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 (Kölli & Köster 2018). For example, 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 COrg stock in the topsoil, and more than 75% of the total COrg is accumulated in the O horizon. The mull humus form soils have the highest COrg stock in the mineral topsoil, accumulating 80% of the total topsoil COrg stock. The Ah horizons of the mull humus soils also have a significantly lower Corg-to-Corg ratio.

Key words: humus forms, boreo-nemoral ecotone, forest type, soil, carbon, nitrogen.
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 Cladinosa-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
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 cm × 20 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 pH$_{\text{H2O}}$ 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 ($C_{\text{ORG}}, \%$) was determined using a total carbon analyser Shimadzu TOC-Vcns solid sample module. The total nitrogen ($N_{\text{TOT}}, \%$) 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 ($C_{\text{HS}}, \%$). 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 $\lambda = 350$ nm to $\lambda = 650$ nm) with Elmer Fluorescence Spectrometer LS 55. The total organic carbon ($C_{\text{ORG}}, \%$) was determined using the modified Kjeldahl method (ISO:11261, 2002).

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Statistical analysis

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

Analysis of variance (One-way ANOVA) was performed to compare properties ($C_{\text{ORG}}, N_{\text{TOT}}, C/N, C_{\text{HS}}, C_{\text{HS}}/C_{\text{ORG}}, \text{HIX,} C\ t\ ha^{-1}, pH_{\text{H2O}}$) 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 Cladina-so-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 Oxalidosa and Aegopodiosa forest types exceeds 20 cm. According

| Forest type                  | O horizon thickness (cm) | Mass of the horizon (t ha$^{-1}$) | Mineral topsoil (A, E horizons) thickness (cm) | Bulk density (g cm$^{-3}$) | pH$_{\text{H2O}}$ |
|-----------------------------|--------------------------|----------------------------------|-----------------------------------------------|---------------------------|------------------|
| Cladina-so-Callunosa (7)    | 3.8 (±1.3)               | 39.2 (±9.2)                      | 6.0 (±3.1)                                    | 1.16 (±0.03)              | 4.7 (±0.2)       |
| Vacciniosa (7)              | 6.7 (±1.6)               | 87.2 (±24.5)                     | 5.1 (±2.3)                                    | 0.97 (±0.08)              | 4.6 (±0.2)       |
| Myrtilloa (7)               | 6.5 (±2.1)               | 68.3 (±7.1)                      | 7.2 (±2.7)                                    | 1.16 (±0.1)               | 4.5 (±0.5)       |
| Hylocomiosa (7)             | 6.4 (±4.4)               | 129.9 (±80.8)                    | 12.4 (±6.2)                                   | 0.89 (±0.2)               | 5.0 (±0.5)       |
| Oxalidosa (9)               | 3.2 (±2.9)               | 60.1 (±49.3)                     | 19.0 (±12.1)                                  | 0.88 (±0.33)              | 5.3 (±0.7)       |
| Aegopodiosa (7)             | 1.2 (±0.5)               | 10.5 (±6.3)                      | 20.0 (±4.9)                                   | 0.86 (±0.14)              | 5.8 (±0.5)       |

Table 1. Morphological, chemical and physical properties of soil humus forms in different forest types (standard errors are given in parentheses)
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 *Cladina*-callunosa and *Vacciniosa* forest soils have the *psammomor* or *mor* humus forms, while the *Myrtillus* forest soils have the *mor* or *moder* humus forms. There is no *mor* humus form in the nutrient-rich forests. In the studied *Oxalidosa* 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 *Cladina*-callunosa forest type and the *psammomor* humus form and between the *Vacciniosa* and *Myrtillus* 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. *Luvisols* 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 *Myrtillus* 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 |
|---------------------------------------|-----------------------------------------------|-----------------------|-------------|
|                                       | *Psammomor* (9) | *Mor* (10) | *Moder* (8) | *Mull* (17) | *Psammomor* | *Mor* | *Moder* | *Mull* |
| *Cladina*-callunosa (7)               | 6 | 1 | – | – | AIC | 30.6 | 50.8 | – | – |
|                                        | P | 0.0006 | 0.57 | – | – |
| *Vacciniosa* (7)                      | 3 | 4 | – | – | AIC | 46.4 | 46.4 | – | – |
|                                        | P | 0.125 | 0.03 | – | – |
| *Myrtillus* (7)                       | – | 4 | 3 | – | AIC | – | 46.4 | 42.9 | – |
|                                        | P | – | 0.03 | 0.08 | – |
| *Hylocomiosa* (7)                     | – | 1 | 2 | 4 | AIC | – | 50.8 | 45.2 | 61.5 |
|                                        | P | – | 0.57 | 0.44 | 0.28 |
| *Oxalidosa* (9)                       | – | – | 3 | 6 | AIC | – | – | 44.2 | 59.0 |
|                                        | P | – | – | 0.19 | 0.06 |
| *Aegopodiosa* (7)                     | – | – | – | 7 | AIC | – | – | – | 27.0 |
|                                        | P | – | – | – | * |

* the humus form occurs in a certain forest type; – not found.
The mean C content in the Aegopodiacea forest type is 15.3%.

The N 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 content in the O horizon of mor humus varies from 0.77% in the Cladina-callunosa forest type to 1.17% in the

| Quaternary deposits (number of sampling plots) | Humus forms (occurrence within sampling sites) | Statistical indicator | Humus forms |
|-----------------------------------------------|-----------------------------------------------|-----------------------|-------------|
| Glaciogluvial (3)                             | Psammomor (8) Mor (10) Moder (8) Moll (17)    | AIC 48.3              | Psammomor   |
| Marine sediments (14)                         | P 0.574                                       | Mor 48.3             | Mor         |
| Aeolian dunes (2)                             | P 0.0036                                      | Moder 43.8           | Moder       |
| Glaciogenic deposits (13)                     | P 0.0142                                      | Moll 52.7            | Moll        |
| Clay (2)                                      | – not found.                                  |                       |             |

| WRB reference soil group (number of sampling plots) | Humus forms (occurrence within sampling sites) | Statistical indicator | Humus forms |
|-----------------------------------------------------|-----------------------------------------------|-----------------------|-------------|
| Arenosols (17)                                      | Psammomor (8) Mor (10) Moder (8) Moll (17)    | AIC 36.062             | Psammomor   |
| Podzols (6)                                         | P 0.00541                                     | Mor 45.872            | Mor         |
| Stagnosols (2)                                      | AIC 48.52                                     | Moder 45.713          | Moder       |
| Gleysols (2)                                        | P 0.02839                                     | Moll 61.135           | Moll        |
| Luvisols (9)                                        | AIC 0.805035                                  |                       |             |
| Cambisols (4)                                       | P 0.3845                                      |                       |             |
| Planosols (2)                                       | AIC 0.54378                                   |                       |             |
| Retisols (2)                                        | P 0.054378                                   |                       |             |

* the humus form occurs in the soil group; – not found.
**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) | Humus forms |
|-------------------------------------------------|-----------------------------------------------|-------------|
|                                                 | Psammomor (9)                                | Mor (10)    | Moder (8) | Mull (7) |
| Pinus sylvestris (25)                           | 9                                             | 10          | 4         | 2        | AIC 36.7 | 37.7 | 45.5 | 37.5 |
| Picea abies (8)                                 | –                                             | –           | 3         | 5        | AIC –    | –   | 43.6 | 60.4 |
| Betula pendula (4)                              | –                                             | –           | 1         | 3        | AIC –    | –   | 45.6 | 60.3 |
| Quercus robur (7)                               | –                                             | –           | –         | 7        | AIC –    | –   | –    | 47.2 |

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

Myrtillus 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 Myrtillus type forests reaches 1.36%, while in the soils in the Myrtillus 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\(_{HS} \) | \( C_{HS} \) (%)* | \( C_{HS}/C_{ORG} \) (%)* | \( C_{HA}/C_{FA} \) | HIX* |
|------------|------------------|------------------|-----|-------------|-----------------|--------------------------|-----------------|-----|
| Psammomor  | 37.1ab           | 0.67a            | 0.91a | 0.08a       | 42.9a           | 14.8a                    | 4.6a            | 0.44ab | 72.5ab | 1.0a | 78.7a |
| Mor        | 38.1ab           | 0.91a            | 1.03a | 0.11a       | 37.8a           | 13.1a                    | 4.4a            | 0.67b  | 80.8a  | 0.51a | 79.7a |
| Moder      | 35.6b           | 2.55b            | 1.21a | 0.27a       | 30.4a           | 9.2a                     | 4.8a            | 1.58b  | 59.7bd | 0.86a | 79.8a |
| Mull       | 27.8bc           | 2.60b            | 1.73a | 0.42b       | 17.2b           | 7.4b                     | 5.6b            | 1.11bc | 45.1ed | 1.13a | 71.3* |

* \( C_{HS} \), 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\text{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\text{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\text{ORG} and N\text{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\textsuperscript{-1}.

The C\text{ORG} stock in the O and A (EA) horizons in the studied forest soils varies from 10.2 t ha\textsuperscript{-1} up to even 117.9 t ha\textsuperscript{-1}. The lowest C\text{ORG} stock in a soil humus form was found in the Cladina-na-caulnusso forest type, while the stock of C\text{ORG} that a humus form can store in the Hylocomiosa forest type reached 73.9 t C ha\textsuperscript{-1} on average (Fig. 2A). The Cladina-caulnusso forests also have the lowest N\text{TOT} stock in a soil humus profile: it was just 0.35 t N ha\textsuperscript{-1} in one of the study sites located in pine (Pinus sylvestris) tree stands. The highest N\text{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\textsuperscript{-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\textsuperscript{-1}.

A comparison of the mean C\text{ORG} stock in the humus profiles in different forest types shows the lowest humus C\text{ORG} stock in the Cladina-caulnusso forests (Fig. 2A). The Vacciniosa and Myrtillosa forest types have relatively similar mean C\text{ORG} stocks in the humus profile: 35.6 and 38.9 t C ha\textsuperscript{-1}, respectively. The Hylocomiosa forests have the highest mean humus C\text{ORG} stock. However, they also have a high C\text{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\textsuperscript{-1}, whereas in the mor humus topsoil in a pine (Pinus sylvestris) tree stand it is 117.9 t C ha\textsuperscript{-1}. The O and Ah soil horizons in the Oxalidosa forest contain 64.2 t C ha\textsuperscript{-1} and in the Aegopodiosa forests – 36.5 t C ha\textsuperscript{-1}. The C\text{ORG} stock in the

![Fig. 2. Mean C\text{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\text{ORG} stock in the O horizon; in grey – the C\text{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.](image-url)
**Fig. 3.** Mean \( N_{\text{TOT}} \) 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 \( N_{\text{TOT}} \) stock in the O horizon; in grey – the \( N_{\text{TOT}} \) 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-callinuosa type forests, the moder humus forms are related to the Vacciniosa and Myrtillosa forest types, and mull humus is formed in the Oxalidosa and Aegopodiosa 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 Oxalidosa 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 accordingly to the second level (for example, eumull, mesomull, etc.) of the EHFIRB classification system (Zanella et al. 2011).

Chemical properties of soil humus forms

The $C_{\text{ORG}}$ 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 $C_{\text{ORG}}$ 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 $C_{\text{ORG}}$ content (< 20%) in the O horizon in the oak (Quercus robur) stand soil. Other studies have not found significant differences in the $C_{\text{ORG}}$ 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 $C_{\text{ORG}}$ content in the O horizons of the psammomor, mor and moder humus forms (Table 6) does not differ from the mean $C_{\text{ORG}}$ 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 $N_{\text{TOT}}$ 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 $C_{\text{ORG}}$ and $N_{\text{TOT}}$ 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 = 30–40) 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 $C_{\text{ORG}}$ content in mineral topsoil correlates with the $N_{\text{TOT}}$ 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 $C_{\text{ORG}}$ 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\textsubscript{ORG} content in the psammomor and mor soils may be explained by intense podzolization. A fraction of the soil organic matter that includes C\textsubscript{ORG} is translocated to the deeper soil horizons (Grand & Lavkulich 2011; Freyerová & Šefrna 2014). The C\textsubscript{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\textsubscript{HA}/C\textsubscript{FA} 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\textsubscript{HA}/C\textsubscript{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\textsubscript{HA}/C\textsubscript{FA} ratio and HIX are highly variable within the mineral topsoil of the studied soils. Although a comparison of the mean C\textsubscript{HA}/C\textsubscript{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 soil 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\textsubscript{ORG} and N\textsubscript{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 Myrtillus 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\textsuperscript{-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 Hylacomiososa and Oxalidosa forest types, where the O horizon mass exceeds 200 t ha\textsuperscript{-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 Hylacomiososa, Oxalidosa 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\textsubscript{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\textsubscript{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\textsubscript{ORG} stock. A similar conclusion, i.e. that the humus form is the most significant factor in determining a litter C\textsubscript{ORG} stock, has also been drawn in European-scale studies (De Vos et al. 2015).

Unlike the litter C\textsubscript{ORG} stock, the studied C\textsubscript{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\textsubscript{ORG} stock in the topsoil. However, the results of our study revealed statistically significant differences in the topsoil C\textsubscript{ORG} stock in different humus forms as well as in different forest types. The mean C\textsubscript{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\textsubscript{ORG} stock between the Cladino­sa-callinusa and Vaccinio­sa forest types, between the Vaccini­osa and Oxali­disa forest types and among the Myrtillo­sa, Hylocomi­osa and Oxali­disa forest types.

In general, our results show a lower C\textsubscript{ORG} stock in the forest topsoil than the mean C\textsubscript{ORG} stock of forest soils found in the BioSoil study in Latvia (Bārdule et al. 2009), where the mean C\textsubscript{ORG} stock was calculated for all forest types, including forests formed on wet mineral soils and organic soils. Nevertheless, the calculated mean C\textsubscript{ORG} stock of 40.8 ha\textsuperscript{-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\textsubscript{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\textsubscript{ORG} stock was 34.6 and 37.1 t ha\textsuperscript{-1}, respectively (Fig. 2). These results are higher than the mean C\textsubscript{ORG} stock in the O horizon in European forests (De Vos et al. 2015). However, other studies report C\textsubscript{ORG} stocks in coniferous forests exceeding 30 t ha\textsuperscript{-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\textsubscript{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\textsubscript{TOT} stock in the topsoil. The N\textsubscript{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 EHF RB classification), develop in the forests formed on dry mineral soils in Latvia. The psammomor humus forms are distributed mainly in the Cladino­sacallinusa forest type, and the distribution of the mor humus forms is related to the Vaccinio­sas and Myrtillo­sas forest types. The glaciogenic and glaciomorphic sediments, as well as the nutrient-rich sod-calcareous 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\textsubscript{ORG} stock in the topsoil (the O and A [EA] horizons). The mean topsoil C\textsubscript{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\textsubscript{ORG} stock is accumulated in the O horizon. The highest topsoil C\textsubscript{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\textsubscript{ORG} stock in the mineral topsoil, where the Ah horizon accumulates 80% of the total topsoil C\textsubscript{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.

**REFERENCES**

Albers, D., Migge, S., Schäfer, M. & Scheu, S. 2004. Decomposition of beech leaves (Fagus sylvatica) and spruce needles (Picea abies) in pure and mixed stands of beech and spruce. *Soil Biology & Biochemistry*, **36**, 155–164.

Bārdule, A., Bāders, E., Stola, J. & Lazdiņš, A. 2009. Latvijas meža augšņu īpašību raksturojums demonstrācijas projekta BioSoil rezultātu skatījumā [Forest soil characteristics in Latvia according to results of the demonstration project BioSoil]. *Mežzinātne*, **53**(20), 105–124 [in Latvian, with English summary].

Bayranvand, M., Kooch, Y., Hosseini, S. M. & Alberti, G. 2017. Humus forms in relation to altitude and forest type in the Northern mountainous regions of Iran. *Forest Ecology and Management*, **385**, 78–86.

Burt, R. (ed.). 2004. *Soil Survey Laboratory Methods Manual*. Soil Survey Investigations. Report, No 42, 736 pp.

Buss, K. 1997. Forest ecosystem classification in Latvia. *Proceedings of the Latvian Academy of Sciences, Section B*, **51**, 204–218.
Carter, M. R. & Gregorich, E. G. 2007. *Soil Sampling and Methods of Analysis* (2nd Edition). CRC Press, Boca Raton, 1224 pp.

Cerli, C., Celi, L., Kaiser, K., Guggenberger, G., Johansson, M.-B., Cignetti, A. & Zanini, E. 2008. Changes in humic substances along an age sequence of Norway spruce stands planted on former agricultural land. *Organic Geochemistry*, 39, 1269–1280.

Chertov, O. & Nadporozhskaya, M. 2018. Development and application of humus form concept for soil classification, mapping and dynamic modelling in Russia. *Applied Soil Ecology*, 123, 420–423.

De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E. & Carnicelli, S. 2015. Benchmark values for forest soil carbon stocks in Europe: results from a large scale forest soil survey. *Geoderma*, 251–252, 33–46.

[FAO] Food and Agriculture Organization. 2006. *Guidelines for Soil Description*. Fourth edition. Food and Agriculture Organization of the United Nations, Rome, 97 pp.

Freyerová, K., & Šefrna, L. 2014. Soil organic carbon density and storage in podzols – a case study from Ralsko region (Czech Republic). *AUC Geographica*, 49, 65–72.

Fröberg, M., Kleja, D., Bergkvist, B., Tipping, E. & Mulder, J. 2005. Dissolved organic carbon leaching from a coniferous forest floor – a field manipulation experiment. *Biogeochemistry*, 75, 271–287.

Grand, S. & Lavkulich, L. 2011. Depth distribution and predictors of soil organic carbon in podzols of a forested watershed in Southwestern Canada. *Soil Science*, 176, 164–174.

Hosseini Bai, S., Xu, Z., Blumfield, T. & Reverchon, F. 2015. Human footprints in urban forests: implication of nitrogen deposition for nitrogen and carbon storage. *Journal of Soils and Sediments*, 15, 1927–1936.

IUSS Working Group WRB. 2015. *World Reference Base for Soil Resources 2014. Update 2015*. World Soil Resource Report No.106. FAO, Rome, 192 pp.

Kalbitz, K. & Geyer, W. 2001. Humification indices of water-soluble fulvic acids derived from synchronous fluorescence spectra – effects of spectrometer type and concentration. *Journal of Plant Nutrition and Soil Science*, 164, 259–265.

Kalbitz, K., Geyer, W. & Geyer, S. 1999. Spectroscopic properties of dissolved humic substances – a reflection of land use history in a fen area. *Biogeochemistry*, 47, 219–238.

Kalbitz, K., Kaiser, K., Bargholz, J. & Dardenne, P. 2006. Lignin degradation controls the production of dissolved organic matter in decomposing foliar litter. *European Journal of Soil Science*, 57, 504–516.

Kanerva, S. & Smolander, A. 2007. Microbial activities in forest floor layers under silver birch, Norway spruce and Scots pine. *Soil Biology and Biochemistry*, 39, 1459–1467.

Kasparinskis, R. & Nikodemus, O. 2012. Influence of environmental factors on the spatial distribution and diversity of forest soil in Latvia. *Estonian Journal of Earth Sciences*, 61, 48–64.

Kölli, R. 2013. Humus cover and its fabric depending on pedo-ecological conditions and land use: an Estonian approach to classification of humus forms. *Estonian Journal of Ecology*, 62, 6–23.

Kölli, R. & Köster, T. 2018. Interrelationships of humus cover (pro humus form) with soil cover and plant cover: humus form as transitional space between soil and plant. *Applied Soil Ecology*, 123, 451–454.

Kölli, R. & Rannik, K. 2018. Matching Estonian humus cover types (pro humus forms) and soils’ classifications. *Applied Soil Ecology*, 123, 627–631.

Korhonen, J. F. J., Pihlatie, M., Punpanen, J., Aaltonen, H., Hari, P., Levula, J., Kieloaho, A.-J., Nikinmaa, E., Vesala, T. & Ilvesniemi, H. 2013. Nitrogen balance of a boreal Scots pine forest. *Biogeosciences*, 10, 1083–1095.

Korkina, I. N. & Vorobeichik, E. L. 2016. The humus index: a promising tool for environmental monitoring. *Russian Journal of Ecology*, 47, 526–531.

Labaz, B., Galka, B., Bogacz, E., Waroszewski, J. & Kabala, C. 2014. Factors influencing humus forms and forest litter properties in the mid-mountains under temperate climate of southwestern Poland. *Geoderma*, 230–231, 265–273.

Martin, D., Srivastava, P. C., Ghosh, D. & Zech, W. 1998. Characteristics of humic substances in cultivated and natural forest soil of Sikkim. *Geoderma*, 84, 345–362.

Muscolo, A., Sidari, M., Pizzeghella, D. & Nardi, S. 2009. Effects of humic substances isolated from earthworm faeces. *Dynamic Soil. Dynamic Plant*, 2, 45–52.

Niemi, R. M., Vepsäläinen, M., Erkoma, K. & Ilvesniemi, H. 2007. Microbial activity during summer in humus layers under *Pinus silvestris* and *Abies incana*. *Forest Ecology and Management*, 242, 314–323.

Peltier, A., Ponge, J.-F., Jordana, R. & Ariño, A. 2001. Humus forms in Mediterranean scrublands with Aleppo Pine. *Soil Science Society of America Journal*, 65, 884–896.

Piccolo, A. 1996. Humus and soil conservation. In *Humic Substances in Terrestrial Ecosystems* (Piccolo, A., ed.), pp. 225–264. Elsevier Science, Amsterdam.

Ponge, J.-F. 2013. Plant–soil feedbacks mediated by humus forms: a review. *Soil Biology and Biochemistry*, 57, 1048–1060.

Ponge, J.-F., Jaboli, B. & Gégoût, J.-C. 2011. Geology and climate conditions affect more humus forms than forest canopies at large scale in temperate forests. *Geoderma*, 162, 187–195.

Qualls, R. G., Takiyama, A. & Wershaw, R. L. 2003. Formation and loss of humic substances during decomposition in a pine forest floor. *Soil Science Society of America Journal*, 67, 899–909.

Quinn, G. P. & Keough, M. J. 2002. *Experimental Design and Data Analysis for Biologists*. Cambridge University Press, New York, 557 pp.

Remy, E., Wuyts, K., Boeckx, P., Ginzburg, S., Gundersen, P., Demey, A., Van Den Bulcke, J., Van Acker, J. & Verheyen, K. 2016. Strong gradients in nitrogen and carbon stocks at temperate forest edges. *Forest Ecology and Management*, 376, 45–58.

Smolander, A. & Kitunen, V. 2002. Soil microbial activities and characteristics of dissolved organic C and N in relation to tree species. *Soil Biology and Biochemistry*, 34, 651–660.

Tan, Kim H. 2005. *Soil Sampling, Preparation, and Analysis* (2nd edition). CRC Press, New York, 672 pp.
Läti parasniiskete mineraalsete metsamuldade huumusvormid, sūsinikuvaru ja orgaanilise aine omaduse

Imants Kukuļs, Oļģerts Nikodemus, Raimonds Kasparinskis ja Zane Žīgure

Viimastel kūnnenditel pōrēvas diskusija par lētā sūrēmā ābolu mūra sūsiniku tālumu un robežu mūru posmās ir mūsdienu lētāa mūra biologijas savācēja. Šajā rakstā mēs apskatām to, ko mēs mācāmies no iepriekšējās mūra mērījumu serijas, kas tika veiktas Latvijas seņūnijās 2017. gadā sākotno mūra mērījumu posma laikā.

Mūsu mērījumu posma, kuru veikumā tika mērīta mūra sūsiniku tālumu, bija izveidota mūra mērījumu serija, kas veikta seņūnijas mūra mērījumu posma laikā. Šajā posma mērījumu serijā tika mērītas seņūnijas mūra sūsiniku tālu, kas atbilst mūra mērījumu posma laikā. Šajā posma mērījumu serijā tika mērītas seņūnijas mūra sūsiniku tālu, kas atbilst mūra mērījumu posma laikā.

I. Kukuļs et al.: Humus forms, C and N stock in Latvian dry forests

Terauda, E & Nikodemus, O. 2006. Element inputs by litterfall to the soil in pine forest ecosystems. *Environmental Biocatalysts*, 1, 145–156.

Trap, J., Bureau, F., Akpa-Vinceslas, M., Deceën, T. & Aubert, M. 2011. Changes in humus forms and soil N pathways along a 130-year-old pure beech forest chronosequence. *Annals of Forest Science*, 68, 595–606.

Vaičys, M., Raugutois, A., Kubertavičienė, L. & Armolaitytė, K. 1996. Properties of Lithuanian forest litters. *Baltic Forestry*, 2, 27–33.

van Reeuwijk, L. P. 1995. *Procedures for Soil Analysis*. ISRIC, Wageningen.

Vesteral, L. 1999. Influence of soil type on mass loss and nutrient release from decomposing foliage litter of beech and Norway spruce. *Canadian Journal of Forest Research*, 29, 95–105.

Vesteral, L., Schmidt, I. K., Callesen, I., Nilsson, L. O. & Gundersen, P. 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. *Forest Ecology and Management*, 255, 35–48.

Vesteral, L., Elberling, B., Christiansen, J., Callesen, I. & Schmidt, I. 2012. Soil respiration and rates of soil carbon turnover differ among six common European tree species. *Forest Ecology and Management*, 264, 185–196.

Zanella, A., Jabiol, B., Ponge, J. F., Sartori, G., De Waal, R. W., Van Delft, B., Graefe, U., Coûts, N., Katzensteiner, K., Hager, H. & Engelsch, M. 2011. A European morpho-functional classification of humus forms. *Geoderma*, 164, 138–145.

Zanella, A., Bolzonella, C., Lowenfels, A., Ponge, J. F., Bouché, M., Saha, D., Kukal, S. S., Fritz, I., Savory, A., Blouin, M., Sartori, L., Tatti, D., Kellermann, L. A., Trachsel, P., Burgos, S., Minasny, B. & Fukushima, M. 2018a. Humusica 2, article 19: Techno humus systems and global change – Conservation agriculture and 4/1000 proposal. *Applied Soil Ecology*, 122, 271–296.

Zanella, A., Fumagalli, C., Callesen, I., Blouin, M., De Nobili, M. & Juilleret, J. 2018c. Humusica 1, article 3: Essential bases – Quick look at the classification. *Applied Soil Ecology*, 122, 42–55.

Zanella, A., Ponge, J. F., de Waal, R. F., Ferronato, C., De Nobili, M. & Juilleret, J. 2018e. Humusica 1, article 1: Essential bases – Vocabulary. *Applied Soil Ecology*, 122, 10–21.

Zanella, A., Ponge, J. F., Hager, H., Pignatti, S., Galbraith, J., Chertov, O., Andreotta, A. & De Nobili, M. 2018e. Humusica 2, article 18: Techno humus systems and global change – Greenhouse effect, soil and agriculture. *Applied Soil Ecology*, 122, 254–270.

Zanella, A., Ponge, J. F., Jabiol, B., Sartori, G., Kolb, E., Le Bayon, R.-C., Gobat, J. M., Aubert, M., De Waal, R. W., Van Delft, B. et al. 2018f. Humusica 1, article 5: Terrestrial humus systems and forms – Keys of classification of humus systems and forms. *Applied Soil Ecology*, 122, 75–86.

Zech, W. & Kögel-Knabner, I. 1994. Patterns and regulation of organic matter transformation in soils: litter decomposition and humification. In *Flux Control in Biological Systems* (Schulze, E.-D., ed.), pp. 303–355. Academic Press, San Diego, CA.