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Review

Humus Forms of Moist and Wet Forest Stands. A Review

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Abstract: The organic layer of forest soils (forest floor) provides important ecosystem functions and serves as a habitat for soil organisms. This review provides an overview of research on humus forms of moist and wet forest stands based on a systematic literature review. Detailed information was collected from around 80 articles and books. It was examined whether the articles include the chemical, physical, or biological properties of humus forms. In addition, selected topics associated with and often used in relation to moist or wet humus forms, like information on morphological properties or information on specific classification systems, are considered. In general, it was found that many articles include the importance of moist or wet humus forms in their classification system. However, there was less or insufficient explanation on morphological properties. The humus forms on poorly drained or even waterlogged sites differ from humus forms on well-drained sites because the water factor affects the processes and thus the morphology very much. High soil moisture (=water saturation) means periodically anaerobic conditions in mineral soil and also very often in organic layers. Hence, soil organic carbon and soil organisms are affected. Especially, the recent literature often deals with climate change and soil organic carbon in moist and wet forest stands.

Keywords: humus form; systematic review; humus form classification; organic surface layer; forest floor; moist humus forms; wet humus forms; soil–water balance

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1. Introduction

Humus forms in forest ecosystems (forest floor) and grassland humus forms are highly influenced by different drainage conditions. Well-drained sites are not affected by stagnant water or groundwater. At poorly drained sites and at sites with very high precipitation, water plays a significant role in the formation of moist or wet humus forms. Anaerobic conditions in the topsoil hinder the decomposition process, as the organic material accumulates with increasing water saturation [1,2]. Soils, in which the organic layer is only saturated in winter but which are aerated in the organic layer and/or the A horizon in summer, have humus forms with high humus contents due to hampered decomposition comparable to terrestrial humus forms [3]. These are called aero-hydromorphic humus forms, whereby a distinction can be made between Moist Mull, as well as Moist Moder and Moist Mor [4,5]. In addition, there are the hydromorphic (wet) humus forms on permanently wet sites [6]. On these sites, mineralization or litter decay is even more inhibited by a lack of oxygen. Aero-hydromorphic and wet humus forms often prevail in the lowlands, especially above Gleysols, Stagnosols, and Histosols. According to IUSS Working Group WRB [7], the organic layers that are under the influence of groundwater or stagnant water are labeled “histic” if the horizon is saturated with water for >1 month in most years. As a result, these horizons are poorly aerated and consist of organic material (=peat formation, paludification). The horizons are usually thicker than 10 cm, and thus, the aerated soil zone is reduced [1].

Although moist and wet humus forms can be of great significance for climate change mitigation due to changes in soil moisture and carbon sequestration, limited information is available worldwide. This review compiles previous classifications and characteristics of humus forms affected by stagnant water or groundwater and provides an overview of the current state of research as well as an outlook on open questions.

Objectives

The aim of this review is to assess if and how moist and wet humus forms are addressed in the current research on the organic surface layers and the A horizon (= forest floor or humus form) with the focus on forest ecosystems in the northern hemisphere. The objectives of the review are the following:

- To give an overview on research about moist and wet humus forms in forests with a specific view on their classification system and morphology;
- To assess which kind of related topics, like soil organisms and vegetation, are addressed in research;
- To recommend further research on the classification and morphology of moist and wet humus forms in forests.

2. Materials and Methods

The preferred reporting items for systematic reviews and meta-analyses (PRISMA) are stated by Page et al. [8] and are originally based on the principles of Pickering and Byrne [9]. The literature research for this review was performed in the scientific databases Scopus and Web of Science. To answer the main research question and find articles published in Scopus and Web of Science, several keywords were queried by entering the following components of the search formula in the title, abstract, or keywords sections. As the search for the terms "moist humus forms" or "hydro humus forms" produced only a single hit, the search was expanded. For this, the keywords of the matching article would be looked at more closely and used for the further search. The terms "forest floor", "humus form", "organic layer", "hydro humus", "wetlands", "classification", and "soil moisture" were used in different combinations in a second search in the same databases (Table 1). Additionally, the first author's personal scientific database was used, called Key Papers, including their references and the standard literature about forest ecosystems; both will be marked in this review.

Table 1. Components for the literature search.

Item	Sub-Item	Details
Keywords	Main keywords	"forest floor", "moist humus forms", "wet humus forms","aerohydro-humus", "hydro humus"
Keywords	Supplemented keywords	"organic layer", "moisture content", "soil moisture",(moist-, wet-) mull, "moder", "mor", "classification","wetlands", "humus form"
Operators		"and"
Time period		1970–2022
Languages		German, English
Document type		Journal paper, Conference paper, Book chapter, Monography

In this regard, the intention of the present review is to provide an overview of articles dealing with the subject of humus forms under moist and wet soil conditions and their morphology. In addition, the distinctive characteristics of humus forms under wet conditions in contrast to terrestrial humus forms will be highlighted. No restrictions were made to the geographic or climatic region, but due to the great dependence on soil moisture, research conducted mainly in the northern hemisphere can be found. Research articles written in English and German were considered for this review. The results of the search and the selection process are shown in the PRISMA 2020 flow diagram (with the new design) according to Page et al. [8]. This flow diagram is very useful to show the change in the number of records identified at the beginning of the search to the number of studies included in the review (Figure 1).

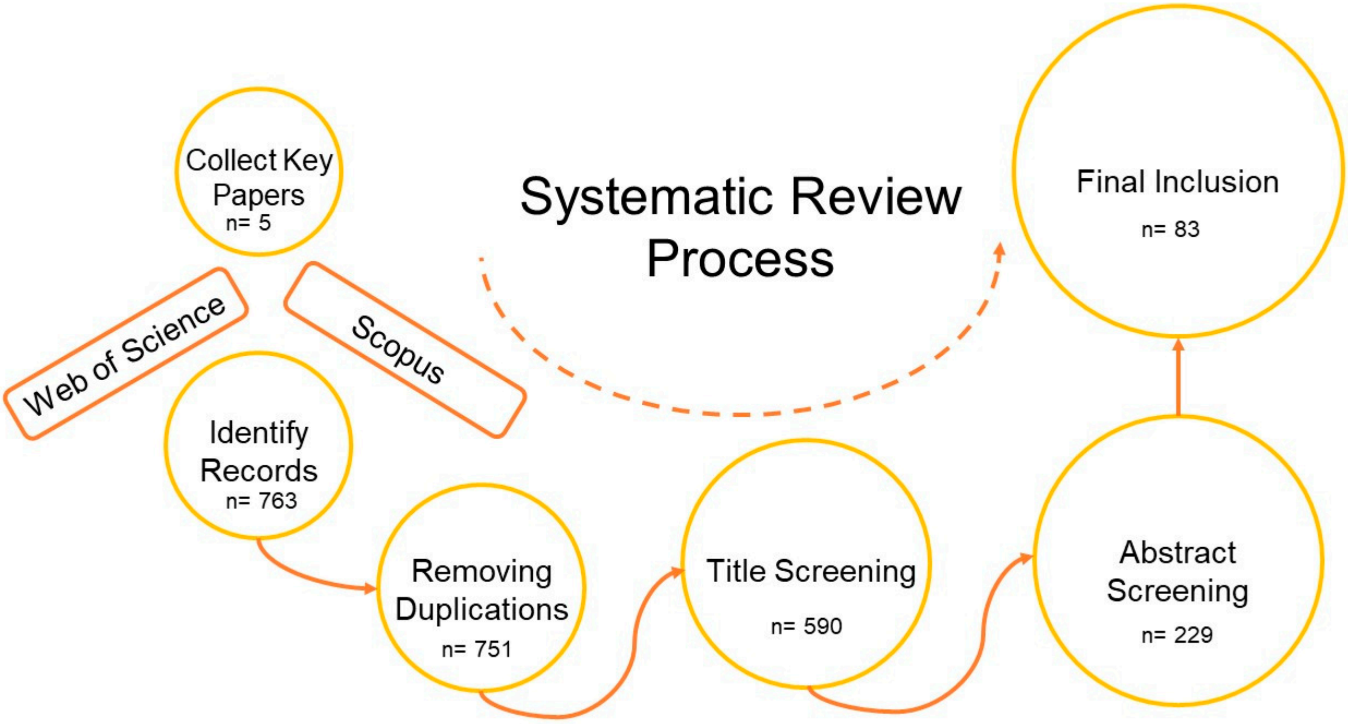

Figure 1. Flowchart for the systematic review process modified from Page et al. [8].

Following the collection of papers from the databases, the next step was to remove duplicated articles. The initial collection of 763 research articles based on the searched database was reduced to 751 studies after duplications were removed. Further, during the study selection some articles could not meet the inclusion criteria (e.g., no detailed information about the organic horizons or the soil type); hence, they were not considered. Some articles were irrelevant and could not be assigned to the actual topic. After that, the data were reduced to 590 records. Through abstract screening, 361 more articles were excluded (as they did not contain relevant and available information about the organic layer or soil information about the study sites), yielding 229 pre-final articles. To review the selected articles, the study area, year, and soil information were scanned in every research. Different categories were specified as you can see in Sections 3.2 and 3.3, and the information about humus forms was classified. Many articles dealt with several topics because the humus form is not a rigid system and depends on various factors. Especially, the chemical, physical, and biological properties were considered in more detail. For this review, the morphology of the organic layer is of particular interest if the sites are under the influence of stagnant water or groundwater. The final data set list for this review of 83 studies was conducted after reading the full articles (Table S1). The data were last updated on 13 December 2022.

3. Results and Discussion

3.1. Overview of Research on Moist Humus Forms and Wet Humus Forms in Forest Stands around the World

Research on moist and wet humus forms was directed in Europe, North America, and Asia between 1970 and 2022 (Table 2). The number of articles published annually fluctuated from 1970 to 2022 but increased in the mid to late 1990s with 14 articles per 5-year period and peaked between 2016 and 2020 with 18 published articles. No relevant information during the literature research could be found for Africa, South America, and Australia. The research mostly focuses on the classification and morphology of humus forms and mentions the moist and wet humus forms. Most of the articles on this topic were found in Europe. In particular, most of the publications are from Germany, Italy, and Eastern European countries, such as Russia, Estonia, and Latvia. The second largest group of articles come from North America, more precisely from Canada, and a few articles are from Iran.

Table 2. Number of articles used in this review published between 1970 and 2022 (shown as 5-year periods).

2021–2022	2016–2020	2011–2015	2006–2010	2000–2005	1994–1999	<1993
7	18	9	10	15	14	10

During the abstract screening and reading of the articles, the literature search revealed various topics related to humus forms. Some of these topics were also found to be very important during the final inclusion. Therefore, in Section 3.1.3, these topics are explained in more detail. One main characteristic is "soil moisture", which is shown in Figure 2 with the terms "soil water content" and "moisture conditions". Also, the soil organic matter morphology with terms, like "thickness" and "structure" (bigger yellow dots), is often used in the screened articles (all shown in Figure 2).

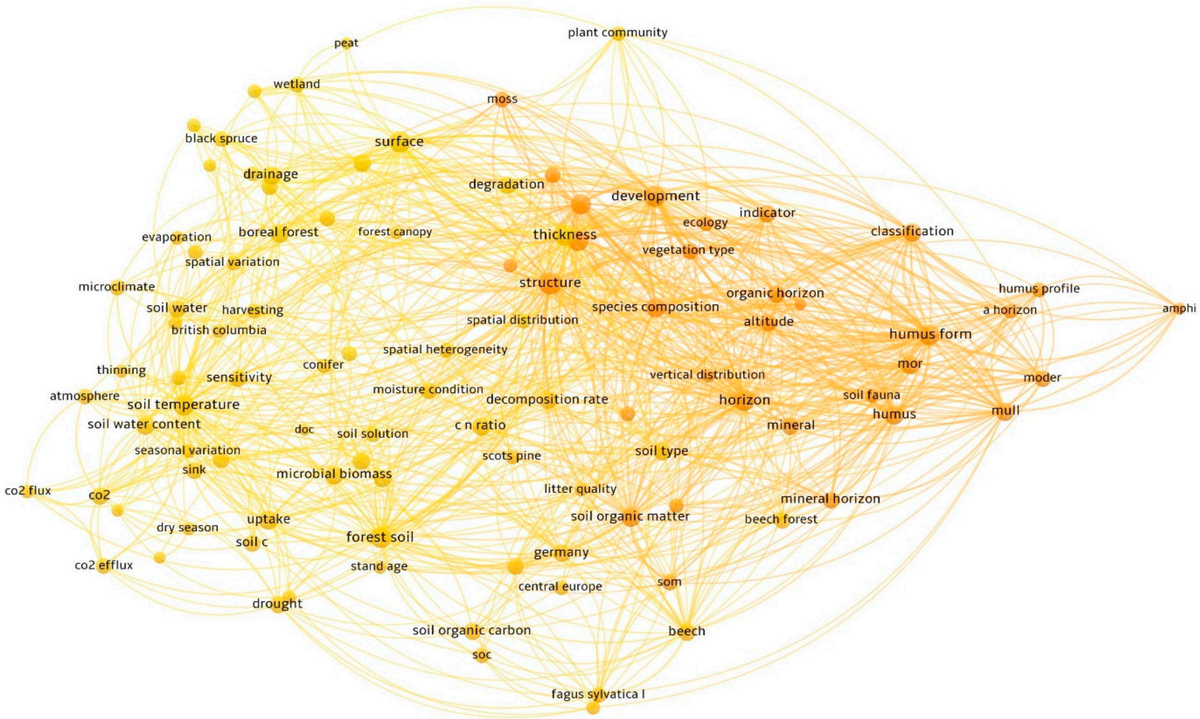

Figure 2. Topics related to the (aero-hydromorphic) humus forms during abstract screening (n = 229); the coloring of the figure was created with VOSviewer 1.6.18 (van Eck, Waltman, The Netherlands, updated 2023 [10]).

3.1.1. Chronological Occurrence of Aero-Hydromorphic and Hydromorphic Humus Forms in the Literature

The term "hydro" was used by Klinka et al. [11] for aero-hydromorphic as well as for hydromorphic humus forms. In detail, hydromorphic humus forms were mentioned in the taxonomic classification of humus forms in British Columbia (Canada), with morphological characteristics of the horizons. The term aero-hydromorphic humus was newly formed and became more frequent in the late 1990s in Germany. Firstly, it was proposed by Milbert and Broll [12] and Graefe and Belotti [6] to express that the humus profile still has a predominantly aeromorphic character (aerobic conditions), although the deeper horizons have shown hydromorphic features [11,13,14]. Aero-hydromorphic humus forms develop on sites with water saturation during spring and dry out during summer (growing season). Soil moisture of the forest floor depends on the terrain topography consequently affecting the occurrence of the moist humus forms. Zanella et al. [3] stated that the semiterrestrial humus forms include those that are water saturated for a period of less than 6 months per year (=Hydroforms), and humus forms that are water saturated for at least 6 months per year (=Histoforms), but these time periods are not further documented or explained. According to Baritz [15], the hydromorphic humus forms develop on very moist sites to anmoor forms or peat. In his explanation, he stated that topsoils are water saturated during most of the year. The existence of a histic epipedon is necessary with a H horizon > 30 cm for a peat. The carbon storage is even higher than in hydro humus forms. Even though Babel [16] mentioned the term *"Feuchtmoder"* (translated in wet moder) under a forest much earlier, publications explaining the aero-hydromorphic humus forms with morphological characteristics came later. The first description of an Oh layer with a smeary consistency and black color under the influence of groundwater was given by Hartmann [17] and was resumed by Beyer [18] for a *Hydro-Mor* (=Anaerober Waldnasstorf [17]; Feuchter Rohhumus [18]). Hartmann [17] emphasized the importance of these humus forms for silviculture. Generally, root activity is inhibited under long-lasting anaerobic conditions. Hence, this knowledge is necessary to select the appropriate tree species on such sites (e.g., English oak (*Quercus robur*) is less sensitive). By contrast, Beyer [18] described the morphological structure and chemical composition of soil organic matter in different humus forms of forest soils in Schleswig-Holstein. Further, the Ah horizon of a *Moist F Mull* (=Feuchter F-Mull) on a Stagnosol was declared as being thicker compared to the A horizons of terrestrial humus forms without the influence of water. Aero-hydromorphic humus forms occur mainly at seasonally moist sites with a similar biocenosis, while for aeromorphic humus forms, additional moisture and wetness indicators needed to be specified [6]. Although the terms *Feuchtmull*, *Feuchtmoder*, and *Feuchtrohhumus* have been used several times in Germany, no uniform definitions and morphological characteristics have been agreed upon so far [5,19].

One of the first research projects about moist humus forms in Germany was conducted between 2000 and 2003 by Erber and Broll [1]. The project with the title "Bedeutung des Bodenwasserhaushalts und der Sauerstoffverfügbarkeit bei der Ausbildung von Humusformen in Wäldern" (importance of soil–water balance and oxygen availability in the formation of humus forms in forests) investigated the morphologic characteristics of aero-hydromorphic humus forms in the interaction with soil moisture, availability of oxygen, and biological activity in deciduous and coniferous stands on six different areas in a low mountain range [1,20,21]. Erber and Broll [1] explained that moist humus forms are characterized by an increasing thickness of the organic layer (due to previous reduced conditions) and an increasing degree of decomposition and humification from top to bottom. When the soils are constantly under reductive conditions with a high water level, peat grows. The growing of peat soils is very well researched [22–24] compared to the research about humus forms in moist and wet forest stands, despite their great importance for carbon sequestration and water retention. If peat growth stops, then at the same time, moist humus forms become dominant due to a change in the moisture condition [1]. The dependence on relief must also be considered, as slope water is more common in the low mountain ranges and even more important in alpine areas.

In the subalpine and alpine zone, microclimatic conditions change over small areas, mainly due to the influence of the microrelief and the exposure. The exposure and the thickness of the snow cover both have a decisive influence on the site conditions. Here, the vegetation composition differs significantly from sites at lower altitudes without snow cover. Even though the region of the alpine zone lies above the tree line, the work around Hiller et al. [25,26] should be mentioned here. They have made an important contribution to the understanding of wet humus forms. The moist humus forms that occur in so-called "snow beds" are also characterized by the influence of slope water [26]. In the tree line ecotone and in the alpine areas, a differentiation according to moisture levels is useful since the soil–water balance plays a decisive role in the formation of the moist humus forms. In the context of grassland humus forms, the consideration of soil–water balance and use in the classification of humus forms is also discussed [12,27]. It is also not sufficient to determine a moist humus form only on the basis of vegetation and soil moisture. Morphological characteristics are necessary to correctly distinguish the aero-hydromorphic humus forms from the aeromorphic ones. In general, the formation of moist humus forms depends on various parameters. Only a few classification systems distinguish those humus forms that develop on sites, which are well drained or highly influenced by water [26].

3.1.2. Aero-Hydromorphic and Hydromorphic Humus Forms in Soil Classification Systems

In Central Europe in particular, the humus forms have received more attention in the current soil classifications, and the influence of water is also often considered here [13,28–34]. So-called "hydro" or "moist" humus forms are available for selection in the classifications. However, there is a lack of clear morphological description, including the thickness, structure, and composition of the organic layers influenced by water. The Swiss soil classification clearly shows the humus forms in a typogram depending on the biological soil activity and the degradation conditions: soil moisture and aeration. Wet humus or hydro forms are also addressed, which are under the influence of high groundwater or slope water levels or occur on soils with inhibited percolation (seasonally stagnic water) [29]. The Polish humus classification system determined five humus forms in forest stands. This classification is based on the degree of soil moisture, and thus, different moisture regimes (called Ksero-, Droso-, Higro-, and Hydro-subtypes) are described [31,32]. According to Nestroy et al. [30], the Austrian Classification included some more details in their description about the hydro (=Feucht) humus forms and mentioned similar to Hartmann [17] and Beyer [18] the black color and smeary consistency of the Oh horizon due to the influence of water. Additionally, a "rotten" smell of the plant residues was mentioned in the classification systems about the semi-terrestrial humus forms. Plant communities are specified in the classification systems mainly as indicators of moisture and wetness (e.g,. peat moss, perennial grasses, cotton grass, reed communities) [30]. Mentioning vegetation combined with the humus form is very common. Vacca et al. [35] summarized that hydro humus forms were found under the riparian vegetation, like woods and shrubs, on soil types, like Fluvisols and Regosols. Hiller [36] explained their hydro humus forms with the vegetation and soil moisture conditions in her research. This problem arises because the exact identification of humus forms is not sufficient, and often, morphological characteristics are not recognizable or too little studied, so they are often substituted by other criteria, such as vegetation [15]. Even if aero-hydromorphic humus forms are mentioned in many European and also other classifications worldwide, it is not sufficient for an explicit differentiation of the profiles with (aero)hydromorphic organic layers between Mor humus forms and Moder humus forms. This increases uncertainty in the assessment of habitats for soil organisms when semi-terrestrial forms dominate [37].

3.1.3. Soil Information Categories from the Literature Search

Information in the articles about site conditions for the development of humus forms as well as information about soil classification and morphology were sorted during the research. Various soil information is used in all of the examined research articles. The number of articles per soil information category is provided in Table 3.

Table 3. Selection of soil information categories from the final articles included in this review *.

Soil Moisture	Oxygen	Soil Organic Carbon	Vegetation	Soil Organisms	Climate Change	Classification & Morphology
19	3	12	8	9	3	29

* Some articles provided more than one category; one was chosen for this review.

The topics of soil organisms, vegetation, and soil organic carbon are aggregated in biological parameters and were considered in 29 articles. Data on soil organisms and processes controlled by these inhabitants of the humus profile are included. The soil microbial community structure and microbial numbers as well as various species characteristics have been investigated as part of the research. Detailed research has been carried out on the distribution of enchytraeids in the organic layer, the occurrence of earthworms, and the dependence of various site factors (such as soil temperature, soil moisture, and soil reaction). Other parameters were the decomposition of the organic layer, organic C (=carbon) accumulation, C mineralization, and soil microbial biomass C. Especially, the thickness of the organic horizons plays an important role under the influence of soil moisture and influences the morphology of the aero-hydromorphic humus forms. In addition to the soil organisms, indicator plants were also described since they are sensitive to soil moisture and soil reaction. These indicator plants are also used to classify the humus form additionally to morphological properties.

Articles containing information about moist and/or wet humus forms in soil classification systems are widely presented in Central Europe and Eastern Europe. Following classification systems from North America and other countries around the world, classification systems with detailed descriptions about the morphology of moist and wet organic horizons are rare. Similar to Baritz [15], it was found that the humus classification systems from France [13] and Canada [38] are most cited and describe a broad range of site properties of typical temperate forest ecosystems.

In general, the ecosystem conditions for the formation of aero-hydromorphic and hydromorphic humus forms and the interaction of wet and moist soils with various forest ecological properties were considered during the literature research and can be presented in a conceptual framework (Figure 3). In this way, this review has also succeeded in presenting the remaining questions on the topic of moist and wet humus forms in forest stands.

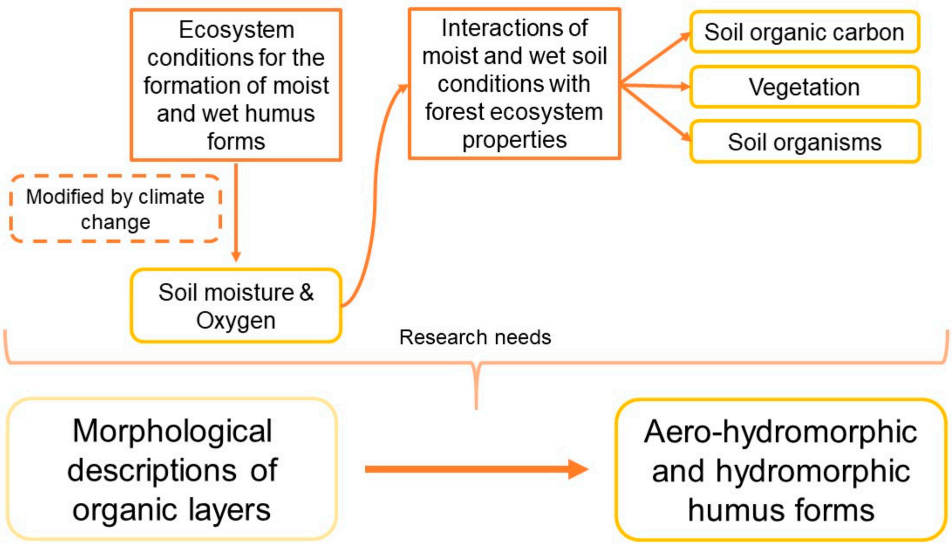

Figure 3. Conceptual framework of the review article (the author's own figure, 2023).

3.2. Conditions for the Formation of Moist and Wet Humus Forms

During the literature research, it was noticed that many articles repeatedly described the same site characteristics of moist and wet humus forms. It is therefore obvious that for the formation of moist and wet humus forms in forest ecosystems, certain preconditions must be fulfilled in order to distinguish them from terrestrial humus forms. In the following sections, these site properties supporting the formation of moist and wet humus forms will be examined in more detail.

3.2.1. Soil Moisture

Information and data about soil moisture related to humus forms in moist and wet forest stands were considered in 19 articles. This category occurred most frequently during the literature research because soil moisture has the greatest influence on the formation of moist and wet humus forms in forest ecosystems. The forest floor is characterized by a high diversity due to the varied composition of coniferous needle and leaf litter and a broad range of soil organisms all influenced by different water conditions. This influence promotes the different composition of the plant communities and the occurrence of special plants (typical moisture indicators = "Feuchtezeiger") [34]. In addition, the change between saturated and unsaturated conditions affects especially the soil chemical processes. If the soil water content changes, the redox potential will also change. Visible indicators of this process are the redoximorphic features, such as mottling and bleaching, in Gley soils (Gleysols) and Pseudogley soils (Stagnosol) (according to ad hoc AG Boden [33] and IUSS Working Group WRB [7]). Oxygen deficiency is referred to as reductomorphosis [39], which is caused by water saturation. Introverted iron (=spots and concretions inside the aggregates) is more characteristic for stagnic soils compared to extroverted iron (=spots and concretions outside the aggregates), which is more common in groundwater affected soils [39,40]. Both are caused in particular by periodic or frequently changing pore water filling. The soil texture and thus the pore size distribution and the spatial arrangement of the pores in the aggregates (inter- and intra-aggregate pore geometry) as well as the chemical–mineralogical stock and the extent of lateral solute transport are significant for the profile morphology [41]. Soils with a clay-rich stagnic impermeable subsoil horizon often have a coarse textural substrate in the topsoil [39]. Thus, the change between saturated and unsaturated conditions in the topsoil, including the organic layer, during the year impacts the habitat of soil organisms and the composition of plant communities. In organic layers, where water rises by capillarity, (aero)-hydromorphic properties are visible and develop on "seasonally waterlogged soils". Other names are perched water [42], "surface water" [7], or in German, "Stauwasser" [33], and additionally "stagnic" conditions occur in the mineral horizon, which means "The soil is saturated with water in one or more layers within 200 cm of the mineral soil surface and also has one or more unsaturated layer" [43]. As already mentioned, the particle size distribution (and with it, the pore size distribution) is the important factor for soils having a waterlogging table and controlling the water saturation also in the organic layer.

One detailed classification in Europe for humus forms in different water regimes was published by the Italian/French group of Zanella et al. [3]. In their approach, (aero)-hydromorphic horizons are submerged and/or water-saturated for more than a few days but less than 6 months per year. Hydromorphic organic horizons are periodically water-saturated and show the effects of temporary anoxia, such as iron-mottling and oxidation and/or colors of reduction, which cover at least 1/3 of the horizon [44,45]. Histoforms and epihistoforms are submerged and/or water-saturated for temporary periods (usually more than 6 months per year) and are characterized by organo-mineral Aa or organic H horizons [3]. Zanella et al. [3] described the moist and wet humus forms in detail with the addition of the suffix letter "g". In this system, this letter is intended to describe the presence of hydromorphic properties in the classification of hydromorphic humus forms [3,44,45]. Even if the classification of Zanella et al. [9] seems comprehensive, studies based on field trials are missing. Therefore, it is essential to support research that deals with wet and moist humus forms on stagnic or gleyic soils in forest ecosystems.

Researchers have been emphasizing for a long time that there is a need to change and to extend the system of humus forms [27,46], as influenced by water-causing special diagnostic horizons. Moist humus forms should be classified as aero-hydromorphic humus forms, and wet humus forms should be classified as hydromorphic humus forms [46]. Further, the importance of the amount of fine humus and the thickness of the horizon (=the storage of soil carbon) increase with increasing soil moisture [47].

In subalpine and alpine regions, moist or wet humus forms can be formed due to the influence of the seasonal snowmelt. Alpine snow beds are characterized by their extremely long-laying snow cover and a very short snow-free period of 2–3 months. During this time, specially adapted plants may develop in the snow beds. The decomposition processes, and thus also the type of humus form, are influenced by the soil moisture supply during snowmelt. Previous classification systems only distinguish between drained and poorly drained sites. However, the humus forms in the snow beds are neither well drained nor are they really waterlogged for a long time. Therefore, Hiller et al. [26] mentioned in more detail that it is necessary to be able to describe these humus forms under temporarily water-saturated conditions only. The different soil moisture levels throughout the year influence the development of special plant communities—as during the growing season, the water–soil conditions promote plant growth and biological activity. In particular, the decomposition and thickness of organic layers can be influenced not only by the relief but also by the inhibited oxygen availability during the snow cover in the snow beds [26,36].

Worldwide, classifications on humus forms are actively updated. Nevertheless research on wet and moist humus forms is currently still unsatisfactory [48], even if hydro intergrades (as a prefix) are possible and recognizable by hydromorphic signs in the A horizon and in the organic layer [44]. Many researchers point out the problems in classifying the humus form under different soil moisture conditions. For example, Füllgraf et al. [49] mentioned the difficulty of classifying the humus form of grasslands and pointed out the importance of considering soil moisture here as well. In the eastern part of Europe, Kõlli and Tamm [50] show in their research the difficulty of classifying humus forms in comparisons of the Estonian humus form classification with the European Reference Base formed under fresh, moist, and wet soil ecological conditions. Here, too, a revision and extension of the European Reference Base is recommended with regard to the humus forms of the northern regions [50–52].

3.2.2. Oxygen

Information and data about the influence of oxygen on humus forms in moist and wet forest stands were considered in only a few articles. With increasing water saturation, the diffusion velocity of oxygen in the pore space decreases drastically, leading to an increase in anaerobic conditions also for the soil organisms. The existing aerobic soil organisms then use the remaining oxygen faster than it can be supplied by diffusion from the atmosphere, and at the same time, the redox potential decreases. Soil temperature is also an important factor similar to the water content for many ecological processes in the soil. It is important to note that the solubility of oxygen in water decreases with increasing temperature. Aggregates and larger humus particles also influence oxygen saturation. Jansen [53] was able to show, with the help of oxygen measurements in hydromorphic organic layers, that the oxygen saturation decreases from the Of horizon to the Oh horizon. This can be explained on the one hand by the accumulation of organic fine matter in the deeper organic horizons [54]. This is accompanied by a reduction in the size of the voids due to a decrease in particle size. In the Ol and still in the Of horizon, mainly larger voids with a good oxygen supply are present [55]. On the other hand, the distance from the oxygen-rich atmosphere increases. Due to this increasing distance and in view of the constant consumption by soil organisms and root respiration, less oxygen reaches the deeper horizons. The differences to the mineral horizons are also clear. The influence of the water content on the oxygen saturation in the organic layer is nevertheless predominant. It can be assumed that oxygen can only be supplied very slowly in humus layers with very high water contents. The reason for the oxygen loss is the simultaneous consumption of dissolved oxygen by the decomposer soil organisms in the organic matter [53]. If the oxygen consumption exceeds the supply from the atmosphere, anoxic areas can quickly form [53]. Measurements of oxygen saturation in the field have also shown that differences in the proportion of fine matter influence saturation. For example, if an Ohf horizon (with a high proportion of organic fine matter) lies below an Off horizon, the oxygen saturation drops from the fully aerobic to the anoxic range. The packing of the organic matter also plays a role here; less anoxic areas are found if the organic matter is packed in friable form [20]. As a consequence of this conclusion, studies on anaerobic microbial processes in forest soils should pay special attention to the litter layer.

3.3. Effects of Moist and Wet Soil Conditions on Important Forest Ecosystem Properties

3.3.1. Soil Organic Carbon

Information and data about soil organic carbon in combination with humus forms in moist and wet forest stands were considered in 12 articles. In the course of climate change, the issue of carbon storage in forests has come back into focus. The articles show how much the moist and wet humus forms can serve as carbon sinks. Humus forms in forest stands have been found to be significant indicators of soil organic carbon storage [56]. German forest soils store around 2500 mill. t of carbon [57].

The decomposition of organic matter under anoxic conditions is strongly limited, which favors the accumulation of organic C in the form of recognizable organic residues and humus components [58]. The thickness of the O horizon is thus strongly influenced by the moisture status of the soil. Peat accumulation begins when organic matter production exceeds decomposition, which occurs especially due to unsustainable forest management in boreal and hemiboreal forest stands [59]. Bārdule et al. [60] showed that in forests in Latvia a statistically higher O horizon thickness was found in moist and wet organic soils than in dry and drained soils for both coniferous and deciduous forests. Thick O layers due to groundwater or temporarily stagnic water conditions are rich in fine humus [61]. A distinction was made between O and H horizons. The O horizons above mineral horizons represent mainly the aero-hydromorphic humus forms, while H horizons represent hydromorphic humus forms.

It is not only an accumulation of organic C found in the thicker organic layers, but higher N contents have also been found due to lower mineralization rates, for example, in the humus form hydromor [57,60].

In contrast, "anmoor" (German term) or peaty H horizons are more representative of hydromorphic humus forms. The H horizon is characterized by its dominant proportion of organic material, which is the result of the accumulation of undecomposed and only partially decomposed organic material under permanently water-saturated conditions. If the water table is high so that the mineral soil is permanently under water, it could be shown that the average thickness of the O horizons was also significantly higher [60]. Despite the wetness, accompanied by reduced oxygen concentration, transformation by soil organisms takes place, especially in Moist Mull humus forms, which in turn leads to low-thickness layers.

Furthermore, the accumulation of organic matter is influenced by the choice of tree species. It was shown that pine and spruce in particular lead to thicker layers on average [60]. However, not only the tree species and their litter but also the age of the forest stand influence the organic layer. Buczko et al. [62] were able to show that large amounts of organic C are bound in the soil under old forest stands that developed on hydromorphic and stagnic soils and where forestry no longer takes place. Olsson et al. [63] could support these statements and found that the wet organic layers were twice as thick as the ones on drier sites. Even though the C storage in the organic layer was not significantly higher despite the thickness, an increasing tendency from dry to wet stands could still be detected. Especially, the low decomposition due to the temporary influence by stagnic water is a cause for this. The distribution and morphology of the humus layer under the influence of groundwater or stagnic water show thick organic layers, which are rich in fine humus [63].

3.3.2. Vegetation

Information and data about vegetation in combination with humus forms of moist and wet forest stands were considered as a main topic in eight articles. In these articles it was obvious that the correlation between vegetation units and humus form is not always clear. Humus forms and the associated soil properties (soil pH, soil moisture, and nutrient availability) must be considered, especially to understand the relationship between soil organisms and plants. In many studies, indicator plants are used to describe the humus form, especially when the descriptions of morphological properties are inadequate and cannot be assigned [34,36,64]. Only very few plant species (or, in the case of microorganisms, functional units) can serve as direct indicators of specific site conditions, while most of them show rather indifferent behavior. Their response to complex factor structures or their requirements are not sufficiently known for a statement about the site conditions. Therefore, plant communities as well as entire biocoenoses (e.g., decomposer communities) are more suitable for site classification, as their composition or dominance relationships within a group (and possibly also within a community) are better known [65].

Indicator plants can not only provide information on the nutrient conditions and soil reaction but also indicate which soil type and which humus form could occur at this site. Vacca et al. [35] showed that Hydro Moder occurred as a humus form on the soil types Fluvisols and Regosols. The determining vegetation was classified as riparian vegetation and was found in the herb and shrub layer. In their studies, Anschlag et al. [66] and Aubert et al. [67] were able to show close connections between the vegetation and the organic horizons. Anschlag et al. [66] mentioned the significance of the herb layer for the thickness of the Oh horizon under needle litter. In the study by Aubert et al. [67], the main focus was on the tree layer and the age structures of the trees and forestry use. Here, too, conclusions could be drawn about the humus form. Unfortunately, such detailed investigations are lacking for the moist and wet humus forms. There are indicator plants that point to wetness and moisture, and thus, references to the humus form would also be possible. Such initial approaches for descriptions can be found in Kopp et al. [68] and long time ago already in the ecograms of Ellenberg [69,70].

Forest management changes the plant cover. If tree species change, the herb layer also changes afterward, and thus, humus forms. The thickness of the humus layer depends not only on the input of litter and the proportion of fine roots but also on soil water dynamics. Additionally, the spatial variability depending on the microtopography is high on many sites. Small troughs with high soil moisture alternate with little dry hills [2]. In the past many forests have been artificially drained by ditches. The drained sites with high drought stress are particularly at a risk during the summer because water can no longer be stored [71]. Nowadays, summer droughts in Europe require an adapted forest management. Closing the ditches is a possibility to keep water in the forests. In the long term, this can also lead to changes in the humus forms or in the thickness of the organic layer (see the section on soil moisture). In general, the articles show that forest management has a considerable influence on the moist and wet humus forms and can influence it both positively and negatively.

3.3.3. Soil Organisms

Information and data about soil organisms in combination with humus forms in moist and wet forest stands were considered in nine articles. The formation of the different humus layers is not only affected by water and other pedological factors. The soil organisms actively change the humus forms and use them as their habitat [65,72]. Soils with the humus form Mull are biologically very active. Enchytraeids and endogenous and anecic lumbricides have been identified in many studies under different conditions [73–76]. Moist Mull is characterized by the presence of enchytraeids that can live in moist and wet conditions. Hence, enchytraeids could be used as indicators of humus forms, similar to the indicator plants [75].

As mentioned above, plant communities and litter quality depend on the soil moisture, and further, the occurrence of micro- and macro-invertebrates depends on the litter composition. Also, a sufficient soil moisture is necessary for microbial growth [77]. The optimal soil moisture for organisms can generally be assumed to be a water potential of -0.05 MPa. In dry conditions, metabolic activity largely comes to a standstill. Nevertheless, microorganisms can survive under these conditions for a long time in many cases [78]. The microbial metabolic activity also decreases in waterlogged soils. One reason for this is the reduced oxygen (O_2) supply to aerobic microorganisms. Soil water not only affects organisms directly through water availability but also influences soil organisms indirectly through changes in the type and amount of water-soluble substances (e.g., nutrients, pollutants), osmotic pressure, and the pH in the soil solution [78].

The water-filled and air-filled pores in the soil serve as a habitat for the soil organisms, and the distribution of the pores depends on the properties of the soil organic matter. Aero-hydromorphic to hydromorphic humus forms with a higher amount of water-filled pores are suitable for different soil organisms. For example, bacteria, protists, and nematodes prefer to live in the water-filled pores. Most arthropods, like collembola, acari, millipedes, and isopods, develop and live in the air-filled pores [79]. The distribution of air-filled and water-filled pores depends on the humus formation and thus on the humus morphological structure [79]. Regardless of the type of the organic layer (Ol, Of, or Oh), water is held more effectively if the pore has a small diameter. This general rule is further influenced by the continuity of the pore space, i.e., the bottleneck porosity increases the water holding capacity and the nature of the solid phase: the more hygrophilic the solid phase, the more effectively the water is held in the pores [79]. On a small scale, the life of soil organisms depends on the properties of the interfaces, namely the solid–liquid, solid–gas, and liquid–gas interfaces, which vary in relation to the Mull or Moder humus forms. For example, minerals (especially clay minerals) and highly humified organic material that predominate in the Mull environment may be highly hygrophilic. In contrast, poorly humified organic matter, which is the parent material for Moder humus forms, is the cause of repulsion between soil and water most of the time. Soil organisms are not passive in this interplay between air and water of soil pores [79]. Organisms that can control the air–water balance in the soil are burrowing earthworms, which are active mainly in Mull. Enchytraeid are active in Moder humus forms [65]. Earthworm movement and feeding activities affect the structure of the pore phase. Earthworms also influence interfacial properties by creating coating surfaces with a highly hygrophilic clay–organic mixture, which is produced by intestinal passage [80]. Life in the Moder humus form has to cope with the water-repellent effect of the solid phase, which is mainly due to the accumulation of hydrophobic organic materials, such as waxes or fatty acids. Soil moisture is one of the most important factors that directly affect the decomposer community in soils of moist and wet forest stands. Additionally, the kind of humus forms is influenced by the activity of soil organisms because of changes in the humus morphology. Some authors described ideas and proposals for soil classification systems that integrate burrowing functional organisms [6,65].

3.3.4. Climate Change

Information and data about climate change in combination with humus forms in moist and wet forest stands were considered as a main topic in three articles. However, in almost every article dealing with humus forms, one details the threat of their function as a habitat for the decomposer community due to climate change. To understand the influence of climate change for moist and wet forests and forest soils, it is important to understand the processes (mineralization and humification) in forest ecosystems. The decomposer organisms, plants, water, and soil properties play an important role for these processes and thus carbon cycling. What happens to the moist and wet forest ecosystems in the future? Humus forms have shown to be good indicators of present and—to a certain degree—also past climate conditions, and thus could be used for predicting future trends of global climate change [81]. Changes in air and soil temperatures cause changes in soil moisture and vegetation [73]. If the hydromorphic soils or the organic layers are permanently or at least seasonally dry, the former C sinks become C sources [82]. In general, the soil temperature depends on the moisture content of the soils because dry soils warm up faster than moist soils due to the heat capacity (warming of soil particles is faster than that of water) [83]. If the soil temperature of wet soils increases, this will lead to a large turnover of carbon and thus also to a great release of carbon dioxide into the atmosphere [60].

Impacts due to climate change are probably very site-specific. Soils with stagnic properties are very vulnerable under the impacts of climate change. In the future, reductomorphic properties will most likely disappear because of decreasing reducing conditions [42]. The humus forms will also change, for example, from wet humus forms to aero-hydromorphologial humus forms. Bojko and Kabala [37] describe in their research a decay of hydromorphic humus forms because of global warming and a decrease in soil moisture.

Even though the systematic literature search found only three articles with the topic of climate change closely related to moist and wet forest stands, this section showed that many other articles deal with the topic of climate change and future changes in forest ecosystems.

4. Research Needs on Moist and Wet Humus Forms

The literature and the results described in detail in this article clearly show that the moist and wet humus forms have received very little attention in previous studies. Most articles have been published in Europe and Canada, while in many countries there seems to be no consideration of wet and moist humus forms. This also becomes clear when one takes a closer look at the soil classification systems of the individual countries. In many classifications, there is the possibility to assign a humus form to the moist humus forms or to the wet humus forms. However, the descriptions of the morphological characteristics of the individual horizons are missing. Not only in the case of moist and wet humus forms, the problem of comparability beyond national borders is difficult. Therefore, the discussion of a uniform cross-national classification, as has already been started by some scientists, should be continued [3,44,46]. This review was also able to show that many researchers had problems classifying their humus forms in their publications due to the lack of morphological descriptions. Alternatively, the decomposer community (enchytraeids and earthworms) or the vegetation or soil moisture conditions were used to describe the moist and wet humus forms [37,64]. The humus form provides a lot of information about the site conditions of a forest, and in order to protect them, we need a detailed characterization of the individual organic layers. Although these are described in many articles, the extent of these descriptions of properties of the organic layers varies greatly. The humus form can provide explicit information about the habitat for soil organisms and the site conditions for vegetation.

The moist and wet humus forms are not rigid systems but are subject to fluctuations that can occur, for example, in the course of the year due to seasonal changes in soil moisture. These fluctuations can lead to different morphological characteristics of the organic horizons. This becomes clear with the example of the Oh horizon. Under the influence of water, this horizon is moist and smeary, but when dried out, it becomes friable. Therefore, in some cases it may be useful to visit study sites several times in order to describe the humus forms on site and to observe them over the course of the year.

It is also important to investigate the indicator function of humus forms for the assessment of soil ecological properties in wet and moist forest stands. Humus form is considered an important indicator for ecological processes at the soil–vegetation interface, in particular also for the species composition of the decomposer community [84,85].

In an on-going project of the University of Osnabrueck, Germany, in cooperation with the Landesbetrieb Wald & Holz (North Rhine-Westphalia), the humus forms in moist forest ecosystems in the Münsterland in Northwestern Germany are investigated by identifying unique classification features for humus forms in moist forests. This project aims to make a contribution to a unique key for moist and wet humus forms [86]. Through the correlations between humus form and recorded soil parameters, the development of moist and wet forest stands under changing climatic conditions can be represented on a spatial scale. Thus, the expected effects of climate change on the soil–water balance and on the distribution patterns of humus forms can be better predicted. This will also provide information on the future functionality of today's moist and wet forest ecosystems, what is of great importance for forest management with regard to necessary, and the sensible adaptation measures to climate change.

5. Conclusions

There is a lack of research on moist and wet humus forms compared to aero-morphological humus forms. Some international classification systems could be identified in this review, which already take into account the influence of the water regime on the forest floor. Also, the degree of decomposition related to moist and wet humus forms is addressed in some classifications. During the literature search, some studies were identified that have already dealt with vegetation and soil organisms in relation to humus forms of moist and wet forest sites.

Nevertheless, the moist and wet humus forms have not yet been investigated in detail, so there is a great need to research a clear description of the morphological properties of the horizons exposed to a periodic or permanent water influence. Furthermore, it should be clarified which water regimes and which decomposer communities, especially the aero-hydromorphic humus forms, serve as an indicator for changes in forest ecosystems. Thus, moist and wet humus forms are indicative of changing water balance conditions in times of climate change. Also, the importance of humus forms as indicators of the decomposer community in moist and wet forest ecosystems in the course of climate change should be further emphasized.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijpb14030058/s1, Table S1: Articles selected from the literature research with title, first author, year, continent & country, category, special data and sites.

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