Plant-to-soil pathways in the subarctic – qualitative and quantitative changes of different vegetative fluxes*

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ABSTRACT

Considering plant-to-soil pathways, decomposition of vegetative fluxes such as litter and litterfall is one of the important processes that adjust the carbon cycle and nutritional elements in the formation of a forest's organogenic horizon. However, there is little information available on this subject, and the fractional structure (amount, type and interrelation) of organic matter also seems to receive little attention. Using 7 different vegetative samples, a field study was performed over 3 years to find the relation between phenolics content and mass losses in the subarctic region (N66° and E31°). In addition, climate effects on this relation were investigated. The data obtained from this field study testify that (i) an intensive loss of organic matter occurred in active parts of various litterfalls and (ii) leached phenols were related with mass losses (decomposition rates) of vegetative fluxes (litterfalls and litters) to the soil. The statistic analysis suggests that (iii) total mass losses of samples (except litter) were connected with both the temperature sum and the precipitation sum, and (iv) phenolics losses also had a similar trend in different kinds of litterfall.

INTRODUCTION

In a plant-to-soil pathway, decomposition of vegetative fluxes such as litter and litterfall is one of the important processes that adjust the carbon cycle and nutritional elements in the formation of a forest's organogenic horizon. This decomposition rate depends upon the litterfall amount and litter quality, and the contents of nitrogen and lignin are very important (e.g. C/N ratio). However, there is little information available on this subject (Ajtay et al. 1997), and the fractional structure (amount, type and interrelation) of organic matters – cellulose, hemicellulose, carbohydrates, proteins, lipids and polyphenols – also seems to receive little attention in the quantification of the decomposition rate. Generally, the accumulation of organic matters in soil takes place in cool areas. On the other hand, in tropical lands, organic matters are decomposed faster than they are supplied from plant to soil (reviewed by Ajtay et al. 1997). Therefore, we carried out a field study to carefully inquire into the relation between quantitative change (mass loss) and qualitative changes (organic matter dynamics) in various vegetative fluxes from plants to soil in a subarctic region over 3 years.

A model suggests that decomposition processes in the boreal zone are divided into two basic stages (Berg and Staaf 1980; Berg et al. 1987): (i) at the first stage, the decomposition rate mainly depends upon the content of water soluble components, the nutritional status and climatic conditions; and (ii) at the second stage, the content of lignin influences the litterfall decomposition. Initial rates of litterfall mass loss are closely connected with initial concentration of water-soluble organic compounds (Berg and Tamm 1991). Instead of a modeling technique, our study intended to directly observe the decomposition processes at each stage in the field.

Some basic groups of organic compounds are recognized as most mobile during the initial stage of litterfall degradation: hydrolized phenolic forms (in particular, tannins) (Kraus et al. 2003) and monomeric phenolic forms (Gallet and Pellissier 1997). Published data (Lorenz et al. 2000) have shown the necessity of inclusion of polyphenols forming complexes with proteins, in a complex of parameters defining litterfall quality under estimation of the decomposition rate. As soluble forms are characterized by high-reactionary ability, they are connected directly with not only the decomposition rate but also nutritional elements, defining their cycles. This interaction occurs through two basic ways (Hättenschwiler and Vitousek 2000): (i) via influence on activity of soil organisms; and (ii) via physical and chemical influence on pools and forms of nutritional elements. In turn, most stable polymeric phenolic forms (e.g. lignin and condensed tannins) influence the formation of mor-type humus, delay of nitrogen mineralization

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and deposition of nutritional elements in a pool of organic matter with low availability (Northup et al. 1998). Thus, attention was focused on phenolic dynamics as an indicator of organic compounds. The main purpose is to investigate the phenolic effects on mass loss. In addition, the relation between climate and these effects is discussed.

MATERIAL AND METHODS

A field survey was conducted in a subarctic region of the Kola Peninsula (the most northern region of the European fringe of Russia) over 3 years in order to achieve the above-mentioned purpose. Needles and wood of *Picea obovata* Ldb. were sampled because the previous study in this field (Lukina and Nikonov 1996) showed that litterfalls were dominantly (~65%) composed of these materials. The amount of bark litterfall originating in *Picea obovata* Ldb. is small (Lukina and Nikonov 1996), but this was also sampled for the reason that its high content of tannins is well known (Hernes and Hedges 2004). Leaves of other species were collected as supplemental samples. Site characteristics and the applied procedure are described below.

Site characteristics

Sixteen sample plots were located in the survey field (N67°51'08" and E32° 47'49" to N66°50'45" and E30°12'34") of the Institute of the North Industrial Ecological Problem. This paper reports the data obtained from the background plot situated 260 km to the south-west of the Monchegorsk industrial complex on the Kola Peninsula. The monitoring site is covered with Al-Fe humus podzols and is situated in spruce forest (mainly *Picea obovata*) with green mosses and dwarf shrubs. Such forest is widely distributed and known as a common forest ecosystem in Northern Fennoscandia.

Sampling

The samples were collected by the litterbag method from October 1996 to October 1999: (i) different litterfalls – *Vaccinium vitis-idaea* leaves (abbreviated as V. v.), *Vaccinium myrtillus* L. leaves (V. m.), *Picea obovata* Ldb. needles, bark and wood (P. o. (n), P. o. (b) and P. o. (w), respectively), *Empetrum hermaphroditum* leaves (E. h.); and (ii) litters – the sampled litter contained reproductive and dead parts of the aforementioned various plants.

Synthetic mesh bags (10×10 cm) with breathability were prepared. Fresh litterfalls (e.g. browned needles, leaves, etc.) were picked off from tree branches and dwarf shrubs in October 1996 and 10g of litterfall was put in each bag. After these bags were sealed to prevent other litterfalls from entering the bags, the sealed bags were placed in two different sites on each sample plot – under the canopy and in canopy gaps. Litter was sampled from the soil O-horizon under the canopy and in canopy gaps in October 1996 and processed in a similar way to the above-mentioned litterfall method. All the samples underwent the decomposition process in the mesh bags during the survey period. Every time one litterbag for each research subject was picked up from the study plots in October 1996 (0 year), October 1997 (the 1st year), October 1998 (the 2nd year) and October 1999 (the 3rd year), determination was conducted in the laboratory for finding mass loss and losses of phenolics contained in the litterfall and litter.

Methodology

Mass loss and phenolic content were determined as follows: (i) the samples were dried at room temperature, and sample humidity for dry-base weight was determined by the hygroscopic coefficient after the litterfall was dried in a desiccator at 105°C; sample masses were weighed with a scale in order to assess their losses on dry base; and (ii) after sub-samples were milled and digested with concentrated HNO_3, phenolics were extracted with ethanol, and then the extracted phenolics were determined by the Swain-Hillis method using Folin--Ciocalteu reagent (Folin and Ciocalteu 1927; Swain and Hillis 1959).

Data processing

Litterfall gradually decomposes, so mass loss related to litter decomposition was calculated according to the weight difference of the samples by year.

Regarding the structure of the ethanol extract, easily oxidized compounds including tannins and other (not condensed) forms of phenols were dominant (Schofield et al. 1998). The results obtained from the phenolic analyses were expressed as quercitin equivalent (milli-mole per kg--sample, abbreviated as mM/kg). Considering the change of total mass loss (TM_{loss}) with time passage, the residual content of phenolics ($Cont_{res}$) (i.e. net content) was different from the measured content (Contmea); the $Cont_{res}$ value can be given by $[(100 - TM_{loss}\%)/100] \times Cont_{mea}$. Phenolics mass loss over three years was given according to $100 \times [(Cont_{res,\ 0\ yr} - Cont_{res,\ 3\ yrs})/Cont_{res,\ 0\ yr}]$.

The Pearson correlation coefficient (r) was applied to evaluate the statistical relations. *P* values were also calculated to statistically evaluate the significant difference. According to a Michelin guide scale, the *P* values were classified as follows: no significant group ($P \geq 0.05$); significant group ($P < 0.05$); highly significant group ($P < 0.01$); and extremely significant group ($P < 0.001$). The number of data in each sample type is expressed by n in this manuscript.

The growing season for vegetation begins from temperature transition (limit) across + 5°C in the study field of the Kola Peninsula (Lukina and Nikonov 1998). Dividing the climate conditions into warm temperature (≥ 5°C) and cold temperature (< 5°C), correlations of loss rates (phenolics and total mass) with climatic variables (temperature and precipitation) were calculated on the basis of the data measured during the study period and the meteorological data derived from the regional meteorological center (Monchegorsk).

RESULTS AND DISCUSSION

Phenols content, the relation of mass loss with phenolics, and the effects of climatic variables on mass loss are summarized on the basis of the results obtained over the 3-year field study.

Dynamics of total phenols in litterfall

The dynamics of phenols in litterfalls and litter are summarized in Figure 1.

According to initial phenols content in litterfall, it is possible to propose the following order of content: *Vaccinium vitis-idaea* leaves > *Vaccinium myrtillus* L. leaves > *Picea obovata* Ldb. needles > *Picea obovata* Ldb. bark > *Empetrum hermaphroditum* leaves > litter (O-horizon) > *Picea obovata* Ldb. wood. Data on mass loss of phenolics during the three-year field experiment testified intensive mass loss of phenols from an active part of the litterfall (Figure 1). The decomposition process began with the litterfall swelling and the leaching of water-soluble components with simultaneous hydrolysis of ester bonds which began at an initial stage of the cells dying (Elin 2001). All the observed litterfalls were characterized by high phenolics content, from 6 mM/kg in Picea obovata Ldb. wood to 37 mM/kg in *Vaccinium vitis-idaea* leaves (Figure 1).

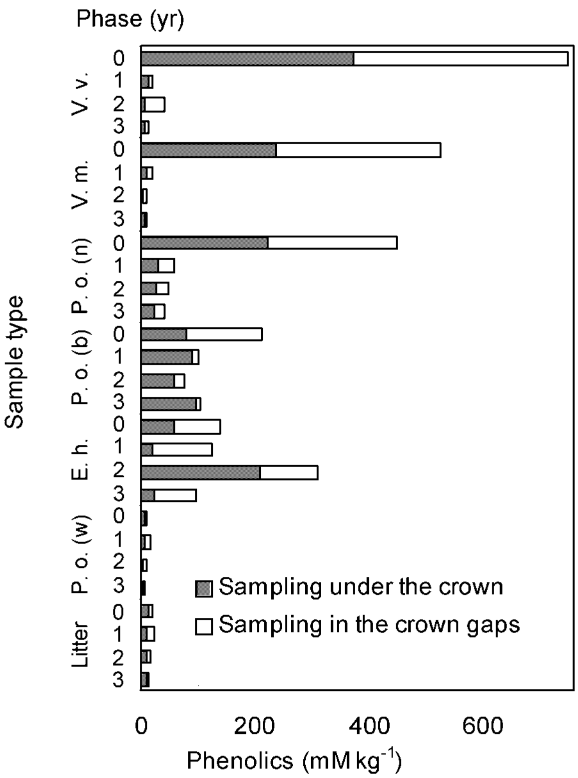

Figure 1. Variations of phenolics (mM/kg) in sample types (*n* = 4, *P* < 0.05) as a function of the decomposition phase (the passage of time) with sampling site as parameter (see the section Materials and Methods for sample abbreviations).

As a rule, live vegetation phenols make up from 1 to 25% in recalculation on dry weight (Hättenschwiler and Vitousek 2000), and sometimes even higher values (up to 60% of dry weight of plants) (Cates and Phodes 1977). The high phenolics content in assimilating tissues is recognized to be one of the characteristics of plants growing in pure soils with low maintenance of nutritional elements. High phenolics content is an important response to soil conditions (Northup et al. 1998).

The initial stages of litterfall decomposition – phenolics leaching rather than biodegradation was marked (Figure 1). This testified the fact that the low-molecular phenolic fraction was lost much more easily than the high-molecular phenolic fraction (Schofield et al. 1998). The process of litterfall decomposition by saprophytes such as fungi was connected with enzymatic action, in particular, phenoloxidase influence. Correlations between water-soluble phenolics content and phenoloxidase activity were not observed (Criquet et al. 2000). Presence of water-soluble phenols relates mainly with leaching of the hydrolized and condensed forms of tannins due to enzymatic destruction of cellular walls and leaching of cell filling (Criquet et al. 2000).

Decomposition in the first year – the greatest phenolics mass loss from litterfall occurred in the first year of decomposition (Figure 1). This testified active leaching by atmospheric precipitation. It is shown that the duration of the initial stage of destructive processes in the boreal zone, as a rule, does not exceed several months (Berg et al. 1987). At initial stages of decomposition, essential mass loss of phenolics from various kinds of litterfall was marked according to other authors also. So, from litterfall of deciduous breeds, the basic part of soluble forms of phenols was lost in the first four months following leaf fall (Kuiters and Sarink 1988). Tannins and other extractive components in willow leaves decreased by half in the first two weeks of the experiment that used the litterbag method (Schofield et al. 1998). In beech litterfall, the residual quantity of phenolic compounds accounted for 17% compared with the initial content after 19 months of the field experiment (Miltner and Zech 1998). Thus, the essential part of phenolics that participates in the formation of mobile forms of organic matter, leaches from the organic horizon and migrates through the soil profile.

Dynamics of total phenols in litter

Total phenols content in litter decreased at a higher rate than the total phenols content in litterfall and after one year was comparable to the phenols content in litterfall after a three-year destructive cycle (Figure 1).

Stabilization – the residual phenolics content in *Picea obovata* Ldb. needles showed 14.3 mM/kg, whereas that in litter was 13.7 mM/kg under the crown in the third year. The variation of phenolics in litter was less than that in litterfall (Figure 1); it was relatively stable; that is, the three-year-period loss of most easily hydrolyzed phenolics forms from litterfall practically came to an end, and the level of phenols in litter was stabilized. It has been reported that the origin of a major share of phenolic compounds in litter is connected with vegetative residues which have a four-year destructive cycle (Whitehead et al. 1981).

Transformation – the process of transformation of phenolic forms in soil conditions can pass several ways (Hättenschwiler and Vitousek 2000): (i) biodegradation and mineralization under action of heterotrophe microorganisms; (ii) polymerization and condensation with humus formation; (iii) adsorption on sesquioxides or formation of chelate complexes with Al and Fe; (iv) leaching from the soil profile as a part of water-soluble organic carbon. Podzol litter is characterized by phenolics mass loss too.

However, the rates were considerably lower than those in an active part of the litterfall (Figure 1). For the three-year period, phenolic losses in litter ranged from 25.8 to 30.6%. Interactions with a mineral phase play a special role (Miltner and Zech 1998). Besides a decrease in migratory activity of phenolics, sorption on a mineral phase promotes a decrease in bioavailability of organic matter due to conformative changes, reducing the opportunity for enzymatic reactions. Some significant value of phenolics may also accumulate on humic compounds. The structure of polyphenolics favorable for the formation of the intermolecular hydrogen bond assumes their existence in the ground in the form of clusters or units and that they are less soluble in water and rarely subjected to enzyme action.

Difference between crown gaps and under crown – there was a clear difference in litter phenolics content depending on whether it was measured under the crown (e.g. 14.0 mM/kg in the initial stage and 10.0 mM/kg in the 3rd year) or in the crown gaps (e.g. 6.0 mM/kg in the initial stage and 4.0 mM/kg in the 3rd year) (Figure 1). It can be related with differences in microorganism biomass and, accordingly, with distinctions in enzymatic activity. Another reason for the difference could be active photo-destruction of phenolics in canopy gaps. Since phenols are referred to as chromophoric systems, their destruction occurs with formation of oxidized forms (hydroquinone and pyrocatechine) under the ultra-violet spectrum (Elin 2001). Under the crown, interaction of free phenolic forms with humic compounds can result in both accumulation and formation of mobile forms; this accumulation is promoted by acidic soil conditions, causing domination of molecular forms of phenols and, as a consequence, their lower mobility (Coulson et al. 1960).

Mass loss rates with maintenance of initial phenolic components

According to the calculated *P* values with respect to mass loss, each sample under the crown was classified as follows: not significant group = *Vaccinium myrtillus* L.; and extremely significant group = *Vaccinium vitis-idaea* leaves, *Picea obovata* Ldb. needles, bark and wood, *Empetrum hermaphroditum* leaves, and litter. Each sample in the crown gaps was classified: not significant group = *Picea obovata* Ldb. wood and litter; and extremely significant group = *Vaccinium vitis-idaea* leaves, *Vaccinium myrtillus* L. leaves, *Picea obovata* Ldb. bark and Empetrum hermaphroditum leaves. Correlation coefficients (r) were calculated from the measured mass losses and initial phenolic content, and the results are summarized in Figure 2. This correlation analysis showed that the high total content of phenolics in an active part of the litterfall retards total mass loss.

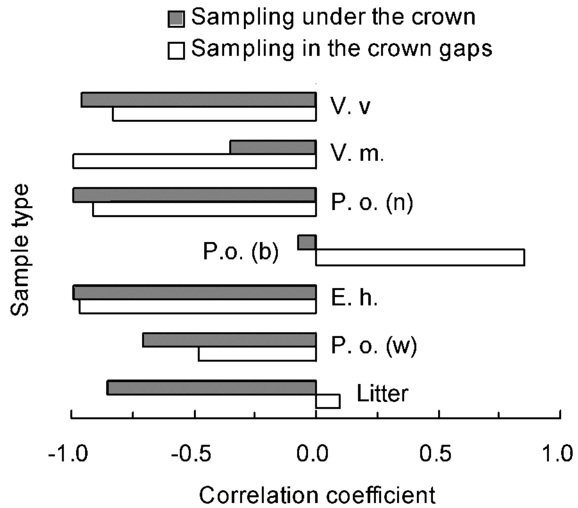

Figure 2. Correlation (r) between mass loss (%) and initial content of phenolics in samples (n = 4) with sampling site as parameter (see the section Materials and Methods for sample abbreviations).

It also follows from Figure 2 that there are generally negative correlation coefficients, and only *Picea obovata* Ldb. bark had a positive relation. This general trend could be caused by primary loss of mass of other organic forms, such as carbohydrates or phenolic forms, extractive by solvents of other polarity. Concerning litter sampled under the crown, there was a negative correlation between mass loss and initial phenolic content; it is considered that the ethanol fraction of phenols was fast lost from the litter or that the immobilization of ethanol formed the aggregative state resulting in a reduction of the destructive process rate.

Relation of mass loss with climatic factors

During the warm period (≥ 5°C) of the decomposition cycle, total mass losses (n = 6, $P < 0.05$) were connected with both the temperature sum ($0.4 < r \leq 0.8$, except litter) and the precipitation sum ($0.4 < r \leq 1.0$). Phenolics losses also showed a similar trend in different kinds of litterfall. There was no clear difference in the correlation coefficients of total mass loss with the precipitation sum between the cold period

(< 5°C) and the warm period (≥ 5°C). Concerning the influence of the temperature sum, the correlation values were negative during the cold period: both litter mass loss and phenolics loss were promoted under severe climate conditions. It is reported that the basic mass loss of litterfall in subarctic regions occurs during the cold period (Coûteaux et al. 1995). One of the possible explanations could be the endothermic nature of organic matter adsorption (Jardine et al. 1989).

Changes in temperature hardly influenced ($|r| < 0.1$) total mass loss of litter in both warm and cold periods; this small influence was possibly connected with the stability of humified organic matter and/or the residues' retentiveness against biodegradation and leaching.

It was found that there was a significant correlation of phenolics loss from litter with temperature ($r = 0.6$ in ≥ 5°C and $r = -0.6$ in < 5°C). This suggests that the temperature may influence the adsorption of phenolics to the litter matrix.

CONCLUSIONS

This paper discusses loss rates of phenolics and mass in different kinds/parts of vegetative residue as a function of the decomposition phase. The obtained results suggested that the dynamics of easily oxidized phenolics may influence the decomposition rate in the monitored subarctic field. It remains for future research to develop a model of the biogeochemical cycle that would confirm decomposition rates of vegetative fluxes to the soil as hey were observed in this study.

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