Supplementary material related to the article: Valery A. Isidorov, Andrej A. Zaitsev. **VOC emissions from soil cover in boreal and temperate natural ecosystems of the Northern Hemisphere**

Litter and LSC biomass distribution

To evaluate the role of the forest leaf litter and LSC in the emission of VOCs into the atmosphere, it is necessary to obtain data not only regarding their emission rates under environmental conditions but also on the mass of the soil cover, both its 'dead' and 'living' compartment. It may seem that the masses of these compartments of the forest floor are difficult to formalise, and therefore, it is difficult to include them in appropriate models.

For use in atmospheric transport models, fairly accurate inventories of the foliar biomass densities for the main tree species have previously been made (Karl et al., 2009; Sindelarova et al., 2014). Taking as a first approximation that in autumn, all the foliage of deciduous trees falls to the ground, the results of these inventories can be used to determine the biomass of the litter of these species. It is likely that the data obtained should be corrected taking into account differences in the biomass values of photosynthetic and yellowed foliage, associated with the outflow of some of the metabolites and water. For species not included in early inventories, allometric ratios can be obtained or found in the literature, allowing one to obtain the required estimate of foliage/litter mass (Matthews, 1997; Somogyi et al., 2008; Teobaldelli, 2008; Park, 2015).

The determination of the litter biomass of evergreens losing foliage throughout the year requires a different approach. In particular, this applies to uneven-aged coniferous forests. It may seem that data on litter mass in such forests are difficult to formalise and therefore difficult to include in appropriate models. However, forests are highly organised systems, and foresters have long established the regular nature of changes in all elements of forest ecosystems (including leaf litter and LSC) in the process of their development (Molchanov, 1971; Kuzmichev, 1977; Antanaitis et al., 1986). Therefore, it is possible to establish a relationship between the main taxonomic characteristics of the stand and the mass of leaf litter in it. In particular, Russian foresters have identified certain patterns in the dynamics of biomass in the vast pine forests of the taiga zone, including litter and plants of the living soil cover (Molchanov, 1971; Vakurov, 1973; Manakov, 1978; Kozhevnikov et al., 1985). For example, on a large volume of field measurements in the pineryes of this zone, it was found that the biomass of coniferous litter (needles) in them increases with age and reaches a maximum at the age of 50–70 years, after which it begins to decrease. A typical trend is shown in **Figure S1** for a blueberry pine forest in southern Karelia.

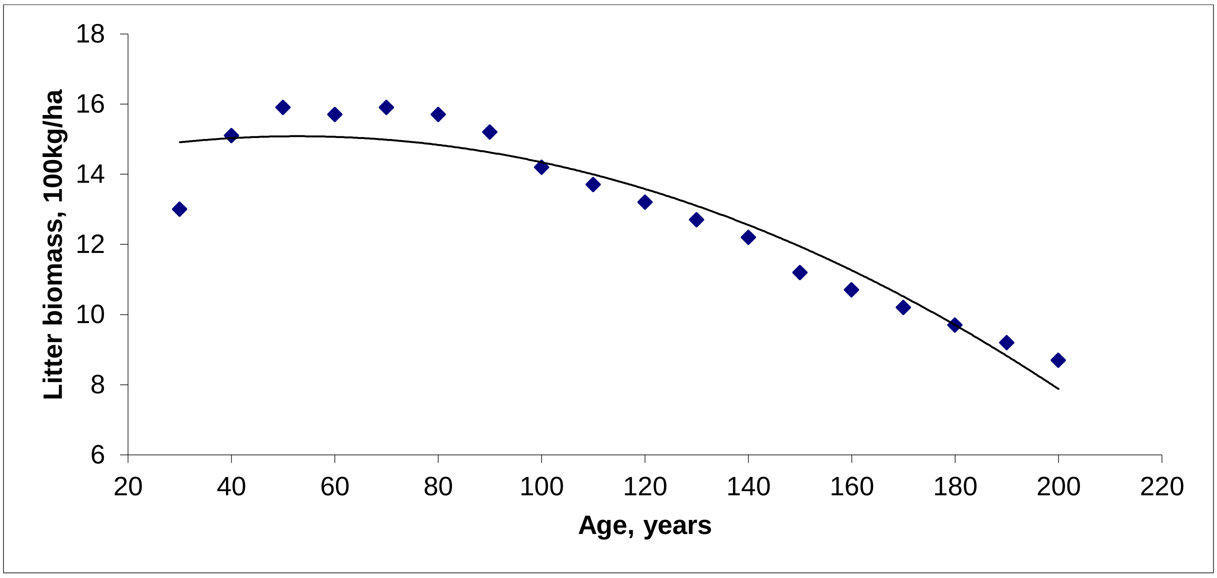

Fig. S1. Dynamics of the mass of coniferous litter (M) in the southern taiga forest-blueberry in Karelia (Russia) depending on age (A). $M = -0.0003A^2 + 0.0351A + 14.157$, $R^2 = 0.9133$. The graph is built according to the tabular data given in the book by Zyabchenko (1984).

However, the accumulation of litter biomass does not pass through a maximum in all forests of the boreal zone. For example, for three types of forests of Evenkia (northeastern

Siberia), consisting of Siberian larch, according to the results of a field study, Krasikov (1985) proposed an exponential equation:

$$M = A^{a''} \times e^{(b'' + c'')}$$

where M is the leaf litter mass (t ha^{-1}) and A is the forest age (years). **Table S1** provides the values of the coefficients *a''*, *b''* and *c''*.

Table S1. The coefficients of the equation for different type of Siberian larch forests.

Forest type	*a''*	*b''*	*c''*
Grassy larch forest	0.837	-2.154	0.00038
Green moss forest	1.159	-3.457	0.00068
Swampy larch forest	0.834	-3.640	0.00077

This unusual biomass trend in deciduous litter owes to the climatic characteristics of this vast region (with an area of 767.7 thousand km², which is comparable to countries such as Turkey and Chile), characterised by long, harsh winters and short but hot and dry summers. Under these conditions, litter decomposition occurs very slowly and accumulates throughout the life of the forest (forest fires play an important role in litter destruction here).

Unfortunately, we were unable to find similar formalized data for deciduous forests. In the literature, one can find only a few reports on this topic, some information of which is presented in **Table S2**.

Table S2. Leaf litter production rate of some shrubs in the Mediterranean region (Viros et al. 2020).

Species	Leaf litter production, $g \cdot m^{-2} \cdot yr^{-1}$	Reference
Cistus albidus (grey-leaved cistus)	637	Rodroguez-Ramirez et al., 2017
Rosmarinus officinalis (rosemary)	385	Rodroguez-Ramirez et al., 2017
Ulex parviflorus (Mediterranean gorse)	323	Rodroguez-Ramirez et al., 2017
Cotinus coggygria (smoke bush)	117	Viros er al., 2020

Quercus coccifera (kermes oak)	538	Arianoutsou, 1989

Analysis of works published in recent years shows that litter is measured in the framework of research on specific sites (Gomez-Armesto et al., 2020; Petritan et al., 2020; Jasińska et al., 2020; Brumme et al., 2021; Ott and Watmough, 2021). For a number of those studies cited in **Table S3**, the refinement of litter biomass is a subordinate task that allows to obtain, when recalculated, data on the mass of chemical elements, for example, C, N, P, Hg, etc., to describe their accumulation in litter and to establish the quantitative series of chemical elements and their ratio (C/N) (Jasi'nska et al., 2020). As a rule, the discussion analyses the local dependences of litter mass on a number of factors: correlation with the basal area, forest inventory characteristics, the effect of microrelief, etc. In some works, long-term data on litter are used to develop a predictive model of annual litter in forests (Saarsalmia et al., 2007).

Table S3. Litter production in some types of forests in the boreal belt of Europe and America

Species	Woods characteristic, position	Leaf litter production, g $m^{-2} \cdot yr^{-1}$	Reference
Norway spruce (*Picea abies*), sitka spruce (*Picea sitchensis*), beech (*Fagus sylvatica*)	south Jutland, Denmark at the Lindet State forest district in Lovrup forest	Norway spruce – 342 sitka spruce - 352 beech - 311	BoPedersen and Bille-Hansen, 1999.
Norway spruce (*P. abies*)	Upland forest site types of Finland	27-465	Saarsalmia, et al., 2007
European beech (*Fagus sylvatica*) – Silver fir (*Abies alba*)	Mixed beech – silver fir portion of the Sinca virgin forest (45°40' N, 25°10'E)	180 -830, Mean – 350. Beech – 66%, silver fir – 16%	Petritan et al., 2020
Scots pine (*Pinus sylvestris*)	Scots Pine Forest, Inland Dunes Toru ´n Basin (N Poland) (52°33' N, 18°25' E)	169.7±7.2 – 183.3±17.7	Jasińska et al., 2020
Oak (*Quercus robur*)	Iberian Peninsula, Atlantic deciduous forests: oak (*Q. robur*), chestnut tree (*Castanea sativa*), maple (*Acer pseudoplatanus*) or deciduous *Prunus* sp. (42^0 25'N; 8^0 04'W)	Total: 2015 - 716±62; 2016 - 583±59; oak, 2015 - 63 %, 2016 - 54 %. Leaves of tree species different from oak, plant debris and flowers: 2015 - 27%; 2016 - 36%. Twigs thinner than 5 mm of diameter: 10%	Gomez-Armesto et al., 2020
European beech (*F. sylvatica*)	Germany woods: Bavaria at Bad Brückenau, Freising, Ebrach, Lower Saxony at Solling, Göttinger Wald, Hesse at Homberg, Rhineland-Palatinate, Kirchheimbolanden Neuhäusel, Neuhäusel Quarz	Mean 312	Brumme et al., 2021
Sugar maple (*Acer saccharum*),	Haliburton Forest and Wild Life	Balsam Fir - 240	Ott and Watmough,

American beech (*Fagus grandifolia*), eastern hemlock (*Tsuga canadensis*), yellow birch (*Betula alleghaniensis*)	Reserve ($45^0$13' N, $78^0$35' W)	Eastern Hemlock - 180 White Pine - 120 Sugar Maple – 3,2 Yellow Birch - 250	2021

According to Bobkova (2007), who determined the litter of needles and leaves in the northern taiga spruce forests of the Komi Republic, northeast of the European part of Russia (64° 30 'N 55° 30' E), in the old-growth blueberry-moss spruce forest of V bonitet, with a wood reserve of 86.94 t ha^{-1}, the annual needle and leaf litter is 0.75 t ha^{-1}, and in the sedge-sphagnum spruce forest of V bonitet, with a timber reserve of 108.65 t ha^{-1}, the litter accounts for 0.96 t ha^{-1}. In the old-age middle taiga spruce forest with long moss-sphagnum (62° 00 'N 50° 30' E), with a reserve of 156.19 t ha^{-1}, the annual litter production is 1.97 t ha^{-1}.

At the same time, studies that interpolate data for geographic taxa of a high hierarchical level (e.g., natural belt) and describe universal geographic characteristics are rare. These include the work of Liu et al. (2003), who provide the characteristics of the mass of leaf litter for boreal forests of Eurasia: the mass of litter averages 261 ± 108 $g·m^{-2}·yr^{-1}$, with an amplitude of 27–508 $g·m^{-2}·yr^{-1}$. The leaves account for 188 ± 77 $g·m^{-2}·yr^{-1}$, with an amplitude of 23–374 $g·m^{-2}·yr^{-1}$. The annual leaf litter production in the boreal forests of Eurasia, according to the authors' calculations, is 1.49 ± 0.61 10^{15} $g·yr^{-1}$, with a total aboveground litter production of 2.07 ± 0.85 10^{15} $g·yr^{-1}$.

Plants of the living soil cover also participate in the formation of the organic matter of forest communities. The mass of this layer in the process of age-related development of the stand changes, but the nature of this change in forests of different types has not been sufficiently studied. Part of the data obtained for the coniferous forests of the boreal zone of Russia have been summarised by Zyabchenko (1984). In particular, this study reports that in the blueberry pine forests of Karelia, the grass-shrub layer is dominated by blueberries (*Vaccinium myrtillus*), red bilberry (*Vaccinium vitis-idaea*) and grasses, among which the most represented are *Melampyrum pratense*, *Avenella flexuosa* and *Maianthemum bifolium*.

The biomass of this layer in the process of the age development of the forest increases from 1.2 t ha^{-1} in young (20 years) stands to 7.6 t ha^{-1} in 110-year-old stands and remains at this level. In addition, green mosses play an important role in this type of forest; their phytomass varies from 1.3 t ha^{-1} in young stands to 7.2 t ha^{-1} in mature stands. Thus, the total phytomass (M, t ha^{-1}) of LSC in forests of this type varies, depending on the age (A, years), from 5.5 to 9.3 t ha^{-1} of absolutely dry matter (**Fig. S2**) and can be described by the following equation:

$$M = -0.0013A^2 + 0.5642A + 36.672 \ (R^2 = 0.937).$$

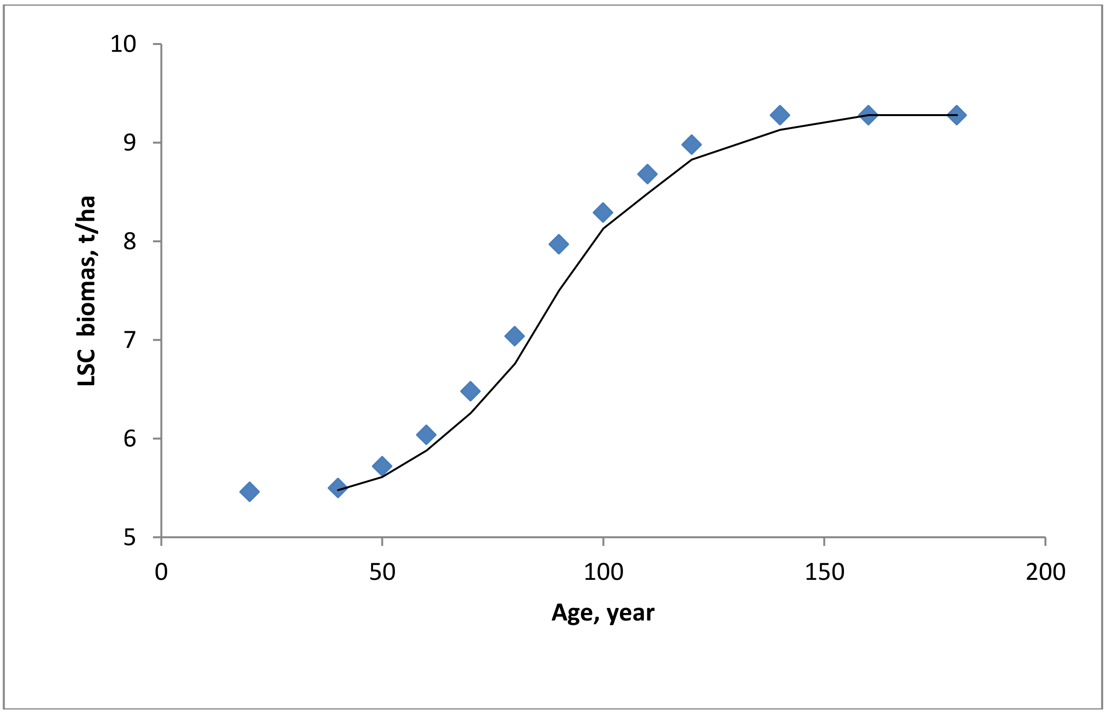

Fig. S2. Changes in the phytomass of the living soil cover (LSC) in blueberry pine forests of Karelia depending on age, after Zyabchenko (1984).

The current increment of the LSC biomass increases to 130 years old from 0.9 to 1.8 t ha^{-1} yr^{-1}, and this value remains constant. In young forests up to about 40 years old, biomass growth occurs mainly due to subshrubs (0.5–0.6 t ha^{-1} yr^{-1}), whereas in older plantations, it occurs due to mosses and lichens (0.6–1.5 t ha^{-1} yr^{-1}). The phytomass litter of LSC (mainly bilberry foliage) varies from about 1.8 t ha^{-1} in 20-year-old forests to 2.3 t ha^{-1} in 200-year-old blueberry pine forests of the southern taiga zone (Zyabchenko, 1984).

In the pine forests of the northern taiga zone, the dynamics and composition of the LSC are different: its biomass changes from 6.8 to 8.5 t ha^{-1} with increasing forest age and remains approximately constant after reaching 50–60 years of age. At the same time, mosses and lichens predominate (71–82%) in the total biomass, and the proportion of dwarf shrubs decreases with age. Most of the dwarf shrubs of the northern taiga under the canopy of closed forests during the 200-year period of development have the same phytomass: red bilberries 0.45 t ha^{-1}, blueberries (*Vaccinium uliginosum*) and crowberries (*Empetrum nigrum*) 0.20 t ha^{-1} each, marsh tea (*Ledum palustre*) 0.25 t ha^{-1} (Zyabchenko, 1984).

The age and biotopic variability of the phytomass reserves of plants in the soil cover are given by Osipov et al. (2014) for the northern taiga (Komi Republic) post-pyrogenic pine forests of different ages. For a humid 60-year-old blueberry pine forest, the phytomass reserve is 3.53 t·ha^{-1}; in the same 94-year-old forest, the phytomass reserve of LSC plants decreases to 2.08 t·ha^{-1}. A similar decrease in plant phytomass with forest age is observed in the blueberry-sphagnum pine forest: in a 60-year-old forest, the stock is 4.37 t·ha^{-1}, whereas in a 90-year-old forest, it is 2.03 t·ha^{-1} (**Table S4**).

Table S4. Plant phytomass of the soil cover of pine plantations (kg ha^{-1} absolutely dry matter) (Osipov et al., 2014)

Life form, species	Moist blueberry pine forest		Blueberry sphagnum pine forest	
	Age, years		Age, years	
	60	94	60	90
Dwarf shrubs:				
Vaccinium myrtillus	549 ± 19	946 ±90	767 ± 18	986 ±110
V. vitus-idaea	539 ± 9	309 ± 50	234 ± 9	76 ±10
V. uliginosum	536 ± 22	69 ± 40	369 ±9	71 ± 20
Empetrum nigrum	30 ± 0,6	19 ± 2	-	47 ± 10
Ledum palastre	< 1	168 ± 70	181 ± 7	<1
Andromeda polifolia	<1	< 1	-	-
Chamaedaphne calyculata	-	-	<1	<1
Herbs	94 ±1	29 ± 6	367± 8	73 ±10
Mosses:				

green	1092 ± 19	423 ±40	294 ± 3	92 ±50
polytrichous	289 ± 9	-	118 ±9	<1
sphagnum	414 ± 13	118± 40	2018 ±18	923 ±50
Lichens	10 ± 0,8	<1	21 ±0,9	<1
Total ground mass	3533 ± 26	2083 ±1	4369 ±28	2304 ± 80

In the structure of the phytomass of soil cover plants, as phytocoenosis develops, as a result of postpyrogenic succession, an increase in the proportion and a decrease in the proportion of mosses occurs. With an increase in the degree of soil moisture, a more intensive development of the grass-dwarf shrub and moss layer is observed (Osipov et al., 2014).

In another study (Gordina, 1979), the productivity of the aboveground phytomass of Siberian lichen pine forests was studied on a territory of 3.14×10^6 ha. The living soil cover in these forests consists mainly of red bilberry and bearberry (*Arctostaphylos uva-ursi*); the continuous lichen cover in them is formed by *Cladonia* sp. and, less commonly, *Cetraria* sp. and green mosses (*Polytrichum* sp.). The relationship between its mass (M, 100 kg ha^{-1}, absolute dry weight) and stand age (A, years) is represented by a polynomial of the second degree:

$$M = 0.0657A + 0.000096A^2 - 1.16$$

with a bias of + 4.2% and a random error of ± 14%.

The living ground cover of forests, along with their tree canopy, is involved in the formation of litter, but there is little information about the extent of this phenomenon. For example, in the already cited work Bobkova (2007) for low-productive spruce forests in the northern taiga zone of Russia (Komi Republic), data on the stock of phytomass of LSC plants, as well as on the biomass of litter formed by them, are given (**Table S5**).

Table S5. Phytomass stock of the living soil cover of spruce forests in the Komi Republic and its annual litter, t ha^{-1} (Bobkova, 2007)

LSC components	Blueberry long-moss spruce forest		Sedge-sphagnum spruce forest		long-moss-sphagnum spruce forest	
	stock	litter	stock	litter	stock	litter
Dwarf shrubs	0.93	0.27	0.29	0.05	0.27	0.07
Herbs	0.23	0.23	0.57	0.57	0.57	0.24
Mosses	5.25	1.3	2.46	0.42	0.42	0.27
Lichens	0.03	0.01	0.03	-	0.03	0.01
Total	6.44	1.81	3.35	1.04	1.29	0.59

In many areas, boreal coniferous forests are subjected to clear felling, and in their place, pine-deciduous stands with various participation levels of birch, aspen, mountain ash and grey alder appear. These plantations are characterised by an intensive accumulation of phytomass as they are at the initial stage of development, but their composition and dynamics have not been sufficiently studied. Part of the phytomass of the stand goes to the forest floor, whereas in forests with a predominance of deciduous species, its percentage is higher. Due to the LSC, 0.38–0.57 t ha^{-1} of organic matter passes into litter, which is 10–16% of the total litter in forests over a period of 30–40 years.

The current trend in geobotany and forestry is the creation of large databases containing copies of national and regional vegetation-plot databases on a single software platform (Holland et al., 2015; Chytrý et al., 2016; Bonary et al., 2019; Jašková et al., 2020; Sabatini et al., 2021). These databases provide useful information on the abundance and projective cover of dwarf shrub species as well as herbaceous plants, lichens and mosses. In particular, the European Boreal Forest Vegetation Database includes vegetation-plot records of all types of forest communities in the boreal and semi-boreal zones from Iceland, Scotland, Norway, Sweden, Finland, Estonia, Latvia, Lithuania, Belarus and the European part of Russia between the 53th and the 69th parallel (Jašková et al., 2020).

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