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A Concept for a Consolidated Humus Form Description—An Updated Version of German Humus Form Systematics

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Abstract: In Germany, the systematics of humus forms has been developed, which is mainly based on morphological characteristics and has been proven via detailed long-term observation. The humus form systematics presented here is an update based on a new approach, clarifying the hierarchical structure into divisions, classes, types, and subtypes. New diagnostic horizons and transition horizons are introduced, uniquely characterising types and subtypes. This paper holds that the humus form is not only a product of decomposition, humification, and bioturbation but also serves as habitat for soil organisms. The processes and the habitat are shaped by soil-forming factors with the main factor being soil water conditions. Thus, on the first level of systematics, aeromorphic and aero-hydromorphic as well as hydromorphic humus forms are differentiated. Many different features of the organic layers and the mineral topsoil can be observed in forests, open grasslands, the mountain zone above the tree line, and natural fens and bogs, as well as degraded peatlands. Features shaping the humus form, such as the proportion of organic fine material and packing of the organic matter as well as the structure of the mineral soil, have now been unambiguously described. However, site-specific soil-forming factors result in typical organic matter characteristics of individual horizons and typical combinations of different horizons. This relationship is illustrated using descriptions of distinct humus forms.

Keywords: decomposition; forest floor; humification; litter; peat; organic matter; soil organisms; topsoil

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1. Introduction

The organic surface layers are part of the pedosphere and thus an important interface between the atmosphere, biosphere, hydrosphere, and lithosphere, shaped by many biotic and abiotic interactions. Occurrence, thickness, and morphological features of distinct topsoil horizons, comprising the organic surface layers as well as the mineral topsoil, indicate pedogenic processes and the allocation and quality of organic matter in a soil profile, predestining these properties as suitable parameters for the differentiation of humus forms [1].

Distinct humus forms differing in morphological, chemical, physical, and biological properties develop due to interactions between all soil-forming factors [1,2]. They are indicators of the long-term impact of natural soil-forming factors and are sensitive to impacts of environmental changes such as eutrophication and climate change. Thus, they provide integrative information about former and present site conditions. Humus form can serve as an early indicator of changes to soil functions because of its significant spatial and temporal variability. Organic surface layers and mineral topsoil are an important process space and a valuable indicator of process rate performance, supporting many functions such as nutrient cycling, water regulation, C sequestration, and habitat provision for a biodiverse faunal and microbial community.

The purpose of systematics is to organise the entire spectrum of knowledge of objects and processes of a subject area into a transparent and manageable form. Soils are classified using two different systems, classification and systematics [3,4]. The main difference between systematics and classification is that the latter names and classifies soils inductively, while systematics considers pedogenic processes and similarity of expression [5]. The world reference base of soil resources (WRB) is a classification system which holds that soil-forming processes contribute to a better characterisation of soils. However, it does not use these processes as differentiating criteria, but accounts only for selected diagnostic characteristics [6]. Broll et al. [7] and Jabiol [8] presented a topsoil characterisation and proposed the inclusion of humus forms in the WRB, but so far humus forms are not considered in the WRB. In German humus form systematics, morphological features resulting from the pedogenic processes, such as decomposition, bioturbation, humification, and mineralisation are classified into a hierarchical system. The identification of a specific humus form requires a clear assignment of categorising properties so that both diagnostic horizons and humus forms can be objectively described and unique processes can be deduced [1,2]. The boundaries of category-forming characteristics are defined by a range of field observations and not arbitrarily drawn (Figures S1 and S2). Transitions should be considered on all levels of systematics and even integration of new classes and types should be possible if new phenomena are observed.

The humus form description is part of a morphogenetic soil systematics system using diagnostic horizons (Table S1) and properties to deduce pathways of soil genesis and formation [9]. The terms used in humus form systematics are defined in Table 1. Humus forms often reflect pedogenic processes which may be related to specific functions. However, functions and dynamics are not always adequately represented in German soil systematics [10]. Recording visible traces of soil fauna activity helps us to describe and distinguish humus forms. Direct evidence of the activity of different soil fauna groups in specific humus forms and their diagnostic horizons has been provided by Hellwig et al. [11].

Table 1. Glossary—Description of terms used in humus form systematics adapted and complemented from [12].

Term	Description
Soil-forming Conditions	
aeromorphic	Morphology indicating soil development under well-aerated topsoil conditions
aero-hydromorphic	Morphology indicating soil development under moderately aerated or poorly drained topsoil conditions
hydromorphic	Morphology indicating soil development under predominantly water saturated topsoil conditions
peat formation	Peat formation is the result of incomplete decomposition of the remains of peat-forming plants induced and controlled by conditions such as waterlogging, low oxygen supply, low nutrient availability, or low litter decomposability.
peat-forming plants, peat-forming vegetation	Plants which are peat-forming under hydromorphic conditions, for example: sphagnum moss, different carex species, different species of the sedge family
cultitropic	Anthropogenic—substantial changes of the nutrients and the base saturation, soil structure due to regular fertilisation and sometimes tillage

Table 1. *Cont.*

Term	Description
Humus form	
humus form	Order of distinct units defined by organic surface horizons and the first mineral horizon with similar morphology, depths and type of boundary of horizons indicating specific conditions for bioturbation, decomposition, humification, and mineralisation.
Horizon	
master horizon	Horizon with an important and dominant soil genetic process such as peat forming or podzolisation, for example: O, H, A, S, G, D, R
mineral master horizon	Master horizon with a content of organic carbon < 15% mass (A, B, C, G, S)
mineral topsoil	Soil layer at the soil surface, with an organic carbon < 15% mass
modified horizon	Horizon with a dominant and a subdominant soil genetic process, such as Ohf, an Of horizon with 30–70% volume of organic fine material
organic master horizon	Master horizon with a content of organic carbon $\geq$ 15% mass (O, H, U)
organic surface layer	Sum of all macroscopically visible distinct organic material characterised by texture and packing of the organic material overlying the mineral soil. Layers may vary in percentages of macroscopically visible plant residues and organic fine material
organic surface horizon	Organic horizon at the surface of soils (O, H or U horizon)
soil horizon	Soil area which summarises common features as a result of soil forming processes
topsoil	All soil layers (organic surface layer and top mineral soil) comprising the humus form. At forest sites, the term forest floor is often synonymously used
transition horizon	Soil horizon with two or three important soil genetic processes, for example Ah-Go (humus accumulation and groundwater influence, typical of transition soil types)
Processes and properties of organic matter	
degree of decomposition and humification	Deduced by the percentage of macroscopically recognisable plant residues and organic fine material in the peat. Ranging from H1 (plant structures completely visible) to H10 (100% organic fine material)
humus	All organic matter on the soil surface and within the soil, comprising dead plant, microbial, or faunal residues and their transformation products
humification	Processes of decomposition and humification of plant material via hydrolysis or oxidation and reduction mediated by soil organisms, resulting in a continuum of organic material (plant, microbial, and faunal metabolites) of various molecular sizes and composition.
organic fine material	Dark-coloured, amorphous organic matter, without macroscopically recognisable tissue structures occurring in the organic surface layer, peat or mineral soil
packaging and structure of O material	Describes how units of the O layers are interconnected
peat	Accumulation of plant material under anaerobic conditions. Plant material varies in the degree of decomposition and humification

The updated version of systematical German humus form systematics, which will be partly published in a German field manual [12], may serve as a tool for a detailed description and evaluation of the research object. In perspective, the application of this version will allow for a better linkage of morphological, biological, chemical, and physical properties as well as soil functions. Thus, the objective of the article is to present the English version of the new structure of this German humus form systematics, to justify the new approach, and to explain details such as the diagnostic horizons.

2. German Humus Form Systematics

2.1. Structure of the Hierarchical Humus Form Systematics

Humus forms are classified on different levels in accordance with distinct criteria, such as soil hydrologic balance and oxygen availability, the occurrence of diagnostic horizons, and distinct sequences of horizons. Criteria are designated by specific morphological features and the occurrence of specific vegetation. Changes to site conditions may result in an imbalance of the dynamics of organic matter, which demonstrates the importance of defining transition humus forms. Depending on the scale and purpose, differentiation between humus forms can be carried out on different levels (Table 2). On the first level, the hydrologic balance of the soil is considered. Under well-aerated conditions, aeromorphic Mull humus forms such as *Typical L Mull* and *Typical F Mull* and humus forms with an Oh horizon such as *Typical Moder* and *Typical Mor* develop. In Figures 1 and 2, selected aeromorphic humus forms and typical sequences of horizons are listed. Moderately aerated and poorly drained conditions will lead to the aero-hydromorphic humus forms *Moist Mull*, *Moist Moder*, and *Moist Mor*. Anaerobic conditions resulting from prolonged water saturation will lead to hydromorphic humus forms: *Anmoor* and *Moor* with different humification levels of the peat (Table 3). Aeromorphic and aero-hydromorphic humus forms dominate on mineral soils but may also occur on primeval peat-forming organic soils if the conditions for peat accumulation are no longer fulfilled.

Table 2. Structure of hierarchical humus form systematics; adapted from [12] (new units are written in red).

Division	Class	Type	Subtype	Code
Aeromorphic and Aero-Hydromorphic humus forms				
	Mull humus forms			M
		L Mull		ML
			A Mull	MLA
			Typical L Mull	MLT
			Rhizo L Mull	MLR
			Moist L Mull	MLF
		F Mull		MF
			L Mull-like F Mull	MFL
			Typical F Mull	MFT
			Rhizo F Mull	MFR
			Moder-like F Mull	MFM
			Moist F Mull	MFF
	Humus forms with an Oh horizon			A
		Moder		AM
			Mull-like Moder	AMM
			Typical Moder	AMT
			Rhizo Moder	AMR
			Pechmoder	AMP
			Tangel	AMA
			Moist Moder	AMF
		Mor		AR
			Moder-like Mor	ARM
			Typical Mor	ART
			Moist Mor	ARF
	Initial humus forms			I
		Initial Mull		IM
		Initial humus form with organic surface layers		IA
	Naturally and Anthropogenically deteriorated humus forms			X
		Naturally deteriorated humus form		XH
		Anthropogenically deteriorated humus form		XR

Table 2. *Cont.*

Division	Class	Type	Subtype	Code
Hydromorphic humus forms				
	Anmoor			O
		Anmoor		OA
	Humus forms of natural fen and bog			
		F Moor		HF
			Mesotrophic F Moor	HFM
			Oligotrophic F Moor	HFO
			Dystrophic F Moor	HFD
		M Moor		HM
			Eutrophic M Moor	HME
			Mesotrophic M Moor	HMM
			Oligotrophic M Moor	HMO
		H Moor		HH
			Polytrophic H Moor	HHP
			Eutrophic H Moor	HHE
			Mesotrophic H Moor	HHM
			Oligotrophic H Moor	HHO

Table 3. Humus forms of natural fen and bog; adapted from [12].

Humus Form Type (Degree of Decomposition and Humification)	Diagnostic horizon (Degree of Peat Decomposition and Humification)	Humus Form Subtype (Range of CN Ratio of the Peat at the Soil Surface)
F Moor (fibric)	Hfn (H1–H4)	Mesotrophic F Moor (≥20–33) Oligotrophic F Moor (≥33–40) Dystrophic F Moor ((≥40))
M Moor (hemic)	Hen (H5–H6)	Eutrophic M Moor (≥10–20) Mesotrophic M Moor (≥20–33) Oligotrophic M Moor (≥33–40)
H Moor (humic)	Hhn (H7–H10)	Polytrophic H Moor (<10) Eutrophic H Moor (≥10–20) Mesotrophic H Moor (≥20–33) Oligotrophic H Moor (≥33–40)

Mull humus forms are differentiated according to their structure, distinctness of horizon boundary, thickness of A horizon, and the occurrence of organic surface layers, indicating the degree of bioturbation and decomposability of litter (Figure 1). Humus forms with an Oh horizon are mainly differentiated by structure, packing, thickness, distinctness of horizon boundaries, and separability of the organic layer from the mineral soil (Figure 2). Gradual variation between humus types leads to transition subtypes such as *Moder-like F Mull*. Furthermore, a high density of fine roots observed as a root felt in distinct horizons results in changes to the morphological, biological, chemical, and physical properties of the humus form, which is evaluated on subtype level, indicated by rhizo humus forms.

humus form, subtype	Typical L Mull	Typical F Mull	Mull-like Moder
sequence of horizons	Ol/(Of),Ax,Au,(Ah)	Ol/(Olf)/Ohf/Ax,Au,Ah	Ol/Olf/Ohf/Oih/A..
thickness of A horizons	≥ 8 cm, often 10 – > 15 cm	< 10 cm, often 5 – < 7 cm	2 – 8 cm, often 2 – < 4 cm
soil structure of A horizons	loamy soils almost granular, clayey soils almost fine subangular or angular blocky	predominant fine subangular blocky, partly granular or coherent	fine subangular blocky, sporadic fine platy
distinctness of horizon boundary (A horizon to subsoil)	clear (20 – 50 mm) to diffuse (≥ 50 mm), clayey soils very clear (< 20 mm)	clear (20 – < 50 mm) to very clear (< 20 mm)	very clear (< 10 mm)
features of Oh horizons	not existing	not existing	generally 2 – 3 (5) mm thick and film-like or patchy in depressions of the mineral soil surface

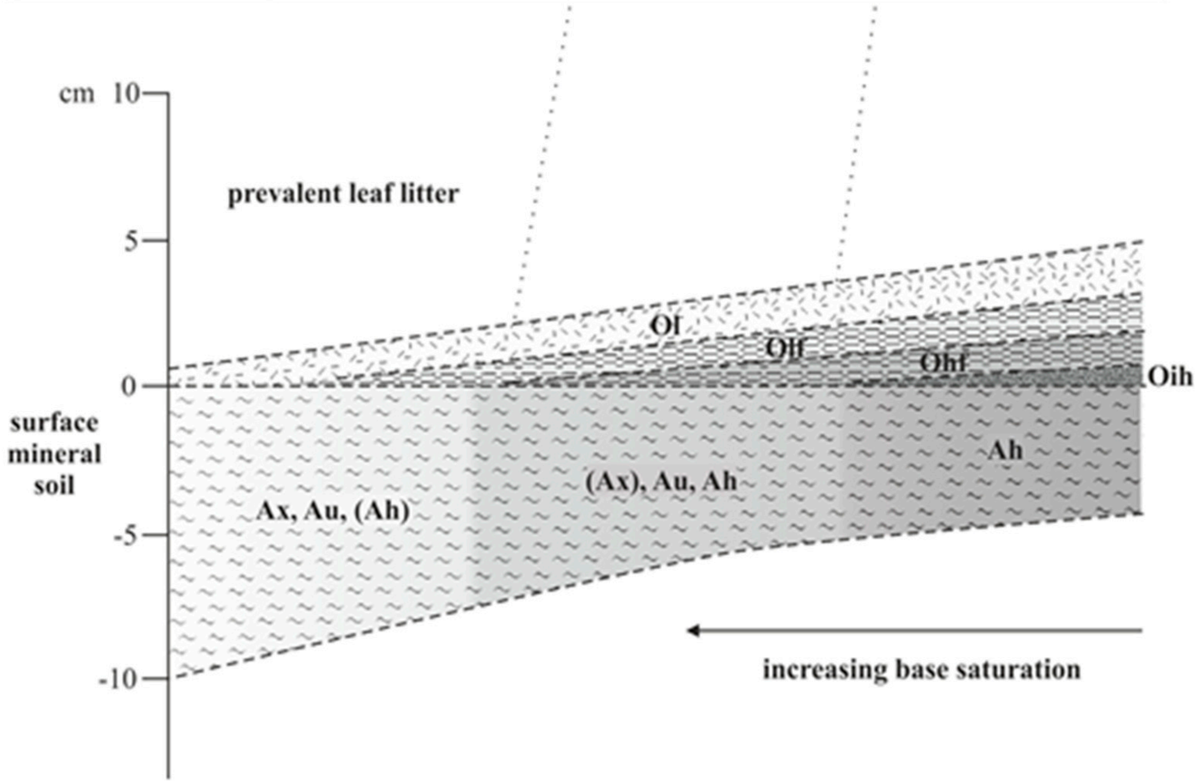

Figure 1. Main features of Mull humus forms. Adapted from [12].

humus form, subtype	Typical Moder	Moder-like Mor	Typical Mor
sequence of horizons	Ol/Of/Obh/Ah or Ol/Of/Obh/Ee-Ah or Ol/Of/Obh/Ah-Ee or Ol/Of/Obh/Ah-Ee + Ee	Ol/Of/Okh/Ah-Ee or Ol/Of/Okh/ Ah-Ee + Ee or Ol/Of/Okh/Ah-Ee/Ee/ K(h)s	Ol/Of/Osh/Ah-Ee + Ee or Ol/Of/Osh/Ah-Ee/Ee/ K(h)s
structure and packing of organic material (Of-horizons)	clotted, or layer-like or bulky	felted or bulky or batch-like or cross linked	intensively felted, flexural
thickness of Oh horizons (definition of varieties)	poor in fine organic matter < 2 cm, rich in fine organic matter ≥ 2 cm	poor in fine organic matter < 3 cm, rich in fine organic matter ≥ 3 cm	poor in fine organic matter < 4 cm, rich in fine organic matter ≥ 4 cm
structure and packing of organic fine material in Oh-horizons	powdery to brittle, partly layer-like	compact, breakable into pieces with unsharp edges	compact, breaks into pieces with sharp edges, partly layers of Oh material
root density in Oh horizons	medium to high (fine roots)	low (fine roots), high (coarse roots)	high (coarse roots)
distinctness of boundaries between O horizons	clear (3 – 6 mm), partly diffuse (≥ 6 mm)	very clear (1 – < 3 mm, partly abrupt (< 1 mm)	mostly abrupt (< 1 mm)
separability between organic layer and A horizon	difficult	good	very good

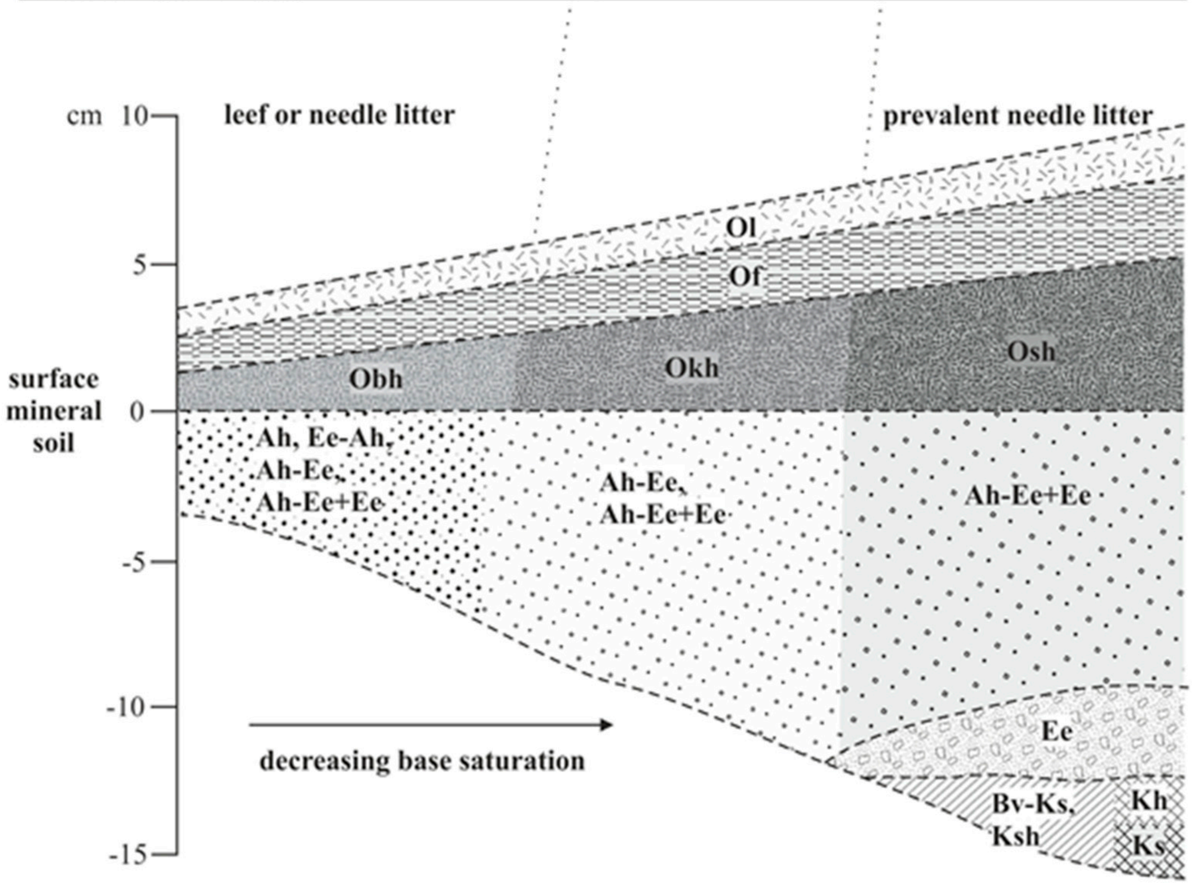

Figure 2. Main features of humus forms with an Oh horizon. Adapted from [12].

Humus forms with features which do not match, such as a sparse litter layer despite dense vegetation but no signs of bioturbation, are disturbed or devastated by litter export and are therefore described as naturally or anthropogenically degraded humus forms. Furthermore, the balance between litter mineralisation and humification may be disrupted due to afforestation of arable land or recultivation. Humus forms developing under such conditions are in an initial stage. With the exception of initial, naturally and anthropogenically deteriorated humus forms, the humus forms presented in Table 2 and the following passages are listed in sequence of the increasing duration of litter decomposition.

2.2. Description of Humus Forms

The results presented here are based on the description of humus forms in central Europe. The relationship between specific site conditions and the features of the humus form may vary in other pedoclimatic regions. The identification of a specific humus form requires a clear assignment of diagnostic horizons, which are further described according to specific features (Tables S1–S9). The decomposability of litter is one factor mediating the processes shaping the humus form; thus, typical CN and CP ratios are observed in specific horizons of humus forms (Tables S10 and S11). In the following, the features described refer mainly to leaf litter. Wood and bark frequently occur in the organic surface layer but, having different decomposability, should be described separately. These components, as well as roots, affect the biological, physical, and chemical properties of the soil. The systematics of humus forms should be further validated by physical and chemical analysis of factors such as pH, CEC, and nutrient status (Table S12), which would better prove the correlation between morphological features and soil functions. The development of humus forms is a highly dynamic process; therefore, transitions between well-defined humus forms occur. In the following, humus forms are described according to their overall features and their occurrence under specific site conditions. At the end of each paragraph describing a humus form type or subtype, distinct features are listed. As the subtype has all the features of the type, distinct features of the type are not repeated.

2.2.1. Division: Aeromorphic and Aero-Hydromorphic Humus Forms

Aeromorphic* and *Aero-Hydromorphic humus forms dominate on mineral soils but may also occur on organic soils if the conditions for peat accumulation are not fulfilled.

Class: ***Mull humus forms***

At sites characterised by a high abundance of soil organisms with activities such as comminution and bioturbation, Mull humus forms are observed. Soil organisms belonging to this group are earthworms, small annelids, and soil-mixing arthropods such as isopods, diplopods, and dipteran larvae (Figures 3 and 4).

The decomposability of litter from trees, herbs, and grasses growing at the sites is mostly good to very good (Table S10). Rapid litter decomposition and humification at the soil surface and incorporation of plant residues into the mineral soil result in a thick A horizon and in narrow-to-moderately low (<15) CN ratios of the A horizon (Table S11). Mostly, the A horizon has a stable granular structure or fine subangular blocky or fine angular blocky structure, with high aggregate stability even under high soil moisture conditions (Tables S5–S7). The A horizon is uniformly coloured (e.g., 10YR 4/1–3/1 or 10YR 3/2–2/2). The Ol horizon may be decomposed within one year, frequently leading to the development of an Of horizon. The distinct feature of a Mull is:

- Oh horizon is never present.

Mull humus forms are further differentiated into types and subtypes according to the duration of litter decomposition and the features of the Ol, Of, (Figure 5a–c) and A horizons (Figure 6).

Figure 3. Diplopod with faunal droppings on fragmented leaf litter (Photo: Otto Ehrmann, Bildarchiv Boden, Creglingen-Münster).

Figure 4. Diptera larvae in an Olf horizon of *Typical Moder* (Photo: Otto Ehrmann, Bildarchiv Boden, Creglingen-Münster).

The humus form type ***L Mull*** (Figure 7) occurs on soils with moderate-to-high base saturation and litter of high decomposability. Due to the rapid decomposition of the litter, with mineralisation rates of 6 months to 2 years, an Ol may not be present all year round. The mineral topsoil has a thickness of >10 cm in most cases and is characterised by high biological activity and an aggregate structure (Figure 6) (e.g., granular, angular blocky, subangular blocky). The aggregates are more stable in loamy and clayey soils. At sites with sandy substrates and with litter with a low or very low CN ratio, litter decomposition takes place rapidly (Tables S10 and S11). Despite bioturbation, no stable granular or subangular blocky structure is formed in the Ah horizon, but finely aggregated humified organic matter is present next to the sandy mineral matrix. The distinct features of the *L Mull* are:

- Ol horizon is present, but is incoherent to sparse;
- Olf horizon is absent, patchy, or thin; and
- Ax, Au, or Ah horizon with signs of high biological activity is present.

(**a**)

(**b**)

(**c**)

Figure 5. (**a**) Ol, (**b**) Olf, and (**c**) Ohf horizons, leaf material: European beech *(Fagus sylvatica)*, Norway spruce *(Picea abies)* (Photos: Gerhard Milbert).

Subtypes

To date, four subtype levels of *L Mull* humus forms have been described. An ***A Mull*** can be observed at sites with particularly high biological activity (Figure 8) due to medium moisture conditions and on substrates with high base saturation (Table S13) and vegetation yielding very rapidly decomposable litter (Table S10). Under these conditions, a litter layer is only temporarily present. The A horizon shows features of high bioturbation and is usually thicker than 10 cm. The distinct features of the *A Mull* are:

- Ol horizon is only temporarily present (autumn to early summer), and
- Olf horizon is absent or only present for a short time (Figure 5b).

Figure 6. Granular structure of an Ax horizon (Photo: Gerhard Milbert).

Figure 7. Overhead shoot of an *L Mull*; the Ol horizon has been partly removed (Photo: Christine Wachendorf).

Figure 8. *A Mull* under common ash *(Fraxinus excelsior)*; typically, the Ol horizon is already decomposed in spring (Photo: Christine Wachendorf).

In a ***Typical L Mull,*** litter decomposition is slower than at *A Mull* sites. The litter is decomposed and incorporated into the mineral soil within <2 years. Due to high soil biological activity, the Ax horizon or Au horizon is usually rich in organic matter and has a predominantly granular or subangular blocky or angular blocky structure. In loamy sand and sandy loam soils, Ah horizons with a less pronounced granular structure and subangular blocky structure can also occur. The A horizon shows clear signs of high biological activity such as earthworm casts and channels showing recent earthworm activity. The A horizon also shows worm casts at the soil surface, occurrence and activity of macro- and mesofauna and their faecal pellets (especially springtails, mites and small annelids, isopods, and millipedes). The distinct features of a Typical *L Mull* are:

- Ol horizon is present almost all year round, and
- Olf horizon is patchy, sparse, and only temporarily present.

A ***Rhizo L Mull*** (Figure 9) develops at forest sites with very easily decomposable litter but low tree density or at permanent grassland sites under low-intensity management. In the A horizon, showing signs of high biological activity, the thick ground vegetation develops a dense system of living fine roots, a root felt (Table S2) with a typical thickness of 3–5 cm. The distinct features of a *Rhizo L Mull* are:

- Ol horizon is present, which is mostly patchy or sparse and patchy.
- Olf horizon is temporarily present.
- Adx horizon, Adu horizon, or Adh horizon is observed with signs of high biological activity.

Figure 9. Root felt in the Adx horizon of a *Rhizo L Mull*, with vegetation of common ash *(Fraxinus excelsior)*, wood melick *(Melica uniflora)* and wood false brome *(Brachypodium sylvaticum)*. Root felt becomes visible after topsoil material has been shaken out (Photo: Christine Wachendorf).

At seasonally wet sites with high base saturation and readily decomposable litter (alder, ash), a ***Moist L Mull*** (Figures 10 and 11) develops if the soil is periodically water-saturated up to the surface, which can be deduced from the species of the herb layer indicating recent alternating moist-to-wet conditions and the blackish colour of the organic surface layer. The thickness of the A horizon is generally 10 to 20 cm with an organic carbon content of 8–<15% by weight. The distinct features of a *Moist L Mull* are:

- Owl horizon is present almost all year round;
- Owlf horizon is present but is patchy and sometimes black smeary leaves are visible and
- hydromorphic features in the A horizon.

Figure 10. *Moist L Mull* showing hydromorphic features, such as mottles of iron oxides in the A horizons (Photo: Christine Wachendorf).

Figure 11. Ol horizon of a *Moist L Mull* showing fresh litter from common ash *(Fraxinus excelsior)*, earthworm cast, and blackish colour of some older litter (Photo: Gerhard Milbert).

The humus form type ***F Mull*** occurs on soils with moderate-to-high base saturation (Table S13). The litter is predominantly moderately-to-readily decomposable (Table S10). An *F Mull* may also develop at sites with poorly decomposable litter such as European beech (*Fagus sylvatica*) if the soils are characterised by a high base saturation. Mineralisation of litter takes usually more than two years. An Of horizon is present throughout the Ol and A horizons. The Of horizon can often be subdivided into two horizons; the upper horizon is poor in fine humus (Olf horizon), and the lower horizon is rich in fine humus (Ohf horizon) (Table S1). In general, the Of material is loose to stacked and with a thickness of the horizon of 1–3 cm. It can be considerably thicker in areas with increased litter input. The litter of the Of horizon, which is partly interspersed with roots and fungus mycelium (Table S3), may be connected to itself in layers or glued together, forming packages (Table S4). In the case of high bioturbation, organo-mineral aggregates are often intermixed in the Of horizon. In general, the mineral A horizon is characterised by signs of high biological activity and by stable aggregates with a subangular blocky or angular blocky structure and less occurrence of granular structure. The boundary between the Ah horizon and the underlying mineral soil horizon is sharp (transition zone < 2 cm) (Table S8), particularly in silty and loamy substrates. The distinct features of the *F Mull* are:

- Ol horizon is present;
- Of horizon is continuous and present all year round; and
- Ax, Au, or Ah horizon is present.

Subtypes

The *F Mull* can be further differentiated into 5 subtypes. In contrast to the *L Mull*, the *F-Mull* occurs at sites with high biological activity but moderately-to-readily decomposable litter. The incorporation of litter into the mineral soil decreases and the duration of litter decomposition increases to 2 to 3 years. The Olf horizon is typically low in fine humus (10 to <30% vol.), which is indicated in the name ***L Mull-like F Mull***. The litter components of the Olf are always loosely-to-weakly connected. The Ax horizon or Au horizon is mostly rich in organic matter (Table S1) and shows a predominantly granular structure or fine subangular blocky and fine angular blocky structure (Tables S5–S7). Its thickness is generally >10 cm. The distinct features of a *L Mull-like F Mull* are:

- Ol horizon is present all year round;
- Olf is continuous and present all year round;
- Ohf horizon is absent; and
- Ax, Au, or Ah horizon is present.

The ***Typical F Mull*** (Figures 12 and 13) is characterised by an Of horizon which is always divided into two parts. Below the Ol horizon, an Olf horizon which is poor in fine humus is formed, followed by a distinct Of horizon enriched in fine humus (Ohf) with a stratified, glued litter packaging (Table S4). The A horizon is mostly <10 cm thick. The distinct features of a *Typical F Mull* are:

- Ol horizon is present all year round;
- Olf horizon and Ohf horizon are continuous and present all year round;
- the thickness of Olf $\geq$ Ohf horizon and
- Ax, Au, or Ah horizon is present.

Figure 12. *Typical F Mull* (Ol/Olf/Ohf/Ax) under European beech (*Fagus sylvatica*) on calcareous parent material (Photo: Christine Wachendorf).

Figure 13. Forest nature reserve, Hellberg, North Rhine-Westphalia. *Typical F Mull*, leaf material European beech (*Fagus sylvatica*), wood melick *(Melica uniflora)* and wood false brome (*Brachypodium sylvaticum*) on Rendzic Leptosol (Photo: Gerhard Milbert).

In forest stands with dense grass cover and under grassland, a 3–5 cm thick root felt, characterised by >50% volume living roots, may develop in the upper A horizon. The distinct features of a ***Rhizo F Mull*** are:

- Ol horizon and Of horizon is present all year round; and
- Adx, Adu, or Adh is present.

On soils with low-to-moderate base saturation and poorly or moderately decomposable litter, the rate of litter decomposition and bioturbation decreases, and a subtype *F Mull* transient to Moder develops. An Of horizon rich in fine humus (Ohf) forms above the mineral soil surface, which is significantly thicker than the overlying Olf horizon. The A horizon is mostly <8 cm thick. The distinct features of a ***Moder-like F Mull*** are:

- Ol horizon and Olf horizon are present;
- Ohf is present, thickness of Ohf >> than Olf horizon; and
- Au or Ah horizon present.

A ***Moist F Mull*** (Figure 14) develops at sites characterised by continuously or periodically wet conditions if the soil is at least periodically water-saturated up to the surface, which is indicated by the occurrence of specific plants and on soils with a low-to-high base saturation and moderately-to-readily decomposable litter (Table S10). The thickness of the hydromorphic A horizon is generally 10–20 cm, with an organic carbon content of 4–8% mass. The distinct features are:

- Owl horizon is present almost all year round;
- Owf horizon is present; and
- hydromorphic features in the A horizon.

Class: ***Humus forms with an Oh horizon***

This class encompasses the types *Moder* and *Mor* (Table 2). These types differ from Mull humus forms in the presence of an Oh horizon underlying the Ol and the Of horizons. Depending on the intensity of organic matter decomposition, Oh horizons may show various forms of packing (Table S4), from friable to compact.

Figure 14. Patchy Ol horizon of a *Moist F Mull* showing fresh fallen litter from common oak *(Quercus robur)* and blackish colour of the Owf horizon (Photo: Gerhard Milbert).

The humus form type ***Moder*** develops on soils with low-to-very low base saturation (Table S13) and moderately-to-poorly decomposable litter (Table S10). Moder humus forms also exist on soils with relatively high base saturation even if plants which contribute very poorly decomposable litter dominate, for example, dwarf shrub heather. The activity of anecic earthworms is strongly reduced compared to soils with Mull humus forms. Besides endogeic and epigeic earthworms, arthropods and microannelids predominate. In Moder humus forms, litter decomposition takes place almost exclusively in the organic surface layers, and only small amounts of litter are incorporated into the A horizon. Therefore, the A horizons of *Moder* are thinner, and the proportion of biogenic granular structures is lower compared to Mull humus forms (Figure 2). Production of soluble humic substances may lead to some bleaching of the A horizon. Ol horizons and Of horizons are always present, with the thickness of the Of horizon being >5 cm in most cases. The minimal mixing of organic matter into the mineral soil is indicated by an increasing thickness of the Oh horizon, with >5 mm in *Typical Moder*. Under the specific conditions of montane and alpine zones of the Limestone Alps, the Moder subtypes *Tangel* and *Pechmoder* are observed. Distinct features of a Moder are:

- Ol horizon and Of horizon are present all year round;
- Obh horizon is present, which is in parts very thin or patchy; and
- a thin Ah horizon or Ee horizon has developed.

Subtypes

Mull-like Moder is a transitional subtype between Mull humus forms and humus forms with an Oh horizon. *Mull-like Moder* develops predominantly on acidic topsoils and soils characterised by a low base saturation, explaining the slight bioturbation in these soils. This leads to features typical of the Ol horizon, and no biologically intermixed mineral components are observed. The litter of the Ol horizon is progressively more glued together with increasing depth, partly showing layer-like packing (Table S4). Its thickness can reach 6 to 7 cm with features of a batch-like packing. The Of horizon consists mainly of needle fragments and leaf fragments. In the lower part of the Of horizon, the content of fine humus increases (Ohf horizon) and is interwoven with fine roots. Below the Of horizon, an Oh horizon occurs in patches; it is usually very thin (2–3 mm). This Oih horizon indicates an initial enrichment of fine humus covering the wavy mineral soil surface, but showing diffuse boundaries between both horizons (Table S8). At forest sites, the Ah horizon is most often <10 cm thick and does not show signs of podzolisation. Thick Ah horizons can be found in soils with high base saturation, although dominated by beech litter. The boundary between the A horizon and the underlying mineral soil containing little or no organic matter is distinct or even abrupt. Distinct features of a *Mull-like Moder* are:

- Ol and Olf horizon are present all year round;
- Ohf horizon is present all year round, usually rooted;
- Oih horizon is present; and
- Ah horizon is present.

The subtype ***Typical Moder*** (Figure 15) is characterised by a diffuse transition between Ol, Of, and Oh horizons. The degree of cross-linking of plant residues increases from the top downwards, especially in coniferous stands, and the Of material can be slightly felted or layer-like (Table S4). Within the Of horizon, the proportion of fine organic matter increases with increasing depth. The packing of the Oh is powdery to friable (resembling coffee grounds) and disintegrates easily into slightly rounded aggregates (Obh) (Table S4). Easily breakable Oh horizons that disintegrate to powder or crumble easily under a slight pressure from the thumb on the coarse aggregates are considered Obh horizons. The Obh may contain interstratified, less decomposable plant residues. The well-rounded aggregates resulting from the disintegration of Obh material can contain needle fragments and arthropod droppings that are embedded randomly in the macroscopically amorphous fine organic matter via biological mixing. The Obh horizon is often strongly penetrated by roots. The transition between the Obh horizon and the mineral soil is diffuse (Table S8). The Ah horizon is usually < 10 cm thick. Depending on the thickness of the Obh horizon, *Typical Moder* is subdivided into the varieties *Typical Moder poor in fine organic matter* (Obh horizon < 2 cm) and *Typical Moder rich in fine organic matter* (Obh horizon ≥ 2 cm). The variety which is rich in fine organic matter is characterised by higher CN ratios. Distinct features are:

- Ol horizon and Olf horizon are present all year round;
- Ohf horizon is present all year round, usually rooted;
- Obh horizon is present;
- indistinct transitions between O horizons; and
- occurrence of a thin Ah horizon or Ee-Ah horizon or Ah-Ee horizon.

Figure 15. *Typical Moder* with needles from Norway spruce *(Picea abies)*, showing Ol, Olf, Ohf, Obh, and Ee-Ah horizon. Transitions between O horizons are indistinct (Photo: Alexander Konopatzky).

In single-layer forest stands of medium or old age, an increase in exposure to light and therefore increased soil temperature can support an extensive presence of the subtype ***Rhizo Moder***, which is mostly linked to the occurrence of a dense sward of wavy hair-grass (*Deschampsia flexuosa*) or reed-grass (*Calamagrostis* sp.). In pine and oak stands, dwarf shrubs (e.g., bilberry and cranberry) can also occur with high coverage. *Rhizo Moder* develops from *Mor* and *Moder* humus forms. Their original Oh horizon is loosened and increasingly mineralised due to intensive rooting and aeration. A differentiation between Odf horizons and Odh horizons and often also between Odh horizon and the uppermost Ah horizon is difficult. The fine organic matter and partly also the Of material are distributed within the root felt. Usually, the CN ratio of the Oh is >22, under dwarf shrubs >25. The Ah horizon can also be densely rooted. Distinct features are:

- Ol horizon is present all year round and
- Odf horizon above Odh horizon is present all year round or features of both horizons (Odf + Odh) exist parallel all year round and
- a thin Ah horizon or Ee-Ah horizon or Ah-Ee horizon occurs.

In high mountain zones, highly variable conditions such as bedrock, climate, and the type of vegetation affecting litter decomposition lead to great differences in the morphology and the thickness of organic surface layers. Two different zonal subtypes of *Moder* are so far known.

The subtype ***Tangel*** (Figure 16) is typically characterised by an Ovh horizon occurring in the contact zone with the bedrock. The Ovh horizon is finely friable and has a loose structure. Compared to the overlying O horizons, the Ovh usually has a higher pH and a lower CN ratio. Often, the Ovh horizon also shows a higher Ca content and contains chippings of limestone. The mineral content in the Ovh may also be increased due to deposition of aeolian dust or mixing of mineral soil via tree throw. The Obh horizon overlaying the Ovh is usually >10 cm thick and has a much lower pH, mostly <4 (pH $CaCl_2$).

Figure 16. Organic surface layer of a *Tangel* under mountain pine *(Pinus mugo)* on limestone (Photo: Gerhard Milbert).

The thickness of the organic layer may vary from >15 cm up to >100 cm. The occurrence of thick organic layers is described predominantly on limestone and dolomite, rarely on silicate rocks. *Tangel* occurs particularly in montane to subalpine zones with high precipitation. The typical *Tangel* frequently occurs where transitions to moist or hydromorphic humus forms are observed. So far, *Tangel* humus forms are insufficiently studied, and soil data are rarely presented. Therefore, no further subdivision is provided, and in the first instance, only *Tangel* on limestone with an Ovh horizon is defined. It can be expected that transitional types to *Mor* or other *Moder* subtypes will occur, as well as *Tangel* humus form on unconsolidated rock. Distinct features are:

- Ol horizon is present all year round;
- Of horizon is present all year round and thin (<5 cm);
- Obh horizon is present, with diffuse boundary with underlying Ovh; and
- Ovh horizon is present and directly overlies the C horizon.

In subalpine and alpine zones with sparse tree cover or dwarf shrub vegetation on limestone or marlstone and between rubble of these rocks, the Moder subtype ***Pechmoder*** (Figure 17) may develop. The name derives from the dark colour (German Pech = pitch). The humus form is characterised by a highly biologically active Oxh horizon that consists mainly of faecal pellets of the mesofauna (springtails, oribatid mites, enchytraeids, insect larvae). The Oxh with a fine granular structure has a high base saturation. Distinct features are:

- Ol and Of horizons are present all year round; and
- Oxh horizon is present that either directly overlies the bedrock, or fills the voids in the rubble or, more rarely, overlies mineral soil.

Figure 17. *Pechmoder*, black Oxh horizon, filling up the surface and the interspace of limestone (Photo: Gerhard Milbert).

Moist Moder (Figure 18) develops in soils which are poor in bases, resulting in poorly decomposable litter, and under the long-term impact of stagnant water or groundwater significantly affecting the properties of the mineral topsoil as well as the organic surface layers. A typical feature of a *Moist Moder* is an Owbh horizon, which is smeary under moist or wet conditions. Water standing on the soil surface is common in late winter and spring; a blackish colour of both the Ol and Of horizons may temporarily indicate the hydromorphic conditions in the entire soil humus profile. *Moist Moder* has typically the following features:

- Ol horizon or Owl horizon is present;
- Of horizon or Owf horizon is present;
- Owbh horizon is present; and

- overlying a hydromorphic topsoil horizon (A horizon with redoximorphic features).

Figure 18. *Moist Moder*, sequence of horizons: Owl/Owf/Owbh/Go-Ah (Photo: Tina Frank).

The humus type ***Mor*** develops on soils with very low base saturation (Table S13) and poorly decomposable litter (Table S10), for example, from spruce, pine, bilberry, cranberry, or heather. A high CN ratio and phenol content of the litter reduce its decomposability. In Mor, biological mixing by endogeic and anecic earthworms is absent. Litter decomposition takes place exclusively in the organic surface layers and is very slow and incomplete. Mor, developed from spruce needle litter, is characterised by very abrupt transitions between the single organic surface horizons as well as between the organic surface layer and the mineral soil. During the separation of distinct horizons in an organic surface layer monolith, the horizons detach easily from each other even under low tensile stress. Organic fine material accumulating in the Oh horizon is compact (Okh) or can even be broken into sharp-edged pieces (Osh). Organic layers of Mor humus forms enhance podzolisation of the mineral soil due to the translocation of mobile humic substances by seepage water. The CN ratio in the Oh horizon is mostly >25, and the CP ratio is >400. The typical characteristics of the humus form type Mor are:

- Ol and Of horizons are present;
- Osh horizon or Okh horizon is present; and
- an acidic bleached horizon (Ee-Ah horizon, Ah-Ee horizon or Ee horizon) is present.

Subtypes

The subtype ***Moder-like Mor*** (Figures 19 and 20) develops on soils with very low base saturation. Very often, they are found in fir or pine forest stands with ground vegetation of wavy hair-grass (*Deschampsia flexuosa*) and bilberry (*Vaccinium myrtillus*). The Oh of this subtype is compact (Okh), and the transitions between Of and Okh horizons as well as those between Okh and mineral soil are abrupt (Table S8) (Figure S1). Plant residues in the Of horizon are matted together, resulting in a layer-like or bulky pattern of packing. In the Of horizon, only some roots may occur, while in the Okh the root density is mostly high, and coarse roots often also occur (Table S2). Depending on the thickness of the Okh horizon, *Moder-like Mor* is subdivided into the varieties *Moder-like Mor poor in fine organic matter* (Okh horizon < 3 cm) and *Moder-like Mor rich in fine organic matter* (Okh horizon $\geq$ 3 cm). Features of a *Moder-like Mor* are:

- Ol horizon, Of horizon and Okh horizon are present; and
- an Ah-Ee horizon or Ee horizon has developed.

Figure 19. Okh horizon with blunt or rounded edges and root penetration (Photo: Gerhard Milbert).

Figure 20. Organic surface layer of a *Moder-like Mor* showing an Ol, Of, and Okh horizon, needle material Norway spruce *(Picea abies)* (Photo: Gerhard Milbert).

The ***Typical Mor*** is distinguished from *Moder-like Mor* by the Oh horizon being sharp-edged crushable (Osh) (Figure 21 and Table S4). The jagged fracture surfaces of the Osh can be recombined seamlessly after breaking. A thick Oh horizon is not always compact throughout but can appear layered to some extent. The single layers, however, remain crushable, forming sharp edges. The Of horizon is often to a large extent layer-like and felted and therefore flexural and easily detached from the Osh horizon. The Of horizon usually consists of several layers, with increasing fine organic matter content with increasing proximity to the Osh. The organic surface layers can be detached from the mineral soil surface easily. Depending on the thickness of the Osh horizon, *Typical Mor* is subdivided into the varieties *Typical Mor poor in fine organic matter* (Osh horizon < 4 cm) and *Typical Mor rich in fine organic matter* (Osh horizon $\geq$ 4 cm). Distinct features are:

- Ol horizon is present all year round;
- Of horizon is present all year round, strongly felted, and flexural;
- Osh horizon is present, sharp-edged, and crushable; and
- Ah-Ee horizon or Ee horizon is present.

Figure 21. Osh horizon with sharp edges (Photo: Ecke von Zezschwitz †).

The subtype ***Moist Mor*** develops in soils with a low base saturation and under the long-term impact of stagnant water or groundwater significantly affecting the properties of the mineral topsoil and the organic surface layers. At these sites, poorly decomposable types of litter prevail. The Owsh horizon is smeary when moist or wet, but breakable. In late winter and spring, standing water is frequently found on the soil surface. The *Moist Mor* is typified by the following characteristics:

- Ol horizon or Owl horizon and Of horizon or Owf horizon are present and
- Owsh horizon is present; and
- overlying a hydromorphic topsoil horizon (A horizon with redoximorphic features).

Class: ***Initial Humus Forms***

Anthropogenic impact such as deposition of organic or mineral substrate or removal of organic surface layers and organic mineral soil affects litter mineralisation and humification and thus the corresponding O and A horizons. Sites characterised by such an imbalance are described by the type of the parent material, content of carbonate, provision of basic cations, kind of vegetation, and type and decomposability of litter. These properties can give an indication whether the humus form is more likely to develop into a mull-like humus form or a humus form with an organic surface layer and to what extent it is significantly influenced by soil moisture.

Initial humus forms developing to a mull-like humus form are described as ***Initial Mull***. The mineral topsoil is characterised by a medium to high content of bases, partly contains lime. The decomposability of litter is medium to high. Features of an *Initial Mull* are:

- Ol horizon is present;
- if an Of horizon is present, it is of minor thickness or is incomplete;
- a horizon is of minor thickness and less structured or an A horizon is absent; and

- distinct features of earthworm activity, e.g., earthworm channels, middens and casts are rarely observed.

Initial Humus Form with surface layers (Figure 22) in a developing stage can be observed on parent material poor in bases, and with vegetation providing litter of low decomposability, such as conifer trees, dwarf shrubs or wavy hair grass *(Deschampsia flexuosa*). If an Of horizon occurs, it is partly differentiated in Olf and Ohf. An A horizon from recent soil development is often absent, frequently an Ai horizon occurs. Distinct features are:

- Ol horizon is present;
- Of horizon is frequently present, but of minor thickness and incomplete; and
- Oh horizon is absent.

Figure 22. Organic surface layer of an *Initial humus form with surface layers* on dune sands (Photo: Gerhard Milbert).

Class: ***Naturally and Anthropogenically degraded humus forms***

Natural processes such as litter translocation via wind or water or anthropogenic litter removal can cause the development of deteriorated humus forms at exposed positions, steep slopes, open stands and overused forest soils.

A ***Naturally degraded humus form*** (German: Hagerhumus) is observed after the export of litter due to translocation by wind, for example. Reduced input of nutrients causes a deterioration of the topsoil. This normally leads to a change of the soil structure in the very upper soil layer (1 cm), to a single grain structure in sandy soils, or in more clayey soils to a coherent structure. In the vicinity of humus forms with an organic surface layer, at positions with deteriorated humus forms, an Oh horizon is partly absent or incomplete. Naturally deteriorated humus forms are clearly differentiated from Mull humus forms with an Ax horizon by an A horizon with less soil aggregation. The humus form is characterised by:

- extensive uncovered surface of the mineral soil despite existing vegetation or
- sporadically occurring soil crust on the surface of the mineral soil consisting of algae, lichens, or a thin cover with mosses.

Anthropogenically degraded humus form (German: Streunutzungsrohhumus) are observed after long-term usage of the organic surface layers, which was practiced until the mid-20th century. This impact led to drastic changes in site conditions affecting pedogenic processes. In most cases, heathland developed on these devastated soils, and litter and even sods were further exported. The ecological properties of humus forms that develop under such conditions conform with few exceptions to the *Mor* humus forms. They have the following characteristics:

- Ol horizon und Of horizon are present, with strongly varying thickness;
- Of horizon is characterised by little organic fine material, which is layer-like felted and flexural;
- Oh horizon is missing or only is 0.5 to 1 cm thick in medium aged and old pine or spruce forests;
- Ah-Ee horizon (often semi- to entirely podzolised soils) has a low-to-medium organic matter content, has a coherent to single grain structure in most cases, and is relatively thin (frequently < 3 cm);
- abrupt transition boundaries between Of horizon and Oh horizon, Oh horizon, and Ah-Ee horizon; and
- Of has a CN-ratio of mostly >32, the N content is always <1.7% weight, and the pH-KCl mostly <pH 3.

2.2.2. Division: Hydromorphic Humus Forms

Aeromorphic humus forms are described frequently. However, *aero-hydromorphic humus forms* and especially *hydromorphic humus forms* are rarely considered (Frank et al., this issue). Criteria to differentiate between hydromorphic humus forms are largely lacking despite their high importance as carbon sink, as climate regulator and as habitat for biodiverse soil organism communities. Natural fens and bogs react sensitively to draining and nutrient inputs. These anthropogenically mediated changes suppress the growth of plants favouring the peat-building process. Thus, in the majority of peatlands, plants typically found on mineral soils invade, leading to the development of humus forms typically observed on mineral soils. Thus, humus forms of natural fens and bogs are rare and have rarely been described so far. ***Hydromorphic humus forms*** develop under the long-term impact of stagnant water or groundwater. The class ***Anmoor*** is characterised by an Aa horizon and has a content of organic carbon between 8 and 15% by mass, occurring mostly as fine humus. The Aa typically has a thickness of 20–40 cm. Varieties are differentiated according to the N content. The pedogenesis of these Aa horizons with intermediate content of organic matter is not yet described, but deposition of mineral soil and temporary aerobic conditions affecting mineralisation of the organic matter are probably factors for the development of Aa horizons.

Humus forms of natural fens and bogs develop when peat is formed in the anaerobic environment by accumulation of incompletely decomposed plant material. The water level must be near or above the soil surface on a long-term average. To describe the process and the various conditions leading to peat accumulation, the following system may be applied. The main controlling variables which control peat formation conditions are the water and nutrient balance and the decomposability of the plant litter. They affect the degree of humification and thus the humus form. Therefore, the degree of decomposition and humification (H 1 to H 10) is included in the naming of bog humus forms [13,14] (Table S9). Humus forms of natural fens and bogs are described only if the water regime is classified as permanently wet with intermittent over-wetting and thus corresponds to the (hydric) formation conditions for peat. Nevertheless, in growing peatlands, seasonal water level fluctuations can also cause phases with aeration of the litter decomposition area, leading to a high degree of humification. The reference horizon or diagnostic horizon is always the peat formation horizon (Hfn, Hen, Hhn) (Table 3) at the soil surface. The combination of the degree of humification (water balance) and trophic characterisation results in the humus forms of growing peatlands, which are summarised in the humus form classification (Tables 2 and 3 and Figures 23–25), irrespective of the type of peat (fen, transitional peat, and raised bog peat).

Figure 23. Oligotrophic *F Moor* derived from sphagnum moss (Photo: Gerhard Milbert).

Figure 24. Oligotrophic *M Moor* (Photo: Gerhard Milbert).

Figure 25. Mesotrophic *H Moor* (Photo: Ulrich Koch).

3. Discussion

The new German humus form systematics presented here is based on a traditional approach focusing on morphological differences between the organic layers. The first steps to subdivide the morphological features of plant litter were published by Müller in 1887 [15]. Hesselmann in 1926 [16] defined the Horizons Of (Förmultningsskiktet) and Oh (Humusämneskiktet) and the humus forms Mull, Moder (Mår) and Mor (Råhumus). Wittich in 1952 [17] added the relevance of the decomposability of leaf and needle litter, and Ewald in 1958 [18] compiled the first ecological systematics of humus forms for forest site mapping. The historical development of German systematics is described by Baritz [19]. Substantial contributions to these earlier versions were provided long ago by Kubiëna [5], von Zezschwitz [2], and Babel et al. [20]. Meanwhile, this approach has been evaluated in the field step by step by the working group on humus forms, a board of the German Soil Science Society, since 1992 [21]. Thus, the original morphological approach has been maintained. The update presented is characterised by the addition of diagnostic horizons to improve the reproducibility of humus form descriptions. Also, the new German approach recognises the strong impact of soil moisture conditions on the humus forms. Therefore, we distinguish now between aeromorphic, aero-hydromorphic, and hydromorphic humus forms. This decision was partly inspired by the Dutch approach [22] but also by the Canadian humus form classification [1], which is based on long-term experience on humus forms of forests with a wide range on drainage conditions. The second main point, which was included in the present update, is the emphasis on the importance of soil organisms. Soil scientists have always recognised that the morphological characteristics of the organic layers are also a product of the activity of soil organisms, not only of the quality and quantity of the litter. However, now we also include a reverse view in the new systematics. This means we stress that humus forms are also habitats for soil organisms [23]. The result of this consideration was the separation on a very high level between humus forms with an Oh horizon and those without an Oh horizon. Faunal faecal pellets are a significant component of organic fine material, accumulating in the Oh horizon. However, interaction with abiotic conditions such as soil moisture, temperature, nutrients, pH modify the further turnover of the organic material. Aging of the faecal pellets under specific conditions leads to morphological changes such as a compact or even sharp edged Oh horizon. The presented systematics therefore focuses on a morphological description rather than the frequently ambiguous distinction between zoogenic and non-zoogenic material proposed by Zanella et al. [24]. In the German systematics, an amphi humus form has not yet been described, as its occurrence is rarely observed and not well described until now. Compared with other European humus form classifications, there are similarities to the Swiss [25] and the Austrian [26] classifications as well as to the Estonian approach [27], for example.

The updated version of German humus form systematics is a complete revision of the former version [28], clarifying the hierarchical structure into divisions, classes, types, and subtypes. New diagnostic horizons and transition horizons are introduced, uniquely characterising types and subtypes. An unambiguous definition of all horizons described is presented, improving the humus form description [21].

Transition horizons Olf and Ohf, differing in the content of organic fine matter, are now defined. The presence of an Ohf differentiates the *Typical F Mull* and *Moder-like F Mull*, a humus form that was last introduced in the new version. Newly introduced is an *A Mull*, with a litter layer only temporarily present, compared to the *L Mull* with an Ol horizon present almost all year round. An Oih horizon is introduced, with its dominant fine organic material occurring in a very thin layer or in patches, indicating an Oh in its initial state, typically observed in *Mull-like Moder*. Furthermore, the Oh horizon is subdivided according to different structures. An Obh, occurring in a *Typical Moder*, consists of loosely packed, powdery material of organic fine matter which easily breaks into subangular blocky aggregates, whereas an Osh, diagnostic of the subtype *Mor*, consists of compacted fine organic material which breaks into aggregates with sharp division surfaces able to fit to each other again. The Okh is transient to the Obh and Osh horizon. It is compact but breaks into pieces with blunt or rounded edges and characterises the *Moder-like Mor*. Furthermore, the temporal influence of stagnant water or groundwater up to the topsoil is marked by the description of an Owl, Owf, Owbh, Owkh, and Owsh, clearly indicating the Moist humus forms. The occurrence of a root felt in different horizons is now distinguished by the modified horizons Odf, Odh, and Adh, considering the different properties of densely rooted horizons. Furthermore, distinctive features of A horizons are now expressed by the differentiation of Ai, Ah, Am, Au, Ax, Ee, and Al, which is now better allocated by means of the unambiguous description of the structure, the grade, and size of aggregates and the aggregate stability. Initial humus forms are introduced, considering for the first time that an imbalance between supply and decomposition of organic matter leads to contradictory morphological characteristics. Humus forms of natural peatland were newly introduced and the horizons with peat growth, Hn, Hfn, Hen, and Hhn, were defined, considering the degree of decomposition and the humification of peat.

4. Conclusions

The updated version of German humus form systematics will serve as a tool for a detailed description and evaluation of the research object, which in perspective would better enable linking morphological, biological, chemical, and physical properties as well as soil functions. The English version of the new structure of German humus form systematics presented here justifies the new approach. Humus form as a habitat for soil organisms and indicator of changes in terrestrial ecosystems is adequately structured by an aeromorphic and aero-hydromorphic, and a hydromorphic division and the addition of clear diagnostic horizons. The humus form is considered the result of interactions between site conditions, simultaneously shaping the chemical and physical properties of the topsoil and the decomposability of the needle and leaf material. The organic surface layer and mineral topsoil, comprising the humus form, is increasingly recognised as an important habitat for soil organisms. In ecological studies, sites with different vegetation types or dominate tree species are often compared, although humus types can vary significantly within sites or may be similar between sites.

Humus forms are very dynamic, and features of the organic matter indicate past and present-day site conditions. Description of humus forms may be used as an early indicator of degradation as well as for successful renaturation. As natural succession is increasingly permitted, the description of Initial humus forms as well as humus forms of natural fen and bog is considered.

Most of the definitions of humus forms and the features of organic horizons are based on observations at forest sites. However, humus forms of mountain areas, humus forms on natural fen and bog as well as initial humus forms or naturally and anthropogenically degraded humus forms are presented. The features of organic horizons may differ on open land sites and need to be investigated in more detail. However, the interactions of soil-forming factors may vary and lead to different morphological features in other geographical regions. Therefore, the transferability of the observations must be carefully checked. The systematics of humus forms should be further validated via chemical, biological, and physical analysis, which would better prove the correlation between morphological features and soil functions. This should be considered, especially for hitherto insufficiently described humus forms. Thus, substantial research is necessary to further develop the systematics and to extend it to regions outside central Europe.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijpb14030050/s1, Figure S1: A soil monolith including the O and A horizons. Figure S2: Frame for describing and sampling organic surface layers; Table S1: Definitions of diagnostic horizons and morphologic features of O horizons [12]; Table S2: Root density (number of roots per area or volume*) and allocation [12]; Table S3: Proportion of fungus mycelium of O horizons [12]; Table S4: Structure and packing of organic material in O horizons [12]; Table S5: Soil structure of A horizons (types of structure, description) [12,29]; Table S6: Size classes for soil structural units [12]; Table S7: Grade of structural units (mineral soil, peat) [12]; Table S8: Distinctness of lower horizon boundaries [12]; Table S9: Degree of decomposition and humification of peat [13,14]; Table S10: Litter decomposability of different forest tree species [30]; Table S11: Classification of CN and CP ratio of organic surface layer and mineral soil horizons [31]; Table S12: Chemical and physical key parameters to characterise humus forms [32]; Table S13: Classification of base saturation [12].

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