues depend on various factors. Concentrations of Mg, N and K were found to decrease with increasing age of beech stands (Trap et al., 2013). In the artificial plantation of black locust, the N, K, Mg, P input with litter was higher in the lower third of the studied slope of Voyskovoye gully (Bessonova et al., 2017). Ca concentration in needle and leaf litter was negatively associated with annual precipitation, probably due to washout by rain and melting snow (Berg et al., 2017).

Numerous works have shown that the content of elements in the litter depends on the tree species (Preston et al., 2006; Ukonmaanaho et al., 2008; Aponte et al., 2013; Jonczak and Parzych, 2014; Boev et al., 2018; Neumann et al., 2018; Becker et al., 2018). Norway spruce (*Picea abies*) and lodgepole pine (*Pinus contorta*) needles litter contain more calcium than Scots pine needles litter (*Pinus sylvestris*). In addition, Ca concentrations in fresh litter are positively related to P, K, and Mg concentrations: for pine species (*Pinus contorta* and *Pinus sylvestris*) Ca content was positively related to Mg and Mn concentrations, for Scots pine (*Pinus sylvestris*) — with Mg content (Berg et al., 2017). In undisturbed 40-year-old Siberian stands, the carbon to nitrogen ratio in cedar litter was 101, in pine was 98, in larch and spruce — 87, in birch — 76 and in aspen — 118 (Reshetnikova, 2011).

The fauna also introduces changes in the chemical composition of plant residues. In the needles falling off after the forest desiccation due to infection of the forest with bark beetles, the concentration of N increased for 1–3 years, and the C : N and C : P ration decreased, indicating decomposition by endophytes already on the trees. At the same time, the concentrations of Mg, K, and P increased in the total litter due to an increase in the proportion of rowan litter (Kopáček et al., 2015).

Seasonal and spatial variability of the chemical composition of tree litter

Seasonal and spatial features of the chemical composition of the litter, both in Russia and abroad, have been studied rather poorly. The larch litter taken in spring was 10% enriched in N and 40% depleted in Ca compared to the litter taken in autumn. Changes in lignin : N, C : N and C : P ratios after the winter season indicated the beginning of litter decomposition (Chuldiene, 2017). According to other data, the nitrogen content in the total pine litter in the conditions of rockfall increased uniformly during the growing season (Kolmogorova, Ufimtsev, 2018). In Finnish forests, there were two main periods when C and N were deposited in the ground: May–October and November–April, with higher depositions in the first period, peaking in September (Portillo-Estrada et al., 2013). In pine forests in Poland, the Mn, Zn and Ni content in pine needles in 2007 was shown to be higher in autumn, whereas in 2009 it was higher in spring (Jonczak and Parzych, 2014). Under the conditions of the rock dump (in the reclaimed areas of opencast coal mine overburden), the content of total phosphorus in the Scots pine litter reached a maximum in the sub-crown and near-front zones of the dense stands (Kolmogorova, Ufimtsev, 2018). In the *Acer negundo* litter, greatest accumulation of the ash component occurs in the under-crown and near-trunk zones of single trees in sparse stands compared to other groups of trees and with control forest (Tsandekova, 2018).

Changes in the chemical composition of tree litter caused by anthropogenic factors

Sharp changes in the functioning of forest ecosystems caused by anthropogenic factors significantly affect the chemical composition of tree litter. In the post-pyrogenic larch forest in the foothills of the Tukuringa Range, the litter is dominated by organic remains enriched in nitrogen but poor in carbon. In larch needles on the control sample plot, the C : N ration approaches 170; in a stand damaged by fire, its does not exceed 110 (Bryanin, Abramova, 2017).

Atmospheric pollution leads to disruption of the processes of retranslocation of elements within trees (Lukina and Nikonov 1996, 1998; Nieminen and Helmisaari, 1996; Rautio et al, 1998; Steinnes et al, 2000; Kiikkilä, 2003; Tarkhanov, 2009; Yarmishko and Lyanguzova, 2013; Sukhareva and Lukina, 2014; Vacek et al., 2016). In the impact zone of the Middle Ural copper smelter compared to the control zone, more Ca was supplied with pine needle litter (Yusupov et al., 1995). The long-term effect of acid precipitation and nitrogen saturation in Czech spruce forests has caused a decrease in Ca, Mg, and Mn concentrations and Ca : Al and Mg : Al ratios, increase in N content and N : Mg ratio in the litter (Kopáček et al., 2010). In defoliating forests and pollution-induced sparse forests in the area of the Severonickel Combine, a deterioration in the quality of plant material was recorded: an increase in heavy metals Ni and Cu and a decrease in Ca, Mn, K, Mg (Lukina et al., 2017; Ivanova et al., 2019), and lignin content increased in the birch leaf litter when approaching the combine (Artemkina, 2018).

DECOMPOSITION OF TREE LITTER IN FOREST ECOSYSTEMS

The evaluation of litter decomposition processes is reflected in numerous works from all over the world. The rate of plant residue mass loss and changes in chemical composition are influenced by various environmental factors: stand composition, soil conditions, weather, microbial activity, etc. (Fig. 1). The current concept is that litter quality is the dominant factor at large spatial scales, and the activity of the decomposing organisms is regulated by climate and litter quality (Bradford et al., 2016).

Influence of natural factors on tree litter decomposition processes

One of the main factors affecting the rate of decomposition is the activity of soil biota: invertebrates, microorganisms, and fungi (Vorob'eva, Naumova, 2009). Litter decomposition in the most surface soil horizon is attributed to the predominance of saprotrophic fungi and the absence of mycorrhizal fungi (Högberg et al., 2017). However, the larger soil fauna is also influential. Slade, Riutta (2012) showed that macrofauna accounted for 22–41% of the total mass loss of leaf litter. Earthworms increased mass loss of litter with lower C : N (Belote and Jones, 2009). In a laboratory experiment, high concentrations of Cd, affecting earthworm activity, inhibit leaf litter decomposition and lead to a decrease in soil fertility (Liu et al., 2020).

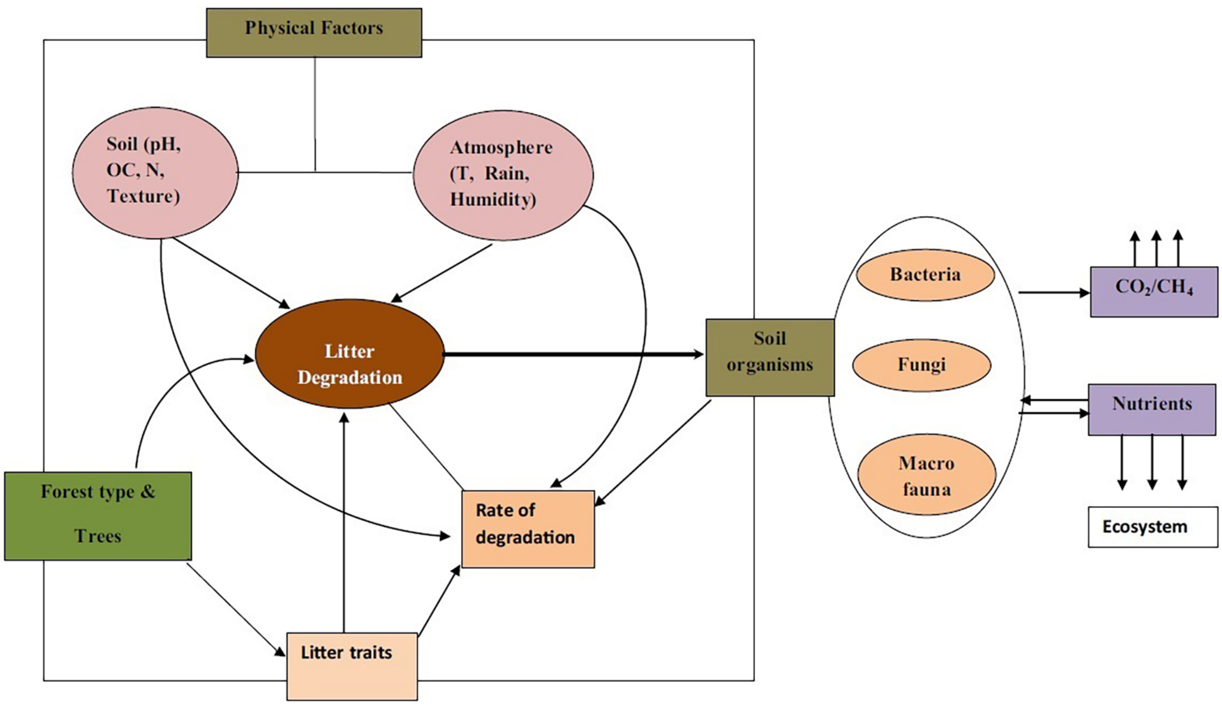

Figure 1. Factors influencing the litter decomposition processes (acc. to Krishna, Mohan, 2017)

The mineralisation of tree litter depends on the hydrothermal conditions of soils (Kuznetsov, 2010; Kuznetsov, Osipov, 2011) and is positively related to mean annual temperature and annual precipitation (Albrektson, 1988; Pausas, 1997; Portillo-Estrada et al., 2016). In Mediterranean sites, the decomposition of senescent pine needles was faster than in continental forests of the Pyrenees, and a sharper reduction in decomposition rates was observed there when stands were thinned (Blanco et al., 2011). A study on the effect of altitude on the decomposition of plant residues revealed that decomposition processes are mainly influenced by the quality of the litter. These processes do not depend so much on altitude but rather on a combination of specific conditions such as temperature, precipitation, different types of forest floor and different trophic interactions between the plants and the microbial community (Marian et al., 2017). The decomposition rate of thin woody residues (branches of different diameters) increased from north to south in a large-scale study with plots along a climatic gradient from Northern Finland to Central Estonia (Vavrova et al., 2009).

Since the fractional and chemical composition of the litter depends on the species composition of the forest stand, the process of its decomposition has corresponding features. It has been demonstrated that the dynamics of the content of elements during the decomposition of litter on Mount Vesuvius in four different pine species (*Pinus pinea*, *P. laricio*, *P. sylvestris* and *P. nigra*) is mainly governed by their original content. For example, *P. nigra* litter, the richest in nitrogen, released N during decomposition. Potassium was accumulating in *P. sylvestris litter*, while Mn was accumulating in *P. nigra* and *P. pinea* litter, which had the lowest initial concentrations of K and Mn, respectively (De Marco et al., 2007). Spruce needle litter, characterized by a higher content of nutrients and narrower C : N and lignin : N ratios, within two years was decomposing noticeably faster than pine needle litter. Wherein the litter of birch leaf (*Betula pendula*), growing in pine forests and characterized by a lower N : P ratio, decomposes faster than downy birch litter (*B. pubescens*) in spruce forests (Ivanova et al., 2019). In coastal forests of British Columbia, grape maple litter with higher concentrations of N, P, Ca, Mg, K, Fe and Zn was decomposing significantly faster than conifer litter (Ogden and Schmidt, 1997). However, the rate of degradation of pure cellulose is higher in spruce-fir forests than in birch forests (Vorobeichik and Pishchulin, 2011). Subordinate foliage plants with sharply contrasting feeding and water yield characteristics compared to the dominant evergreen plants significantly influenced litter decomposition at the community level, despite their low abundance (Guo et al., 2020).

A number of experiments in different types of terrestrial ecosystems have shown: the decomposition process depends on the fractional composition of the incoming litter (Bobkova, 2000; Fang et al., 2015). In undisturbed of 40-year stands in Siberia, woody species that annually shed their leaves (needles): larch, aspen and birch (Reshetnikova, 2011; Vedrova, Reshetnikova, 2014) are characterized by the maximum mass loss in the annual cycle of decomposition.

Many studies have shown the influence of the initial quality of the litter, determined by concentrations of nutrient, heavy metals, element ratios, on the decomposition rate (Berg, 2000; Wardle et al., 2003; De Marco et al., 2007; Zhang et al.,2008; Berg, McClaugherty, 2008; Rahman et al., 2013; Tu et al., 2014; Lukina et al., 2017; Ivanova et al., 2019). Litter with a higher nitrogen content decomposes faster than those with low nitrogen and high lignin concentrations (Wardle et al., 2003). Accordingly, the stoichiometric C : N and lignin : N ratios in plant residues have a significant effect on decomposition: the narrower these ratios, the higher the rate of decomposition (Berg and McClaugherty, 2008; Lukina et al., 2017; Ivanova et al., 2019). At the early stages of decomposition, nitrogen has a stimulating effect, while at later stages, on the contrary, it inhibits the decomposition rate, while Ca and Mn have a significant positive effect (Berg, 2000; Berg and Meentemeyer, 2001; Davey et al., 2007; Berg, 2014). Some authors have studied an excessive intake of one element, most commonly nitrogen. Tu et al. (2014) found that high nitrogen input reduced the rate of decomposition in forests, and the mass of undecomposed litter was closely related to residual lignin during the decomposition process. During the early stages of decomposition, nutrients such as nitrogen and phosphorus as well as water-soluble organic compounds have the greatest effects, whereas in the later stages lignin is the main determinant of decomposition dynamics (Rahman et al., 2013). Mineral N application or mixing of litter of different quality, expressed in C : N ratio and N content, increased the intensity of mineralization of N-poor litter fractions and inhibited the release of CO_2 during the decomposition of N-rich litter (Bonanomi et al., 2014; Larionova et al., 2017). Under the conditions of the incubation experiment, sodium chloride and sodium sulphate exhibited an inhibitory effect on the biota involved in the decomposition of birch litter, while, in contrast, when the litter was treated with solutions of iron salts, an increase in the mineralising activity of the biota was observed (Smirnova et al., 2017).

Changes in the chemical composition of plant residues during decomposition

In the process of mineralization of plant material, changes in the chemical composition are observed. Pine and spruce needle litter at the initial stages of decomposition (up to 165 days) releases monoterpene hydrocarbons in the gas phase at a rate comparable to emissions from living needles of these trees (Isidorov et al., 2010). In undisturbed 40-year-old Siberian stands, as plant residues decompose, their carbon, P and K contents decrease and Mg concentration increases (Reshetnikova, 2011). Changes in the content of elements can be interrelated. In the subarctic to cool-temperate highlands of Canada, the decomposition of assimilating tree organs litter usually retained N in the decomposing litter until about 50% of the initial C remained. Peak N content in litter was observed to be between 72% and 99% of the original remaining C with C : N ratios ranging from 37 to 71. The rate of phosphorus loss inversely correlated with the initial concentration of phosphorus in the litter, which varied from 0.02% to 0.13%. There was a trend toward higher nitrogen and phosphorus retention during litter decomposition at sites with lower C : N and N : P ratios, respectively (Moore et al., 2006). As the leaf/coniferous litter decomposes, an increase in Ca concentration is shown, often followed by a decrease. The maximum calcium concentrations are positively related to manganese and negatively related to nitrogen, which can have a direct influence on the decomposition rate (Berg et al., 2017).

Seasonal and spatial variability of tree litter decomposition

Seasonal and spatial patterns of decomposition, in turn, depend largely on the activity of soil destructors and the influence of trees: in winter the process slows down considerably (Vorob'eva, Naumova, 2009). Litter mass losses in spruce and pine forests were higher between tree crowns compared to undercrown spaces (Lukina et al., 2017; Ivanova et al., 2019), but net cellulose degradation rates were higher in spruce-fir and birch forests under tree crowns compared to canopy gaps (Vorobeichik and Pishchulin, 2011).

Anthropogenic factors influencing the processes of decomposition of tree litter

Forest management can change the rate of decomposition and cycling of elements. In beech and spruce forests with high intensity forest management, higher rates of litter decomposition and release of most nutrients were observed than in unmanaged deciduous forests (Purahong et al., 2014). In a plantation of Chinese pine (*Pinus tabulaeformis* Carriere), N during litter decomposition was accumulating until the ratio of acid-non-hydrolysable residues to nitrogen was reached 57–69. At the same time, thinning accelerated the decomposition of nitrogen-poor litter and also increased nitrogen accumulation (Chen et al., 2014). In 4–6-year old cutover patches after clear-cutting in medium taiga spruce forests, the highest decomposition rate was observed for birch leaves in the first year, while for spruce and pine needles an increase in decomposition rate was observed in the second year of the experiment. The tree litter components belonging to the inactive fraction (branches, bark, cones) were decomposing very slowly (Likhanova, 2014). In the post-fire larch forest (12 years after the fire), in the initial stages of decomposition, as well as in the control larch forest, the maximum losses were observed in the first 75 days of the experiment, and the decomposition rate in the studied forest ecosystems decreased in the series: grass–leaves–needle–branches (Abramova et al., 2018).

The extremely change in the litter decomposition processes is brought about by airborne industrial pollution. In the area affected by airborne emissions from the smelter, the proportion of poorly decomposed dead wood was higher than in the background area in the southern taiga, indicating a strong inhibition of tree residues degradation (Bergman, Vorobeichik, 2017). Soil contamination with heavy metals (Cu, Pb, Cd, Zn) reduced the rate of cellulose degradation in spruce-fir forests and birch forests by 2.7–5.4 times (Vorobeichik, Pishchulin, 2011). The use of tree-ring dating and an exponential decomposition model made it possible to determine that pollution had led to a decrease in the rate constant of wood decomposition by 16–60% (Dulya et al., 2019). In the Sudbury (Ontario) copper-nickel smelter impact area, a decrease in the rate of litter decomposition was observed (Freedman, Hutchinson, 1980). There, during the period of significant emission reductions, a decrease in the decomposition rate of white birch (*Betula papyrifera* Marshall) leaf litter was still observed and an increase in Cu and Ni in the litter was recorded, indicating that atmospheric inputs of Cu and Ni from Sudbury smelters remained high enough at the time of the 1999–2001 experiment to have a negative impact on degradation processes (Johnson, Hale, 2004). Scots pine needle litter 0.5 km from the Outukumpu copper smelter in the Harjavalta region in southwestern Finland had the lowest mass loss rate — 28.1%, while in the background it was 37.9% for the entire time. In addition, copper and nickel accumulation and a decrease in the carbon/nitrogen ratio have been observed in the impact zone over time (McEnroe and Helmisaari, 2001). In Belgium, in sandy soils contaminated with metals, a change in chemical composition during decomposition was observed: samples with initially low metal content were enriched in Cd and Zn, while metal losses were observed for samples with high content (Van Nevel et al., 2014).

In the vicinity of the Severonickel Combine near Monchegorsk, a decrease in the rate of decomposition of birch leaves was observed (Kozlov, Zvereva, 2015); in spruce and pine forests, a decrease in the rate of litter decomposition was noted, associated with a decrease in litter quality: increased initial content of heavy metals Ni and Cu, low content of nutrients and an increase in the lignin : N, C : N ration. In addition, during decomposition, plant residues in spruce and pine forests lost Ca, Mn, K, and Mg more intensively compared to the background and accumulated lignin, Al, Fe, Ni, and Cu (Lukina et al., 2017; Ivanova et al., 2019).

CONCLUSION

Tree litter acts as a link between tree vegetation and soil. Data on the content of elements in the litter allows us to estimate the amount of elements entering the soil and predict the rate of decomposition, during which the elements are released and re-engaged in biogeochemical cycles. In recent decades, factors affecting the litter formation and decomposition, taking into account the producing species, have been extensively investigated. Although the quantitative and qualitative characteristics of tree litter and its decomposition and mineralisation processes have been studied, the spatial and seasonal variability of these parameters and processes have been studied insufficiently. There are not enough studies devoted to the influence of local sources of air pollution — metallurgical complex enterprises, thermal power plants, nuclear power plants and others — on the tree litter. Understanding the processes of adaptation of forest ecosystems to climate change, the variability of ecosystem functions of forests requires research into the variability of size, fractional composition, chemical composition and decomposition processes of tree litter, taking into account seasonal and spatial variability (forest canopy pattern structure) under conditions of combined natural and anthropogenic factors, including atmospheric pollution. This will improve forecasts of further changes in forest ecosystems and develop recommendations for optimizing production processes to reduce the impact on forest ecosystems.

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