

Humus forms, carbon stock and properties of soil organic matter in forests formed on dry mineral soils in Latvia

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Received 16 July 2019, accepted 16 October 2019, available online 5 March 2020

Abstract. Over the last decades, more attention has been paid to carbon accumulation in soil, more recently, to soil humus forms, as they indicate environmental conditions and state of soil organic matter. There is insufficient information on the impact of soil and forest type on the chemical properties of soil, soil organic matter and humus form. Knowledge about the chemical properties of humus is crucial for modelling C and N accumulation and storage in forest soils. On this account, the aim of this study was to characterize soil humus forms, humus chemical properties and C stock and to determine the spatial distribution correlations between soil humus forms in forests formed on dry mineral soils. We studied humus forms in 44 sampling sites located in different types of forests. Soil samples were collected from genetic O and A (EA) horizons and analysed for organic carbon (C_{ORG}) and total nitrogen (N_{TOT}) content and NaOH extractable organic matter. Generalized linear model analysis showed that the distribution of the *psammomor* and *mor* humus forms is related to oligotrophic forest types, while glaciogenic and glaciolimnic sediments constitute the main precondition for the occurrence of the *mull* humus form. The *psammomor* and *mor* humus forms have the lowest C_{ORG} stock in the topsoil, and more than 75% of the total C_{ORG} is accumulated in the O horizon. The *mull* humus form soils have the highest C_{ORG} stock in the mineral topsoil, accumulating 80% of the total topsoil C_{ORG} stock. The Ah horizons of the *mull* humus soils also have a significantly lower $C_{\text{HS-to-C}_{\text{ORG}}}$ ratio.

Key words: humus forms, boreo-nemoral ecotone, forest type, soil, carbon, nitrogen.

INTRODUCTION

Soil plays a key role in all terrestrial ecosystems, especially its most dynamic part, soil humus, which provides living organisms with structural elements and energy (Zanella et al. 2018d). The importance of soil humus has recently been stressed in a series of ‘Humusica’ publications on topics related to classification (Zanella et al. 2018c, 2018f), ecology, organic matter decomposition (Zanella et al. 2018b), agriculture, human impact and environmental challenges (Zanella et al. 2018a, 2018e).

Studies on soil humus have resulted in common knowledge that its formation is a complex process influenced by several abiotic factors, such as climate, parent material, soil properties (Vesterdal 1999; Ponge et al., 2011), and biotic factors, the most significant of which are vegetation, plant communities, the quality and amount of litter (Peltier et al. 2001; Albers et al. 2004; Niemi et al. 2007) and the activity of soil micro- and macro-organisms

(Smolander & Kitunen 2002; Kanerva & Smolander 2007). The sum of all factors and the state of the ecosystem result in a soil humus form as the morphological feature of the organic and underlying organo-mineral horizons of the topsoil (Zanella et al. 2011).

Humus forms reflect the pedoecological conditions and productivity of soil (Kõlli & Köster 2018). For example, *mor* humus develops in oligotrophic forests (Chertov & Nadporozhskaya 2018), on a non-calcareous parent material (Labaz et al. 2014), which leads to the accumulation of organic matter and formation of an O horizon (Ponge 2013). In eutrophic forests, on soils rich in free calcium carbonate (Chertov & Nadporozhskaya 2018; Kõlli & Rannik 2018), earthworms and other soil macrofauna incorporate organic matter into the mineral soil, forming an organo-mineral (A) horizon of *mull* humus (Ponge 2013).

Soil humus forms also indicate changes in soil pollution with heavy metals (Korkina & Vorobeichik 2016), and N

variability and pathways in soil and ecosystem (Trap et al. 2011). Humus forms may be used as indicators to detect climate change and the impact of environmental pollution on forest ecosystems. However, wider and more common use of humus forms as an ecological indicator is limited due to incomplete knowledge about their dependence on ecological conditions and the impact of soil and forest types on the chemical properties of soil, soil organic matter and the humus form concerned. The description, classification and mapping of humus, along with information about its chemical properties, also constitute crucial knowledge for modelling C and N accumulation and storage in forest soils. This knowledge can also help evaluate the impact of land management and pollution on a forest ecosystem. That being the case, the aim of this study was (i) to characterize soil humus forms, humus chemical properties and soil organic carbon stock in forests formed on dry mineral soils and (ii) to determine the spatial distribution correlations between soil humus forms in the said forests.

MATERIALS AND METHODS

Study sites

Research of humus forms by soil sampling was conducted in 44 sampling sites in different types of forests formed on dry mineral soils from 2009 to 2015. Twenty-eight sampling

sites were randomly established in the former European second-level forest monitoring programme sites. Additional 16 sampling sites were established in territories where the age of forests exceeds 60 (Fig. 1). Altogether seven sampling sites were established in each of the *Cladinoso-callunosa*, *Vacciniosa*, *Myrtillosa*, *Hylocomiosa* and *Aegopodiosa* forest types (Buss 1997), and nine sampling sites were established in the *Oxalidosa* forest type.

Sampling and analysis

The digging of soil profiles was performed in all sampling sites. Soil profiles were described according to *Guidelines for Soil Description* (FAO 2006). Soil classification was made according to the international FAO (IUSS Working Group WRB 2015).

During the field studies soil parent material and the dominant tree species of the forest stand in the sampling site were described. The forest site types were described according to the Latvian forest ecosystem classification (Buss 1997).

Topsoil was described according to the European Humus Form Reference Base (EHFRB; Zanella et al. 2011) humus form classification. The field works were carried out to determine properties of soil O and A horizons (thickness, structure, material, pH).

Soil samples were collected from genetic horizons of topsoil: from the organo-mineral (Ah, AEh, EAh) and

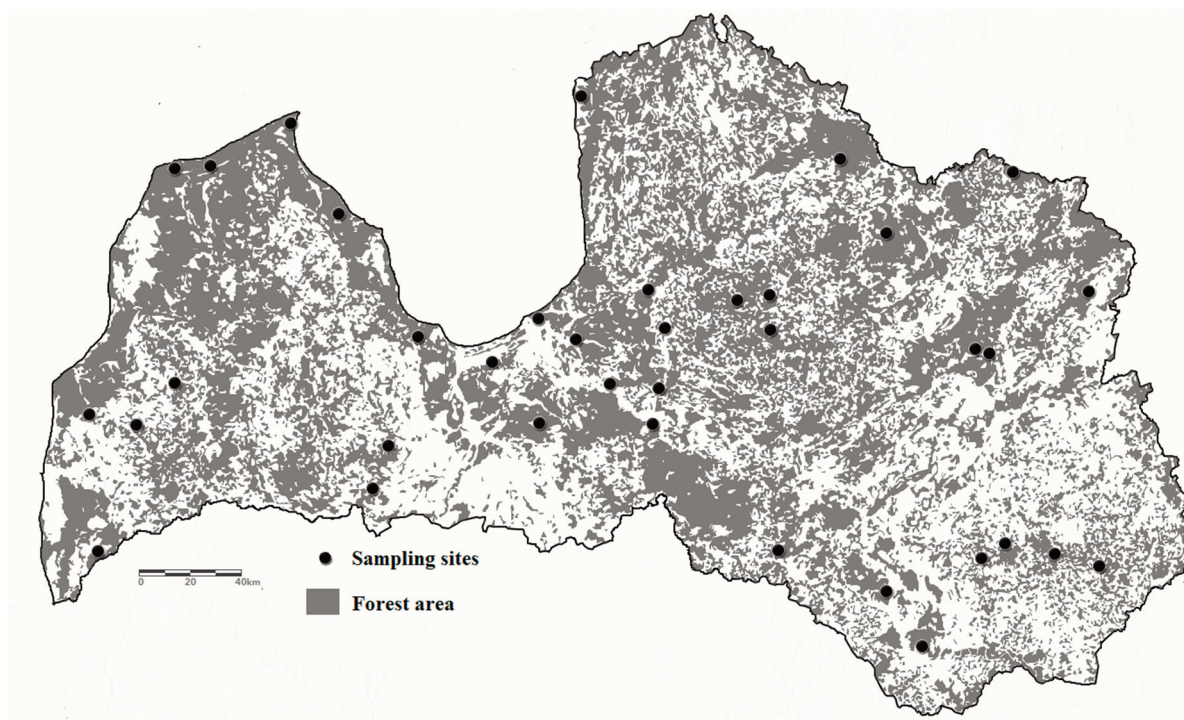


Fig. 1. Location of sampling sites in Latvia.

organic (O, H) horizons. Mineral soil samples for determination of soil bulk density were collected with the core sampler ($D = 3.5$ cm). Mass of the litter (organic O) horizon was calculated from samples collected with the metal frame ($20 \text{ cm} \times 20 \text{ cm}$).

Air-dried soil samples were sieved through a 2-mm sieve and prepared for physical and chemical analyses. The soil particle size was determined by pipette analysis; before analysis samples were treated with 0.1 M NaOH (van Reeuwijk 1995). The soil $\text{pH}_{\text{H}_2\text{O}}$ was measured in water suspension with a glass electrode pH-meter WTW inoLab (10 g soil sample to 50 mL water) (Burt 2004). The total organic carbon (C_{ORG} , %) was determined using a total carbon analyser Shimadzu TOC-Vcsn solid sample module. The total nitrogen (N_{TOT} , %) was determined using the modified Kjeldahl method (ISO:11261, 2002).

Humic substances (HS) from soil were extracted by using procedures recommended by the International Humic Substances Society (Tan 2005). Alkaline extracts were diluted with deionized water (1:100 volume-to-volume ratio). Obtained solutions were analysed for carbon content in the humic substances (C_{HS} , %). Fluorescence emission spectroscopy was used to determine the organic matter humification index (HIX). Emission spectra for all aqueous solutions were recorded (scan speed 500 nm/min, excitation $\lambda = 350$ nm, slit width 10 nm, wavelength range from 380 to 650 nm) with Elmer Fluorescence Spectrometer LS 55. The HIX was calculated as fluorescence intensity ratio at 510 to 460 nm wavelength (Kalbitz et al. 1999; Kalbitz & Geyer 2001). For humic acid (HA) purification, 99 mL of HS alkaline extract was acidified with HCl (37.2% HCl to $\text{H}_2\text{O} = 1:2$) solution to $\text{pH} < 2$. The precipitated HA from fulvic acids (FA) were removed by filtration. The FA solution was analysed with the Shimadzu TOC-Vcsn analyser for carbon content in FA (C_{FA}). The carbon content of HA was calculated by the formula $\text{C}_{\text{HA}} = \text{C}_{\text{HS}} - \text{C}_{\text{FA}}$. The $\text{C}_{\text{HS}}/\text{C}_{\text{ORG}}$ ratio was calculated from C content in HS (C_{HS} , %) and C content in soil (C_{ORG} , %); the $\text{C}_{\text{HA}}/\text{C}_{\text{FA}}$ ratio was calculated from C content in HA (C_{HA} , %) and C content in FA (C_{FA} , %) (Martin et al. 1998); the C/N ratio was

obtained from organic carbon (C_{ORG} , %) and total nitrogen (N_{TOT} , %) content in soil (Carter & Gregorich 2007).

A generalized linear model (GLM) analysis was carried out to determine the correlations between soil humus forms and environmental factors (Quinn & Keough 2002). Binary values were added for all factor types (0 – not observed in the sampling site; 1 – observed in the sampling site). The GLM in R 2.11.1 software was used to investigate the correlations (the level of significance $p < 0.05$) between humus form spatial distribution and forest type, dominant tree species and soil parent material.

Statistical analysis

Physical and chemical properties of topsoil were included in the data statistical analysis. Statistical analyses (arithmetic mean values, standard deviation, ratios) were calculated using Microsoft Excel 2016 software.

Analysis of variance (One-way ANOVA) was performed to compare properties (C_{ORG} , N_{TOT} , C/N, C_{HS} , $\text{C}_{\text{HS}}/\text{C}_{\text{ORG}}$, HIX, C t ha^{-1} , $\text{pH}_{\text{H}_2\text{O}}$) of soil O and A (EA) horizons between different humus forms. The significance of the differences was determined with Tukey's HSD post-hoc test ($\alpha = 0.05$). Calculations were performed using SPSS PASW Statistics 18 software.

RESULTS

Properties and forms of humus in forests formed on dry mineral soils in Latvia

The topsoils in the studied forests have developed different morphological properties. A humus layer with a thin O horizon and underlying AE (E) horizons has formed in the *Cladinosa-callunosa* forests. The mean thickness of the humus layer there is 9.8 cm (Table 1). The mean humus layer thickness of the soil in the *Oxalidososa* and *Aegopodiososa* forest types exceeds 20 cm. According

Table 1. Morphological, chemical and physical properties of soil humus forms in different forest types (standard errors are given in parentheses)

Forest type (number of sampling plots)	O horizon thickness (cm)	Mass of the horizon (t ha^{-1})	Mineral topsoil (A, E horizons) thickness (cm)	Bulk density (g cm^{-3})	$\text{pH}_{\text{H}_2\text{O}}$
<i>Cladinosa-callunosa</i> (7)	3.8 (± 1.3)	39.2 (± 9.2)	6.0 (± 3.1)	1.16 (± 0.03)	4.7 (± 0.2)
<i>Vacciniosa</i> (7)	6.7 (± 1.6)	87.2 (± 24.5)	5.1 (± 2.3)	0.97 (± 0.08)	4.6 (± 0.2)
<i>Myrtillosa</i> (7)	6.5 (± 2.1)	68.3 (± 7.1)	7.2 (± 2.7)	1.16 (± 0.1)	4.5 (± 0.5)
<i>Hylocomiosa</i> (7)	6.4 (± 4.4)	129.9 (± 80.8)	12.4 (± 6.2)	0.89 (± 0.2)	5.0 (± 0.5)
<i>Oxalidososa</i> (9)	3.2 (± 2.9)	60.1 (± 49.3)	19.0 (± 12.1)	0.88 (± 0.33)	5.3 (± 0.7)
<i>Aegopodiososa</i> (7)	1.2 (± 0.5)	10.5 (± 6.3)	20.0 (± 4.9)	0.86 (± 0.14)	5.8 (± 0.5)

to the EHFRB humus form classification (Zanella et al. 2011), a *mull* humus form has formed in 17 of the 44 studied sites, *moder* humus – in 8 forest soils, *mor* – in 10, while a *psammomor* humus form was characteristic of nine studied soils in oligotrophic forests.

Hylocomiosa forests have the highest variability of humus forms: there is *mor* humus in one, *moder* humus in two and *mull* humus in four of the *Hylocomiosa* forest sites (Table 2). The *Cladinosa-callunosa* and *Vacciniosa* forest soils have the *psammomor* or *mor* humus forms, while the *Myrtillosa* forest soils have the *mor* or *moder* humus forms. There is no *mor* humus form in the nutrient-rich forests. In the studied *Oxalidos* forest sites, three soils have the *moder* and four soils have the *mull* humus forms. Soils in all studied *Aegopodiosa* forest sites have the *mull* humus form.

Using generalized linear models (GLMs), a significant correlation of spatial distribution was found between the *Cladinosa-callunosa* forest type and the *psammomor* humus form and between the *Vacciniosa* and *Myrtillosa* forest types and the *mor* humus form. At the same time, the spatial distribution of the *moder* humus form was not linked to a specific forest type (Table 2).

Geological conditions make another significant factor that defines the spatial distribution of soil humus forms. The GLMs show a significant correlation between marine sediments and the *psammomor* humus form and between glaciogenic deposits and the *mull* humus form (Table 3). *Mor* humus develops in soils on glaciofluvial and marine deposits, aeolian dunes and limnic material, and *moder* humus develops in soils on limnic material, glaciolacustrine and glaciogenic deposits, although none of these correlations are statistically significant.

More significant correlations between humus forms and soils are explained by the WRB reference soil group (Table 4). A GLM revealed a significant correlation between *Arenosols* and the formation of *psammomor* and *mor* humuses in Latvian forests. *Luvissols* account for the spatial distribution of the *mull* humus form. All sites of *Stagnosols* and *Gleysols* have the *moder* humus form, while sites of *Planosols* and *Retisols* have the *mull* humus form, although binary GLMs do not let us consider these correlations as significant.

The dominant tree species in a forest stand is a statistically less significant factor for the development of a particular humus form compared to the forest type, Quaternary deposits or WRB reference soil group (Table 5). Nevertheless, the *mor* or *moder* humus forms develop in spruce (*Picea abies*) and birch (*Betula pendula*) stand soils and *mull* humus develops in oak (*Quercus robur*) stand soils. The GLM analyses allow us to maintain that the development of the *mull* humus form is not associated with pine (*Pinus sylvestris*) forests.

Chemical description of soil humus forms and their organic matter

Organic carbon content is a significant parameter characterizing the soil O horizon and a humus form. The *psammomor* and *mor* humus forms have the highest mean C_{ORG} content in the O horizon (> 37%). The mean C_{ORG} content in the soil O horizon with *moder* humus varies from 34.4% in the *Hylocomiosa* to 36.6% in the *Myrtillosa* forest types (Table 6). Soils with *mull* humus have the lowest mean C_{ORG} content (27.8%) in the O

Table 2. Distribution of humus forms in sampling sites and relationship between forest types and humus forms (significant correlations [*p* < 0.05] are boldfaced)

Forest type (number of sampling plots)	Humus forms (occurrence within sampling sites)				Statistical indicator	Humus forms			
	<i>Psammomor</i> (9)	<i>Mor</i> (10)	<i>Moder</i> (8)	<i>Mull</i> (17)		<i>Psammomor</i>	<i>Mor</i>	<i>Moder</i>	<i>Mull</i>
<i>Cladinosa-callunosa</i> (7)	6	1	–	–	AIC	30.6	50.8	–	–
					P	0.0006	0.57	–	–
<i>Vacciniosa</i> (7)	3	4	–	–	AIC	46.4	46.4	–	–
					P	0.125	0.03	–	–
<i>Myrtillosa</i> (7)	–	4	3	–	AIC	–	46.4	42.9	–
					P	–	0.03	0.08	–
<i>Hylocomiosa</i> (7)	–	1	2	4	AIC	–	50.8	45.2	61.5
					P	–	0.57	0.44	0.28
<i>Oxalidos</i> (9)	–	–	3	6	AIC	–	–	44.2	59.0
					P	–	–	0.19	0.06
<i>Aegopodiosa</i> (7)	–	–	–	7	AIC	–	–	–	27.0
					P	–	–	–	*

* the humus form occurs in a certain forest type; – not found.

Table 3. Distribution of humus forms in sampling sites within the areas of deposits and correlations between Quaternary deposits and humus forms (significant correlations [$p < 0.05$] are boldfaced)

Quaternary deposits (number of sampling plots)	Humus forms (occurrence within sampling sites)				Statistical indicator	Humus forms			
	<i>Psammomor</i> (9)	<i>Mor</i> (10)	<i>Moder</i> (8)	<i>Mull</i> (17)		<i>Psammomor</i>	<i>Mor</i>	<i>Moder</i>	<i>Mull</i>
Glaciogfluvial (3)	1	2	–	–	AIC	48.3	48.3	–	–
					P	0.574	0.1009	–	–
Marine sediments (14)	7	5	1	1	AIC	38.1	49.3	43.8	52.7
					P	0.0036	0.168	0.2211	0.0142
Aeolian dunes (2)	–	2	–	–	AIC	–	44.9	–	–
					P	–	0.9946	–	–
Limnic material (3)	–	1	2	–	AIC	–	50.975	41.9	–
					P	–	0.654	0.059	–
Glaciolacustrine (7)	1	–	1	5	AIC	48.4	–	45.6	59.0
					P	0.6616	–	0.7715	0.069
Glaciogenic deposits (13)	–	–	3	10	AIC	–	–	45.4	51.163
					P	–	–	0.5874	0.0019
Clay (2)	–	–	1	1	AIC	–	–	44.6	62.6
					P	–	–	0.2748	0.738

– not found.

Table 4. Distribution of humus forms in sampling sites within the areas of deposits and correlations between Quaternary deposits and humus forms (significant correlations [$p < 0.05$] are boldfaced)

WRB reference soil group (number of sampling plots)	Humus forms (occurrence within sampling sites)				Statistical indicator	Humus forms			
	<i>Psammomor</i> (9)	<i>Mor</i> (10)	<i>Moder</i> (8)	<i>Mull</i> (17)		<i>Psammomor</i>	<i>Mor</i>	<i>Moder</i>	<i>Mull</i>
Arenosols (17)	8	7	2	–	AIC	36.062	45.872	44.919	–
					P	0.00541	0.02839	0.3884	–
Podzols (6)	1	3	1	1	AIC	48.52	48.624	45.713	61.135
					P	0.805035	0.10482	0.9175	0.259
Stagnosols (2)	–	–	2	–	AIC	–	–	38.45	–
					P	–	–	*	–
Gleysols (2)	–	–	2	–	AIC	–	–	38.45	–
					P	–	–	*	–
Luvisols (9)	–	–	1	8	AIC	–	–	45.307	50.182
					P	–	–	0.54378	0.00541
Cambisols (4)	–	–	–	4	AIC	–	–	–	54.446
					P	–	–	–	0.9926
Planosols (2)	–	–	–	2	AIC	–	–	–	58.784
					P	–	–	–	*
Retisols (2)	–	–	–	2	AIC	–	–	–	58.784
					P	–	–	–	*

* the humus form occurs in the soil group; – not found.

horizons of all studied soils. The mean C_{ORG} content in the *Aegopodiosa* forest type is 15.3%.

The N_{TOT} content in the O horizons increases in the following order: *psammomor* < *mor* < *moder* < *mull*

(Table 6). The O horizon of *psammomor* humus contains 0.89% to 0.96% of total nitrogen. The N_{TOT} content in the O horizon of *mor* humus varies from 0.77% in the *Cladinosa-callunosa* forest type to 1.17% in the

Table 5. Distribution of humus forms in sampling sites and correlations between dominant tree species and humus forms (significant correlations [$p < 0.05$] are boldfaced)

Dominant tree species (number of sampling plots)	Humus forms (occurrence within sampling sites)				Statistical indicator	Humus forms			
	<i>Psammomor</i> (9)	<i>Mor</i> (10)	<i>Moder</i> (8)	<i>Mull</i> (17)		<i>Psammomor</i>	<i>Mor</i>	<i>Moder</i>	<i>Mull</i>
<i>Pinus sylvestris</i> (25)	9	10	4	2	AIC	36.7	37.7	45.5	37.5
					P	*	*	0.6677	0.0001
<i>Picea abies</i> (8)	–	–	3	5	AIC	–	–	43.6	60.4
					P	–	–	0.1333	0.1378
<i>Betula pendula</i> (4)	–	–	1	3	AIC	–	–	45.6	60.3
					P	–	–	0.712	0.1528
<i>Quercus robur</i> (7)	–	–	–	7	AIC	–	–	–	47.2
					P	–	–	–	*

* the humus form occurs in the soil group; – not found.

Myrtillosa forest type. The O horizon in the *moder* humus form has a mean N_{TOT} of 1.21%. The richest in nitrogen are the O horizons in the *mull* humus soils, where the mean N_{TOT} content is 1.73%, which is almost two times higher than that in the *psammomor* and *mor* humus soils.

The C/N ratios in the O horizons of the studied soils vary from 42.9 in the soils with the *psammomor* humus form to 17.2 in the soils with the *mull* humus form. The mean C/N ratios in the O horizons of the *mor* and *moder* humus form soils are 37.8 and 30.4, respectively (Table 6).

The organic matter content and properties of mineral topsoil are largely dependent on soil formation processes. The mineral topsoil (E or EAh horizons) of the *psammomor* and *mor* humus soils have a lower C_{ORG} content: the mean C_{ORG} content does not exceed 0.91%. Organic matter in the soils with the *moder* and *mull* humus forms is accumulated in the Ah horizon. The mean C_{ORG} content in the Ah horizons of soils with *moder* humus in the *Myrtillosa* type forests reaches

1.36%, while in the soils in the *Myrtillosa* type forests it is 4.4%. The mean C_{ORG} content in the *mull* humus soils is 2.6% (Table 6).

Like with the C_{ORG} content, the N_{TOT} content in mineral soil depends mainly on soil formation processes. The N_{TOT} content is less than 0.1% in the E horizons of soil with the *psammomor* humus form and varies from 0.03% to 0.18% in soil with *mor* humus. The *moder* and *mull* humus soils have more than 0.2% N_{TOT} in the Ah horizon (Table 6).

The mean C/N ratio in the mineral topsoil decreases in the following sequence: *psammomor* > *mor* > *moder* > *mull*. The mean values are 14.8 > 13.1 > 9.2 > 7.4, respectively.

The studied soils also have different proportions of a humic fraction in soil organic matter. The highest C_{HS}/C_{ORG} ratio is found in the *psammomor* and *mor* mineral topsoils, where organic matter contains 72.5% of humic fraction carbon. The humification index of the humic fraction is relatively similar among different humus form soils: HIX varies from 78.7 to 79.8 in the

Table 6. Properties of soil organic matter within different humus form soils

Humus form	C_{ORG} (%)		N_{TOT} (%)		C/N		pH_{H2O}	C_{HS} (%)*	C_{HS}/C_{ORG} (%)*	C_{HA}/C_{FA} *	HIX*
	O horizon	E, A horizons	O horizon	E, A horizons	O horizon	E, A horizons					
<i>Psammomor</i>	37.1 ^b	0.67 ^a	0.91 ^a	0.08 ^a	42.9 ^a	14.8 ^a	4.6 ^a	0.44 ^{ab}	72.5 ^{ab}	1.0 ^a	78.7 ^a
<i>Mor</i>	38.1 ^{ab}	0.91 ^a	1.03 ^a	0.11 ^a	37.8 ^a	13.1 ^a	4.4 ^a	0.67 ^b	80.8 ^a	0.51 ^a	79.7 ^a
<i>Moder</i>	35.6 ^b	2.55 ^b	1.21 ^a	0.27 ^a	30.4 ^a	9.2 ^a	4.8 ^a	1.58 ^b	59.7 ^{bd}	0.86 ^a	79.8 ^a
<i>Mull</i>	27.8 ^{bc}	2.60 ^b	1.73 ^a	0.42 ^a	17.2 ^b	7.4 ^a	5.6 ^b	1.11 ^{bc}	45.1 ^{cd}	1.13 ^a	71.3 ^a

* C_{HS} , carbon content in soil humic substances; C_{HS}/C_{ORG} , the proportion of humic carbon in the total organic matter; HIX, the ratio of HS fluorescence emission intensity at 510 and 460 nm; C_{HA}/C_{FA} , the ratio of humic-to-fulvic acid carbon; ^{a, b, c, d}, different letters within the column indicate significant ($p < 0.05$) differences between humus forms according to Tukey's test.

psammomor, *mor* and *moder* humus soils and is 71.3 in the *mull* humus soil (Table 6).

A comparison of the mean values reveals several statistically significant differences among different humus form soils (Table 6). Soils with the *mull* humus form have a significantly higher pH in mineral soil compared to soils with other humus forms in dry mineral forests. The C_{ORG} content is significantly lower in the *psammomor* and *mor* humus form topsoils (the AE and E horizons) than in the *moder* and *mull* humus form topsoils (the A horizon).

According to the characteristics of the O horizon, statistically significant differences exist in the *mull* humus form soils, which have a significantly lower C_{ORG} content in the O horizon than the *mor* humus form soils (Table 6). The C/N ratio in the O horizon of the *mull* humus form soils is significantly lower than in all other humus form soils (Table 6).

In addition, no statistical differences among the studied humus form soils were found when comparing the mean HIX, $C_{\text{HS}}/C_{\text{ORG}}$ and $C_{\text{HA}}/C_{\text{FA}}$ values.

Organic carbon and total nitrogen stock in humus forms in forests formed on dry mineral soils in Latvia

The O horizon and mineral topsoil play an important role in the accumulation of organic matter in forest soils. The C_{ORG} and N_{TOT} stock in soil is dependent on the content of organic matter, litter mass and bulk density of mineral soil. Nutrient-rich coniferous forests (*Vacciniosa*, *Myrtillosa* and *Hylocomiosa*) have a higher litter mass (Table 1). Soil bulk density in mineral topsoil varies from 0.86 to 1.16 g cm⁻³.

The C_{ORG} stock in the O and A (EA) horizons in the studied forest soils varies from 10.2 t ha⁻¹ up to even 117.9 t ha⁻¹. The lowest C_{ORG} stock in a soil humus form was found in the *Cladinosa-callunosa* forest type, while the stock of C_{ORG} that a humus form can store in the *Hylocomiosa* forest type reached 73.9 t C ha⁻¹ on average (Fig. 2A). The *Cladinosa-callunosa* forests also have the lowest N_{TOT} stock in a soil humus profile: it was just 0.35 t N ha⁻¹ in one of the study sites located in pine (*Pinus sylvestris*) tree stands. The highest N_{TOT} stock in a humus profile was found in the *Oxalidosa* and *Aegopodiosa* type forest soils: for example, the O and Ah horizons in the *Oxalidosa* birch (*Betula pendula*) forest soil contain 18.1 t N ha⁻¹, and the *Aegopodiosa* forest soil humus profile in a mixed oak (*Quercus robur*), birch (*Betula pendula*) and ash tree (*Fraxinus* sp.) stand contains 11.9 t N ha⁻¹.

A comparison of the mean C_{ORG} stock in the humus profiles in different forest types shows the lowest humus C_{ORG} stock in the *Cladinosa-callunosa* forests (Fig. 2A). The *Vacciniosa* and *Myrtillosa* forest types have relatively similar mean C_{ORG} stocks in the humus profile: 35.6 and 38.9 t C ha⁻¹, respectively.

The *Hylocomiosa* forests have the highest mean humus C_{ORG} stock. However, they also have a high C_{ORG} stock variability within the studied forests: soils with *mull* humus in a mixed oak (*Quercus robur*) and pine (*Pinus sylvestris*) forest store 28.5 t C ha⁻¹, whereas in the *mor* humus topsoil in a pine (*Pinus sylvestris*) tree stand it is 117.9 t C ha⁻¹. The O and Ah soil horizons in the *Oxalidosa* forest contain 64.2 t C ha⁻¹ and in the *Aegopodiosa* forests – 36.5 t C ha⁻¹. The C_{ORG} stock in the

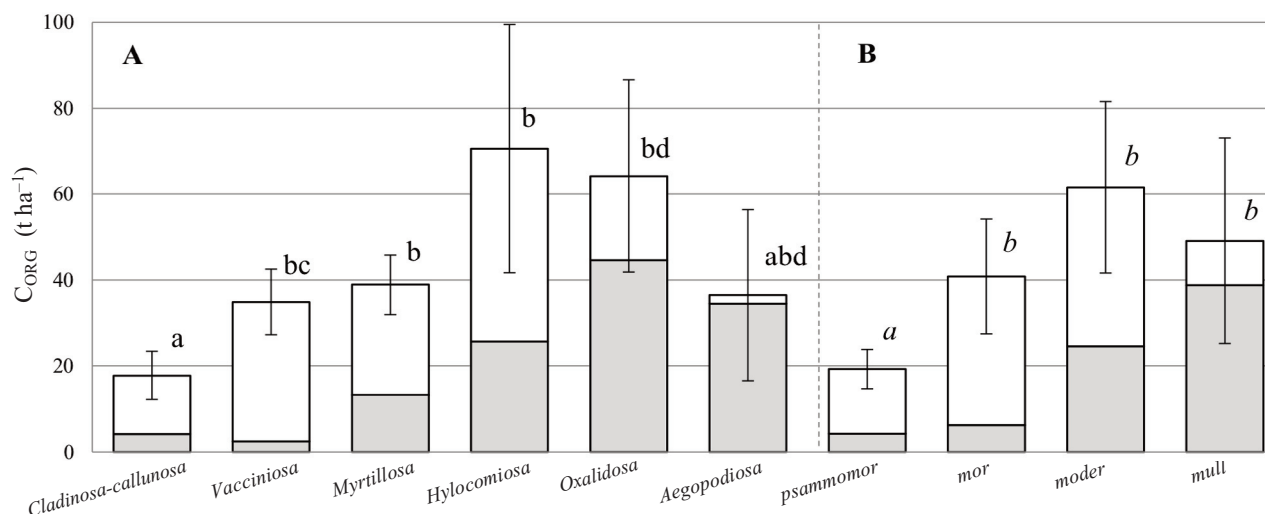


Fig. 2. Mean C_{ORG} stock and distribution in topsoil in different types of forests formed on dry mineral soils (A) and humus forms (B) in Latvia: in white – the C_{ORG} stock in the O horizon; in grey – the C_{ORG} stock in the A (AE, EA) horizon. Vertical bars show standard deviations of the mean; small letters indicate statistically significant ($p > 0.05$) differences between types of forest (regular letters) or humus forms (italic letters) according to Tukey's test.

Cladinosa-callunosa forests is significantly lower than the C_{ORG} stock in the soils of the other studied forest types. The analysis also shows significant differences in the C_{ORG} stock in the humus profile between the *Vacciniosa* and *Oxalidosa* forest types.

A comparison of the mean humus C_{ORG} stock in different humus forms shows that soils with *psammomor* humus have a significantly lower C_{ORG} stock than the soils with other humus forms (Fig. 2B). The mean C_{ORG} stock in the O and EA_h (E) horizons of soils with *psammomor* humus is 19.3 t C ha^{-1} , in the *mor* humus soils 40.8 t C ha^{-1} , in the *moder* humus soils 61.6 t C ha^{-1} and in the *mull* humus soils 49.1 t C ha^{-1} .

A soil humus form impacts the C sequestration mechanisms in the soil. In the soils with the *psammomor* and *mor* humus forms, a significant amount of the total C_{ORG} stock is accumulated in the O horizon (78.9% and 84.6% of the total C_{ORG} stock in the *psammomor* and *mor* humus profiles, respectively). The O horizons of the *moder* humus soils accumulate on average 60.9% of the total C_{ORG} stock (Fig. 2B). In the *mull* humus soils, a substantial share of the organic carbon accumulates in the mineral topsoil, where the mean C_{ORG} stock in the Ah horizon is 38.8 t C ha^{-1} (80.4% of the total humus organic carbon stock, significantly higher compared to other humus form soils).

Compared to the organic carbon stock, the total nitrogen stock in the topsoil of the studied soils varies among forest types in a different way. The highest humus N_{TOT} stock was detected in the *Oxalidosa* forest soils, where it reaches 9.53 t N ha^{-1} (Fig. 3A). The mean N_{TOT} stock of 1.03 t N ha^{-1} in the *Cladinosa-callunosa* forest

soils is significantly lower than in the *Myrtillosa*, *Hylocomiosa*, *Oxalidosa* and *Aegopodiosa* forest soils. Statistically significant differences were also identified between the *Vacciniosa* and *Hylocomiosa*, between the *Vacciniosa* and *Oxalidosa* and between the *Myrtillosa* and *Oxalidosa* forest soils.

A comparison of the mean nitrogen stock in different humus form soils shows significant differences among all studied humus form soils (Fig. 3B):

- the soils with the *psammomor* humus form differ from the soils with the *mor*, *moder* and *mull* humus forms; the *psammomor* humus soils have a significantly lower N_{TOT} stock in the O horizon; the *psammomor* humus soils have a significantly lower N_{TOT} stock in the mineral topsoil than the *moder* and *mull* humus soils;
- the soils with *mor* humus differ from the *moder* and *mull* soils in terms of the humus N_{TOT} stock and differ from the *mull* humus soils in terms of the N_{TOT} stock in the mineral topsoil;
- the soils with the *moder* humus form significantly differ from those of the *mull* humus form in terms of the N_{TOT} stock and the N_{TOT} stock in the soil Ah horizon.

In contrast to the organic carbon accumulation, the soil O horizon plays a less important role in the accumulation of total nitrogen in a humus profile. The O horizon accumulates 54.9% of the humus N_{TOT} stock in the *psammomor* humus soils, 65.1% in the *mor* humus profile, 34.3% in the *moder* humus profile and just 11.6% in the O and Ah horizons of the *mull* humus soils (Fig. 3B).

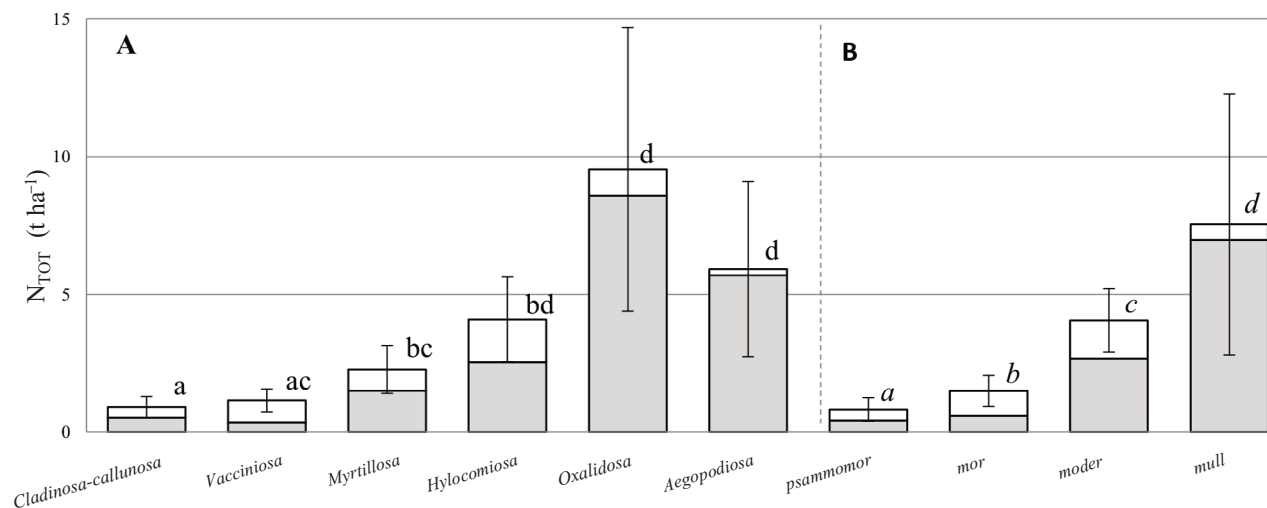


Fig. 3. Mean N_{TOT} stock and distribution in topsoil in different types of forests formed on dry mineral soils (A) and humus forms (B) in Latvia: in white – the N_{TOT} stock in the O horizon; in grey – the N_{TOT} stock in the A (AE, EA) horizon. Vertical bars show standard deviations of the mean; small letters indicate statistically significant ($p > 0.05$) differences between types of forest (regular letters) or humus forms (italic letters) according to Tukey’s test.

DISCUSSION

Spatial distribution of soil humus forms

According to the humus form classification (Zanella et al. 2011), the *psammomor*, *moder* and *mor* humus forms develop in forests on dry mineral soils in Latvia. A forest type plays a significant role in the spatial distribution of soil humus forms. *Psammomor* humus develops in the *Cladinosa-callunosa* type forests, the *mor* humus forms are related to the *Vacciniosa* and *Myrtillosa* forest types, and *mull* humus is formed in the *Oxalidososa* and *Aegopodiososa* forest types (Table 2). These results coincide with studies in Estonia (Kõlli 2013) and show that a forest type is one of the major factors effective in the boreo-nemoral zone. At the same time, the formation of *moder* humus under different forest conditions, mainly in the *Myrtillosa* and *Oxalidososa* forests, indicates that other factors also influence the development of soil humus forms.

Correlations between humus forms and geological conditions (Table 3), as well as studies on soil diversity in Latvia (Kasparinskis & Nikodemus 2012), show that geological conditions are a significant abiotic factor that determines the availability of nutrient elements in soil and soil reaction. Like in other studies, the parent material rich in base cations determines the formation of the *mull* humus forms, whereas the acidic parent material determines the formation of *mor* humus (Ponge et al. 2011).

From all of the studied factors, the dominant tree species has the smallest impact on the spatial distribution of humus forms. Specific tree species do not determine the formation of a definite humus form. Based on the study results, we are able to say that the *mull* humus forms do not develop in the pine (*Pinus sylvestris*) forests and the formation of *mor* humus is less likely in a broadleaf forest. A similar conclusion, namely, that the formation of a humus form is influenced not by specific tree species but by the proportion of coniferous and broadleaf trees, has been made in other studies conducted in the boreal and boreo-nemoral zones (Vesterdal et al. 2008; Kõlli 2013; Labaz et al. 2014).

Overall, the results of the study demonstrate the need for further research to include more detailed and more precise information concerning the morphological, chemical and physical properties of soil and humus. In addition, soil humus forms should be described according to the second level (for example, eumull, mesomull, etc.) of the EHFRB classification system (Zanella et al. 2011).

Chemical properties of soil humus forms

The C_{ORG} content in the O horizon of the studied soils varies from 15.3% to 46.7%. Similar differences, where the *mull* humus forms had a significantly lower C_{ORG}

compared to the *moder* and *mor* humus forms, were detected in a study in Poland (Labaz et al. 2014). In our study, these differences were caused by the low C_{ORG} content (< 20%) in the O horizon in the oak (*Quercus robur*) stand soil. Other studies have not found significant differences in the C_{ORG} content between oak and coniferous litter (Vesterdal 1999; Remy et al. 2016). Accordingly, these results indicate that litter sampling must be performed more precisely in broadleaf forests.

The mean C_{ORG} content in the O horizons of the *psammomor*, *mor* and *moder* humus forms (Table 6) does not differ from the mean C_{ORG} content of 37.1% in European forests (De Vos et al. 2015) and 28.6% in forest soils in Latvia (Bārdule et al. 2009).

The N_{TOT} content in the O horizon of the *psammomor* and *mor* humus soils (Table 6) is lower than that found in other studies in Latvia (Terauda & Nikodemus 2006; Bārdule et al. 2009) and Europe (Korhonen et al. 2013). In *moder* and *mull* humus, however, it is quite close to that reflected in the results of other studies (Bārdule et al. 2009).

These differences in the C_{ORG} and N_{TOT} content also determine the differences in the C/N ratio in the O horizon. A statistical analysis shows that only in *mull* humus the C/N ratio is significantly lower than in all other humus form soils (Table 6). The C/N ratio in the O horizon of the *mull* humus forms is below 30 and corresponds to the ecological conditions described in the humus classification system (Zanella et al. 2011). Furthermore, the mean C/N ratio in the O horizon of the *psammomor* ($C/N > 40$) and *moder* humus forms ($C/N = 30\text{--}40$) corresponds to the classification, while the mean C/N ratio in *mor* humus is below 40. These differences may be related to the fact that some of the study sites are located not far from the city of Riga and may therefore be exposed to N deposition through atmospheric pollution (Hosseini Bai et al. 2015). Differences and variations in the litter C/N ratio have been corroborated in other studies in Europe. For example, the C/N ratio in the O horizons of *mor* humus in mountains in Poland is around 27 (Labaz et al. 2014), and the results of a study in Estonia show that the C/N ratio in the O horizon of *moder* humus may be around 20 (Kõlli 2013). These results urge us to suggest that even if litter is suitable for fast mineralization, a colder and wetter climate in the boreo-nemoral zone can slow down the decomposition process (Ponge et al. 2011; Bayranvand et al. 2017).

The C_{ORG} content in mineral topsoil correlates with the N_{TOT} content in the A (EA) horizons. The content of these elements is dependent on soil formation processes as well as on mechanisms whereby soil organic matter is transported to the mineral soil. The mean C_{ORG} content in

the EA horizons of *psammomor* and *mor* is less than 1%, while in the A horizons of the *moder* and *mull* soils it exceeds 2.5% (Table 6). Such a statistically significantly lower C_{ORG} content in the *psammomor* and *mor* soils may be explained by intense podzolization. A fraction of the soil organic matter that includes C_{ORG} is translocated to the deeper soil horizons (Grand & Lavkulich 2011; Freyerová & Šefrna 2014). The C_{ORG} content reaches 4.4% in the *moder* humus soils in spruce (*Picea abies*) forests and 5.8% in the Ah horizon of the *mull* humus form in a mixed oak (*Quercus robur*) and birch (*Betula pendula*) forest. These results match the findings of other studies (Vesterdal 1999; Vesterdal et al. 2008).

The soil formation processes and the element cycle are also responsible for the differences in the chemical properties of the topsoil organic matter of humus forms. The *psammomor* and *mor* humus form soils have a significantly higher proportion of humic substances and a higher $C_{\text{HS}}/C_{\text{ORG}}$ ratio in the mineral topsoil than the *moder* and *mull* humus form soils (Table 6). Humic substances form more than 70% of total organic carbon in the *psammomor* and *mor* humus topsoil, while the $C_{\text{HS}}/C_{\text{ORG}}$ ratio is lower than 65% in the *moder* and *mull* humus soils. These differences are caused by different soil faunal activities. The *psammomor* and *mor* humus soils have low earthworm and other soil macrofauna activity. Because of this, the mainly soluble fraction of soil organic matter from the O horizon reaches the mineral topsoil (Qualls et al. 2003; Cerli et al. 2008). However, the earthworm activity is high in the *mull* humus form soils. As a result, non-humified organic matter is mechanically brought into the Ah horizon of the soil (Muscolo et al. 2009).

The HS properties, $C_{\text{HA}}/C_{\text{FA}}$ ratio and HIX are highly variable within the mineral topsoil of the studied soils. Although a comparison of the mean $C_{\text{HA}}/C_{\text{FA}}$ ratio values does not show any significant differences among humus forms, there is still a higher proportion of the FA fraction in the *mor* humus topsoil than in other soils (Table 6). These results may be explained by slow litter turnover, which in some cases may reach seven years (Zanella et al. 2011). Such a slow process, when litter gradually goes through a full decomposition cycle, is favourable for the formation of soluble organic compounds (Fröberg et al. 2005; Kalbitz et al. 2006). A higher FA fraction in the *psammomor*, *mor* and *moder* humus mineral soils may also be related to coniferous litter that releases the FA fraction during the decomposition (Vaičys et al. 1996; Qualls et al. 2003). A high proportion of the HA fraction in the *mull* humus mineral topsoil is a result of more efficient humification in leaf litter (Zech & Kögel-Knabner 1994) and stabilization of the humic fraction in organo-mineral complexes (Piccolo 1996).

In addition, no statistical differences among the studied humus form mineral topsoils were found when comparing the mean HIX values. These results may indicate that the factors affecting the humification processes (soil moisture, litter quality, oxygen, microorganisms, etc.) are relatively similar in forests growing on dry mineral soil.

Organic carbon and total nitrogen stock

The C_{ORG} and N_{TOT} stock in soil is dependent on the content of organic matter, litter mass and bulk density of mineral soil. The research results show that the mean litter mass in the *Vacciniosa* and *Myrtillosa* forest types (Table 1) corresponds to the mean mass of the OFH horizon in European forests (De Vos et al. 2015). The mean litter mass in the *mull* humus soils of the studied *Aegopodiosa* forests is 3 t ha⁻¹ higher than the calculated mean OL horizon mass in European forests. The greatest litter mass differences can be observed in the *moder* humus form soils in the *Hylocomiosa* and *Oxalidososa* forest types, where the O horizon mass exceeds 200 t ha⁻¹, which is twice as much as the mean OFH horizon mass in forests in Europe (De Vos et al. 2015). The high mass of the O horizon in Latvian forests is probably related to the climate conditions, as the characteristic excess of precipitation over evaporation impedes the decomposition of organic matter (Ponge et al. 2011).

The bulk density of mineral topsoil (Table 2) in the *Hylocomiosa*, *Oxalidososa* and *Aegopodiosa* forests is slightly lower than the calculated mean soil bulk density in forests in Latvia (Bārdule et al. 2009). It does not differ significantly from the mean soil bulk density in European forests either (De Vos et al. 2015).

The calculated C_{ORG} stock in the O horizon and in the mineral topsoil differs among the studied forest types and humus forms (Fig. 2). The significant differences in the C_{ORG} stock in the O horizon among different humus forms indicate that a humus form must be considered when determining and forecasting a soil C_{ORG} stock. A similar conclusion, i.e. that the humus form is the most significant factor in determining a litter C_{ORG} stock, has also been drawn in European-scale studies (De Vos et al. 2015).

Unlike the litter C_{ORG} stock, the studied C_{ORG} stock in the mineral topsoil only partly supports the results of a regional-scale study in Europe (De Vos et al. 2015). According to De Vos et al. (2015), a soil humus form is a more significant factor than a forest type among numerous examined factors that impact C_{ORG} stock in the topsoil. However, the results of our study revealed statistically significant differences in the topsoil C_{ORG} stock in different humus forms as well as in different forest types. The mean C_{ORG} stock in the *psammomor* humus form topsoil is significantly lower than in the studied *mor*, *moder* and *mull*

humus form soils. Moreover, there are significant differences in the topsoil C_{ORG} stock between the *Cladinosa-callunosa* and *Vacciniosa* forest types, between the *Vacciniosa* and *Oxalidosa* forest types and among the *Myrtillosa*, *Hylocomiosa* and *Oxalidosa* forest types.

In general, our results show a lower C_{ORG} stock in the forest topsoil than the mean C_{ORG} stock of forest soils found in the BioSoil study in Latvia (Bārdule et al. 2009), where the mean C_{ORG} stock was calculated for all forest types, including forests formed on wet mineral soils and organic soils. Nevertheless, the calculated mean C_{ORG} stock of 40.8 t ha^{-1} in the studied *mor* humus is approximately twice as high as the values obtained in Estonia (Kõlli 2013). At the same time, the C_{ORG} stock in *mor* humus is comparable to Estonian *moder-mor* humus. These differences may be related to differences in humus classification.

Mor and *moder* humus accumulates carbon mainly in the O horizon, where the mean C_{ORG} stock was 34.6 and 37.1 t ha^{-1} , respectively (Fig. 2). These results are higher than the mean C_{ORG} stock in the O horizon in European forests (De Vos et al. 2015). However, other studies report C_{ORG} stocks in coniferous forests exceeding 30 t ha^{-1} (Cerli et al. 2008; Remy et al. 2016).

In the *mull* humus soils, organic carbon accumulates in the mineral topsoil. These results well correspond with other studies demonstrating that the mineral topsoil (the Ah horizon) accumulates 64–96% of the total organic carbon in a humus profile (Vesterdal et al. 2012; Kõlli 2013; Remy et al. 2016).

Significant differences recorded in the topsoil N_{TOT} stock between the *psammomor* and *mor* humus forms, between the *mor* and *moder* humus forms and between the *moder* and *mull* humus forms (Fig. 3) indicate that a humus form is an important factor in determining the N_{TOT} stock in the topsoil. The N_{TOT} stocks in the humus forms in the studied forests formed on dry mineral soils in Latvia are similar to those in the soil humus cover in Estonian forests (Kõlli 2013).

CONCLUSIONS

Four humus forms, *mor*, *moder*, *mull* and *psammomor* (according to the EHFRB classification), develop in the forests formed on dry mineral soils in Latvia. The *psammomor* humus forms are distributed mainly in the *Cladinosa-callunosa* forest type, and the distribution of the *mor* humus forms is related to the *Vacciniosa* and *Myrtillosa* forest types. The glaciogenic and glaciolimnic sediments, as well as the nutrient-rich sod-calcerous and sod-gleyic soils are the main factors responsible for the occurrence of the *mull* humus form.

The *psammomor* humus form soils have the lowest C_{ORG} stock in the topsoil (the O and A [EA] horizons). The

mean topsoil C_{ORG} stock in *psammomor* humus is two times lower than in the *mor* humus form soils. In the *psammomor* and *mor* humus form soils, more than 75% of the total C_{ORG} stock is accumulated in the O horizon. The highest topsoil C_{ORG} stock occurs in the *moder* humus form soils: its O horizon accumulates 61% of the total topsoil carbon stock on average. The *mull* humus form soils have the highest C_{ORG} stock in the mineral topsoil, where the Ah horizon accumulates 80% of the total topsoil C_{ORG} stock.

The differences in the litter composition and the nutrient cycle affect the properties of soil organic matter. The O horizon of the *mull* humus form soils has a significantly lower C/N ratio than that of the *mor* humus form soils. In addition, the proportion of humic substances in the mineral topsoil of the *mull* humus form soils is significantly lower than in other humus form soils.

Finally, it is worth noting that studies on soil humus forms can provide significant information about forest ecosystems. Further research should include humus forms in forests formed on moist and wet soils. Special attention should be paid to territories where humus forms are dependent on drainage.

Acknowledgements. We thank the anonymous reviewers for useful comments on the manuscript. The study was supported by European Social Fund Activity Programme Supplement 1.1.2.1.2. sub-activity ‘Support for Doctoral Studies Implementation’ Project ‘Support for Doctoral Studies at University of Latvia’ (2009/0138/1DP/1.1.2.1.2/09/IPIA/VIAA/004) and by University of Latvia grant No. AAp2016/B041//Zd2016/AZ03 within the project ‘Climate change and sustainable use of natural resources’. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

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Lāti parasniiskete mineraalsete metsamuldade humusvormid, süsinikuvaru ja orgaanilise aine omadused

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Viimastel kümnenditel pööratakse üha suuremat tähelepanu süsiniku talletumisele mullas ja humusvormidele, mis on olulised keskkonna ning mulla orgaanilise aine seisundi indikaatorid. Teadmised mulla ja metsakasvukohatüübi seostest mulla keemiliste omaduste, mulla orgaanilise aine ja humusvormidega ning süsiniku ja lämmastiku ringe ja varudega on veel ebapiisavad. Uurimuse eesmärk on selgitada erinevates metsakasvukohatüüpides kuivade ja parasniiskete mineraalmuldade humusvormide, huumuse keemilise koostise ning orgaanilise süsiniku varu eripärasid. Mullauurimise välitööd ja proovide kogumised metsakõdu- (O), huumus- (Ah) ning eluviaal-huumushorisondist (EAh, AEh) viidi läbi 44 uurimispunktis aastatel 2009–2015. Uurimisaladel oli kõige rohkem vähearenenud liivmuldi (*Arenosols*), leedemuldi (*Podzols*) ja leetjaid muldi (*Luvisols*). Euroopa humusvormide klassifikatsiooni alusel esines uurimisaladel neli humusvormi: *psammomoor* (9 uurimisala), *moor* (10), *moder* (8) ja *mull* (17). Tulemused näitasid, et *psammomoor*- ja *moor*-humusvormid on levinud vähearenenud liivmuldadega oligotroofsetes metsakasvukohatüüpides. *Mull*-humusvormi kujunemise eelduseks on peamiselt glatsiaalset ja limno-glatsiaalset päritolu lähtekivimid. *Psammomoor*- ja *moor*-humusvormides on kõige väiksem orgaanilise süsiniku varu ning sellest enam kui 75% on talletunud metsakõdus. Orgaanilise süsinikuga võrreldes on lämmastiku akumulierimisel O-horisondil palju väiksem tähtsus. *Psammomoor*-humusvormides on orgaanilise süsiniku varu üle kahe korra väiksem kui *moor*-humusvormiga muldades. *Moder*-humusvormidega muldades on suurim orgaanilise süsiniku koguvaru. *Mull*-humusvormiga muldades on 80% süsinikust talletunud huumushorisondis ja teiste humusvormidega võrreldes on neis oluliselt väiksem huumusainete ning orgaanilise süsiniku suhe. Edasistes uuringutes on vajalik analüüsida märgadel muldadel tekkinud humusvorme ja erilist tähelepanu tuleks pöörata kuivenduse mõjule.