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Review

A Standardized Morpho-Functional Classification of the Planet's Humipedons

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Abstract: It was time to take stock. We modified the humipedon classification key published in 2018 to make it easier and more practical. This morpho-functional taxonomy of the topsoil (humipedon) was only available in English; we also translated it into French and Italian. A standardized morpho-functional classification of humipedons (roughly the top 30–40 cm of soil: organic and organomineral surface horizons) would allow for a better understanding of the functioning of the soil ecosystem. This paper provides the founding principles of the classification of humipedon into humus systems and forms. With the recognition of a few diagnostic horizons, all humus systems can be determined. The humus forms that make up these humus systems are revealed by measuring the thicknesses of the diagnostic horizons. In the final part of the article, several figures represent the screenshots of a mobile phone or tablet application that allows for a fast recall of the diagnostic elements of the classification in the field. The article attempts to promote a standardized classification of humipedons for a global and shared management of soil at planet level.

Keywords: humipedon; humus system; humus form; humusica; carbon cycle; soil classification; global change; soil biodiversity

1. Introduction: A Humipedon Classification Is Needed

There are abiotic and biotic soils [1]. Abiotic soils are, for example, the rocky surfaces of bodies evolving outside the Earth's atmosphere, such as the moon, Mars, and comets or asteroids. These abiotic soils correspond to rocks transformed by the actions of physical and chemical forces, in the absence of living organisms. True terrestrial soils have new functional characteristics that are very different from those of abiotic soils. These new features are purely of biotic origin.

All terrestrial soils are biotic soils (i.e., endowed of variable biological activity) and correspond to a biotic matrix made of living and dead organic substances, mineral substances, and a periodical or continuous dynamic fluid that connects the different parts of this living soil. A biotic soil acts as an ecosystem [2,3] where plants, animals, and microorganisms interact and use the physical and chemical environment [4,5] for building a living structure. When environmental conditions become difficult for the living beings inhabiting the soil (extreme temperatures and absence of liquid water, presence of high-energy radiations) [6], terrestrial soils resemble abiotic soils. The depth of the soil depends on this aspect; at a certain depth, microorganisms change/disappear [7–10], and the soil becomes a more or less abiotic substrate. Notice that even in harsh environment, surface rocky substrates are generally rich in microorganisms, and that in geological periods many rocks are themselves biogenic (i.e., limestone, coal, oil shale . . .) [11].

In scientific publications with the objectives of safeguarding and managing the environment, the survival of the planet's biodiversity is now presented as linked to a living soil matrix that guarantees its dynamic recycling and influences the planet's climate [12–18]. Indeed, in the course of geological times, the humipedon has behaved like the planet's air, changing as a consequence of the development of the biodiversity (microbial diversity, fundamentally), while remaining closely and indelibly connected with the biosphere as a whole [19].

Soil classification is important for exchanging knowledge among scientists and understanding how soil works [2]. In this moment of crisis in the planet's biodiversity [20–24], the ability to classify the soil becomes essential because a large number of living beings are found in the "topsoil" (which from now on in the text will be referred to as "humipedon") [25–29]. The humipedon corresponds to the organic (OL, OF, OH, and H) and organomineral (A, AE) soil-surface horizons, roughly the top 30–40 cm of a biotic earthy soil [30,31]. Knowing how to link the quantity and quality of organic matter (OM) in the soil [15,32–35] to the type of humipedon, enables a sustainable use of the soil for agricultural and forest purposes, and can contribute to climate-change mitigation [36–42]. A morpho-functional classification of the humipedon is now available [43]; accessible by direct naked-eye observation, or with the help of a 10 × magnification lens, some morphological characters allow a first understanding of the soil functioning. In particular, the observation reveals the vertical structure in horizons of the soil, and the biological actors of such a spatial organization. For example, it is possible to know how long it takes in natural conditions for a specific litter type to be integrated into the mineral soil [44]; or to recognize the main animal groups associated with the biodegradation (mineralization and humification), or the shape and size of their excrements [45].

To put it briefly, this classification corresponds to a rough distribution of all humipedons into 20 "humus systems"; the most common of these can even be subdivided into 3–4 more detailed "humus forms". An application can display dichotomous-like keys, photographs, and information on these humus systems and forms in three languages (English, Italian, and French). We present below an update of this classification that is valid for European temperate and Mediterranean terrestrial environments, and which has recently also become valid for Brazilian equatorial forests [46]. It has been used successfully in Iran, in the Caspian Hyrcanian temperate forests and in southern semiarid forest ecosystems in Zagros Mountains [47,48]; in Russia, trying to connect humus systems to the biological quality of the soil [14]; and France, comparing sites with mine deposits [49]. Recently, we have been testing the classification in Japan, on volcanic soils (to be published). Studies are underway to adapt the classification to agricultural [50] and urban [51] soils as well.

2. A Soil Parted in Subunits and Horizons

Soil as a whole is simply too complicated to understand. We need to break it down into functional subunits. We divided the body of insects into the head, thorax, and abdomen; for the soil it is useful to have three functional constituents too: Humipedon, Copedon, and Lithopedon. These sections arise from the fact that the soil-formation processes act both

from above (actions of living organisms as plant roots, animals, and microorganisms with consequent litter recycling and formation of new organic components = Humipedon), and from below (weathering of the rock, water dynamics, bank of mineral elements = Lithopedon), converging at the center of the soil profile (formation of new mineral components, new physical environment = Copedon). These subunits are composed of layers called “horizons”, and the attentive observer can understand how these horizons interact in each subunit, for a complex and harmonious functioning of the soil as a whole (Figure 1).

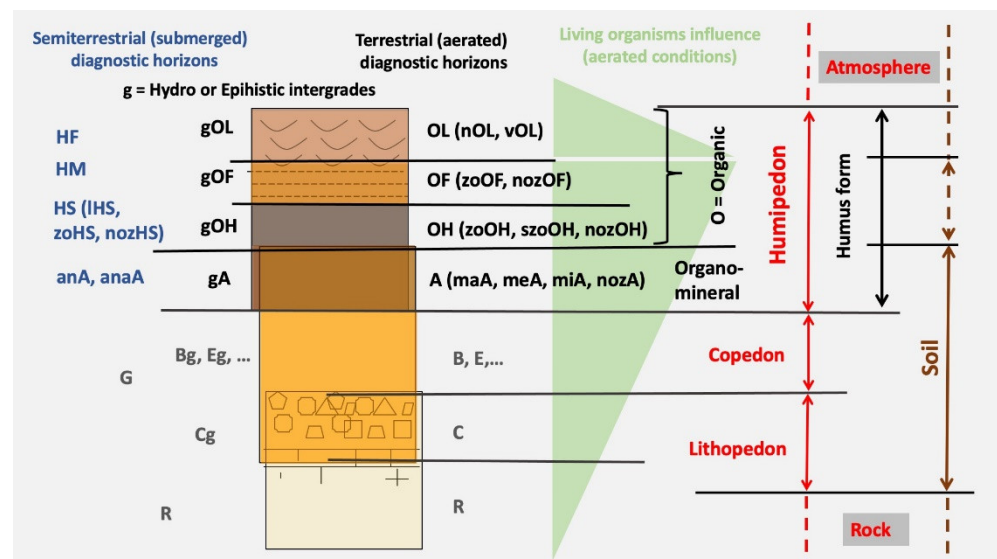


Figure 1. Soil subunits and horizons. From [43], modified (addition of Semiterrestrial diagnostic horizons). Humipedon horizons enlarged: Semiterrestrial Histic organic horizons [31] HF, HM, HS (IHS, zoHS, nozHS) and organomineral anA (Anmoor A horizon); Hydro and Epihistic intergrades horizons [52,53] gOL, gOF, gOH, gA; Terrestrial horizons “O” organic (OL, OF, OH; zo = zoogenic; noz = nonzoogenic; szo = slightly zoogenic) and “A” organomineral horizons (maA, meA, miA, nozA, respectively biomacro, biomeso, biomicrostructured, and nonzoogenic A horizons) [30]. Semiterrestrial humipedons may be very thick (peaty soils, until many m) or superficial (<1 m) and lying on hydromorphic Copedon and Lithopedon horizons; Terrestrial humipedons occupy approximately the first 30 cm of the profile, followed by the more mineral “E” and “B” Copedon horizons resting on “C” horizons and the weathered, altered “R” layer of the Lithopedon. Although organisms are present throughout the soil profile, they are more numerous in the Humipedon, for reasons related to the availability of nutrients and organic matter as a food resource. Reprinted/adapted with permission from Ref. [43]. 2019, *Soil Sci. Soc. Am. J.*

3. The Environment in Which the Targeted Humipedon Is Found

Soil organisms and biota activities evolve with the environment and generate horizons and subunits in tune with it. Once the vertical structure of the soil is unveiled and the humipedon is circumscribed, it is necessary to establish in which main “ecological frame” the observed topsoil is located. On a large scale, five sets of humipedons can be identified:

1. Terrestrial: humipedons that never submerged for more than a few days per year; peaty and water-filled horizons absent. These humipedons belong to Mull or non-Mull systems (Moder, Mor, Amphi, and Tangel);
2. Histic Semiterrestrial: submerged humipedons characterized by peaty horizons; presence of a water table (perched or not). These humipedons belong to Fibrimoor, Mesimoor, Amphimoor, Saprimoor, and Anmoor systems;
3. Aqueous Semiterrestrial: humipedons by the sea in tidal area, or submerged;
4. Para systems: humipedons connected to the other three groups (Para = next to) in a dynamic way; they either precede the others in time or develop with them (overlapped, juxtaposed). These are Archaeo (extremophile microorganisms), Anaero (submerged

organotrophic microorganisms), Crusto (cyanobacteria, lichens, algae, fungi), Rhizo (roots, rhizoids), Bryo (mosses), and Ligno (decaying wood agents) systems.

5. Anthropogenic systems: Agro (natural humipedons anthropogenically transformed for agricultural purposes) and Techno (manmade imitation of natural humipedons, e.g., compost, or without a specific purpose (waste dumps, etc.)).

Intergrades between Terrestrial and Semiterrestrial humipedons can also be identified using the Hydro prefix if hydromorphic features are present in a Terrestrial humipedons, or the Epihistic prefix when some Terrestrial horizons take place in Histic humipedons. The classification also enables us to recognize vertical and horizontal transitions, or mosaics between the above cited sets of humipedons (Figure 2).

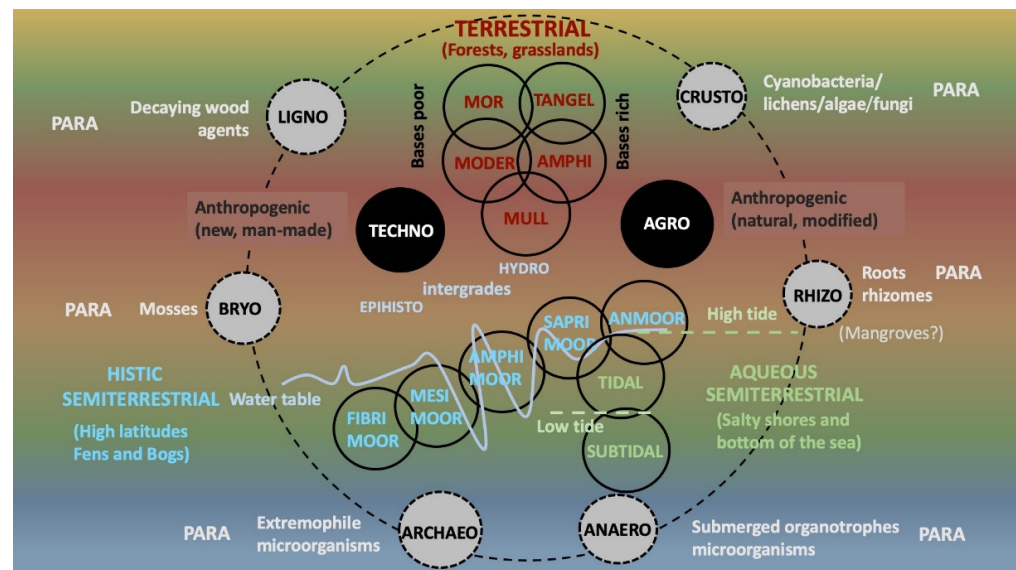


Figure 2. Slightly modified diagram (modified from [2]) showing all humus systems described in dedicated articles [44,52–56]. Terrestrial systems are placed at the top of a circle next to the Forests Grasslands title. They are divided vertically into non-Mull (Mor, Tangel, Moder Amphi) and Mull, and horizontally left to right into Bases poor (Mor and Moder) and Bases rich (Tangel and Amphi), with a nearly neutral Mull in between. Next to these, there are two anthropic systems, Techno (new systems manufactured by man) and Agro (natural systems modified by man for agricultural purposes) in black. Immediately below in blue are the partially submerged systems (Fens and Bogs, Histic systems), with a gray line indicating the oscillation of the water table (sometimes perched). From left to right of the figure, the systems pass from the permanently submerged Fibrimoor, to the Mesimoor, Amphimoor, Saprimoor, to arrive to the less-submerged (6 months per year, influenced by a slow oscillating water table) Anmoor. In the center of the circle, between the Terrestrial and Histic systems, there are the Hydro transitions closest to the Terrestrials’, and Epihisto more similar to the Histics’. The systems dependent on daily tidal cycles, called Aqueous, and divided into Tidal (submerged at high tide) and Subtidal (submerged even at low tide), are shown in green-blue at the bottom left. In gray along the dashed circle are the Para systems, which correspond to particular stages of the evolution of the soil. Initial and progressive stages are with the nonsubmerged systems Crusto, Bryo, Rhizo, and Ligno, or submerged such as Archaeo and Anaero. One has likely already seen very common Bryo systems even on walls or roofs of houses; they are classified as Edifisoils by Markiewicz et al. [57]. These Para systems can exist alone or in combination with other systems. Reprinted/adapted with permission from Ref. [2]. 2018, *App. Soil Ecol.*

It is not possible to summarize the classification and complexity of humipedons in a few lines. For a precise general picture on the classification, we recommend reading the article “Essential bases—Quick look at the classification” [54]. More detailed information is published in articles 1 to 15 of two Special Issues [58,59]. Applications of classification and insights can be read in articles collected in a third Special Issue [60]. Below we present

only the classification key of the Terrestrial and Semiterrestrial (Histic or Aqueous) systems, which are the most commonly considered in management or nature-protection plans. Their recognition key underwent a slight modification in 2020, abandoning the pH as a discriminating character. The role of parental material in the formation of the A horizon was preferred to pH, accompanied by characters related to soil structure and pedofauna.

4. Systems and Forms of the Main Terrestrial and Semiterrestrial Humipedons and Recent Advances in Humus Classification

There is a useful way to classify *Terrestrial humipedons*: packing them in five humus systems divided into 3–4 humus forms. Each system corresponds to a mode of operation. The Mull system is made of large worms’ droppings, generally developing in temperate climate environments and on nonacidic rock (prevalent bacterial decomposition that incorporates all litter into the soil in a few months, in and out of the intestines of earthworms); the Moder is instead built by arthropods and enchytraeids in colder and more acidic environments; the Mor is mostly found in extremely cold and humid environments, and is poor in fauna (animals are very rare, prevalent fungal decomposition that generally takes a few years to integrate the litter into the soil); the Amphi, which arises in contrasting environments (alternately wet or dry, open or closed canopy, old or young sylvogenetic phases, etc.) is made up as a sandwich, composed of two separate layers: an A horizon formed by earthworms, on which lies a organic layer deriving from the activity of arthropods and enchytraeids; finally, the Tangel is typical of limestone mountain environments and resembles a Moder, with an increase in pH with depth, possibly with an A horizon in contact with a calcareous rock, the whole being very organic and exaggeratedly thick (Figure 3).

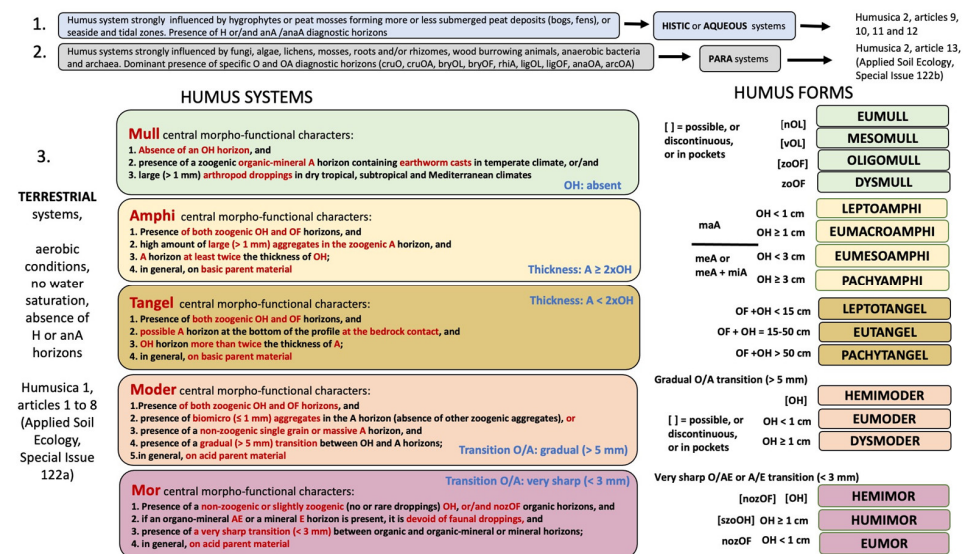


Figure 3. Main terrestrial humus systems (left) subdivided into humus forms (right). Modified from [44]. The first two sections at the top of the figure contain references to the diagnostic horizons that separate the Earth systems from the Histic, Aqueous, or Para systems. The characters to be considered for a quick classification of terrestrial humipedons are highlighted in red. A first quick and rough subdivision into the 5 systems could be the following: Mull: no OH horizon—it is a system determined by earthworms or large arthropods that completely consume all the litter; Amphi and Tangel: with OH horizon and generally on basic parent material (calcareous or high base saturation of topsoil horizons); Moder and Mor: with OH horizon and generally on acidic parent material (acidified topsoil horizons) or siliceous bedrock with low ANC (acid-neutralizing capacity); Amphi: with the thickness of the A horizon at least twice that of the OH horizon (it is a system determined by earthworms but in periodically arid environments); if the A horizon is less than twice the thickness of the OH we are in a Tangel (a system determined by arthropods in a calcareous and cold environment); Moder: with a gradual transition between the OH horizon and the A horizon (system dependent on

arthropods that are also able to colonize the mineral part of the soil); if the OH/A transition is well-defined, we are in a Mor (system with distinct separation of the organic and mineral part of the soil profile, generally determined by mainly fungal decomposition, in a cold and acidic environment). Reprinted/adapted with permission from Ref. [44]. 2018, *App. Soil Ecol.*

The organization of the key requires the classifier to first find the humus system to which the humipedon belongs. In the left large squares of Figure 3, the text highlighted in red defines each humus system in a simple and practical way:

- (a) Mull system (top square, absence of OH horizon = Mull system); or
- (b) Non-Mull systems (with OH horizon = all the other systems):
 - (b1) Non-Mull systems 1, on basic parent material (calcareous or high base saturation of topsoil horizons) divided according to the thickness of the OH and A horizons: if $A \geq 2 \times OH$, Amphi, if $A < 2 \times OH$, Tangel; or
 - (b2) Non-Mull systems 2, on acidic parent material (acidified topsoil horizons) or siliceous bedrock with low acid-neutralizing capacity (ANC), divided according to the type of transition between the organic (O horizons) and organic-mineral (A) or mineral layers of the profile. If the transition is gradual, which means that migrant animals may form an organic-mineral A horizon, then it is a Moder. With a clear and sharp transition instead, which means that the soil fauna does not incorporate organic matter in the mineral matrix, it is a Mor.

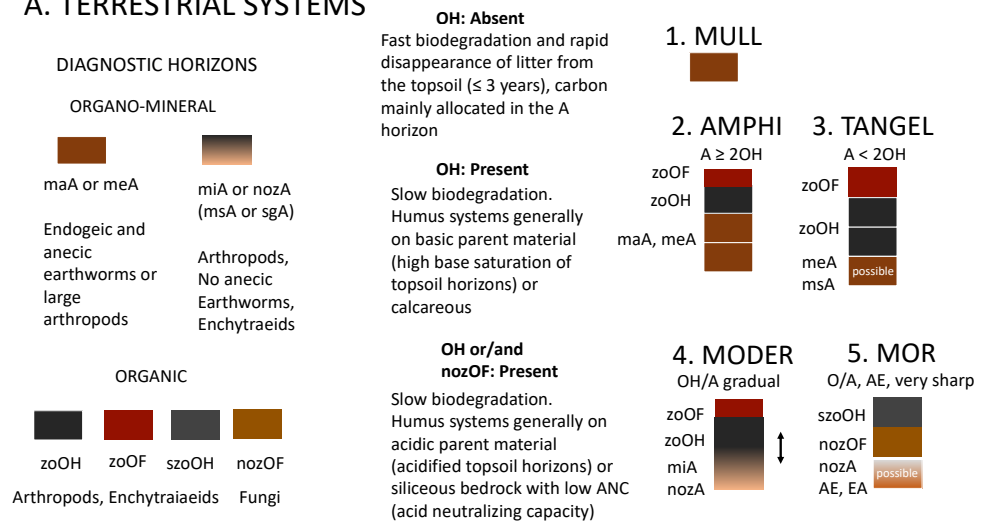
During field investigations, this subdivision is very practical and is also shown in Figure 4A. This version of the key does not include pH as a diagnostic character compared to the taxonomic key presented in Special issue 122a in 2018 [44]. The pH helped to distinguish Moder from Amphi and Mull systems in Europe, but this parameter did not work in a tropical environment, where Mull and Amphi can have A horizons as acidic as in Moder conditions. Therefore, a universal key was adapted based on other characteristics, such as the structure and size of the aggregates, the thickness, and the transition between diagnostic horizons, which fit a more extensive set of ecosystems.

Two more words about the Amphi system, which does not seem to be known in other topsoil-classification references (<https://forestfloor.soilweb.ca> (accessed on 27 June 2022)) [61,62]: Usually the activity of the anecic worms results in the disappearance of the zoOF and zoOH horizons, and this generates a Mull. If these horizons persist on an A horizon built by earthworms, we obtain an Amphi. The situation of instability of organic zoOF and zoOH horizons is revealed by the presence of dejections and galleries of anecic worms. The Amphi system may be the result of a stable cohabitation of epigeic and endogeic earthworms, or of transient and dynamic anecic activity. This occurs in a situation of dry/wet or hot/cold alternation and along the sylvogenetic cycle [63]. For details on the classification and in-depth information, consult the Supplementary Materials 1.

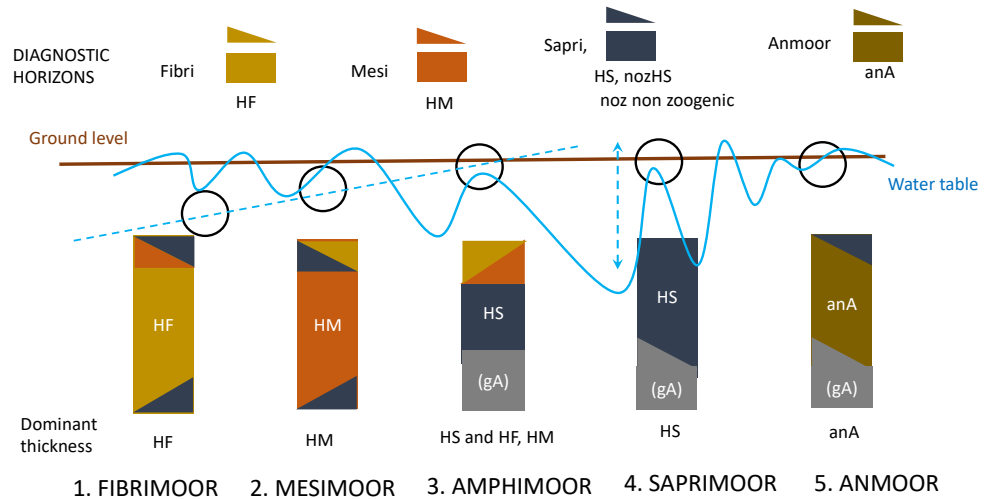
Histic semiterrestrial humipedons have also been classified in a simple way (Figure 4B). The morpho-functional classification is based on the presence of a dominant horizon, or in one case on the equal value of two horizons, within the humipedon. In these moist environments, the humipedon can be very deep ($\gg 1$ m). For classification purposes, it was decided to limit the survey to the first 40 centimeters of humipedon [64]. The choice for a reference of a surface section of 40 cm comes from the ecological viewpoint that plant roots rarely go deeper into these asphyxiated environments, and from the practical and economic viewpoint that the agronomic use of these soils generally stops at this depth. Thus, five humus systems have been described, each divided into 3–4 humus forms, reaching a total of 13. The central and diagnostic features of each system are listed below:

Anmoor: within the control section (40 cm below the surface), presence of a dominant anA organomineral horizon; Zoogenic HS possible but never thicker than anA; humus forms of wet base-rich soils or soils enriched by base-rich groundwater around springs and in nondynamic parts of brook or river valley systems (parts of floodplains, lacking dynamic floods or inundations with fast currents);

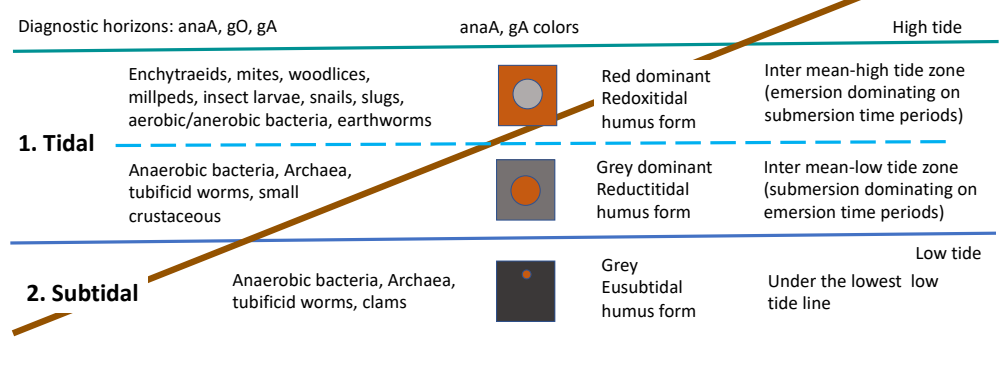
A. TERRESTRIAL SYSTEMS



B. SEMITERRESTRIAL HISTIC SYSTEMS



C. SEMITERRESTRIAL AQUEOUS SYSTEMS



Crusto, Mull and Moder as prefixes are often necessary to precise Redoxitidal humipedons

- Crusto: presence of aqueous litter laying on rock or mineral horizons without other humus horizons (example: Crusto Redoxitidal);
- Mull: presence of anecic or endogeic earthworms; example Mull Redoxitidal
- Moder: presence of arthropods or epigeic earthworms, that can be associated to the origin of the gA horizon; example Moder redoxitidal

Figure 4. Schematizing the classification of Terrestrial (A), and Semiterrestrial Histic (B) or Aqueous (C) humus systems. Five morpho-functional systems are proposed for Terrestrial and Histic Semiterrestrial, and two of them for Aqueous Semiterrestrial.

Saprimoor: within the control section (40 cm below the surface), zoHS dominant (nozHS possible but thinner than zoHS), HF or HM never present within the first 40 cm; humus forms of moist base-rich mineral soils or eutrophic organic soils in mostly drained brook valley systems or fens and floodplains;

Amphimoor: within the control section (40 cm below the surface), presence of both zoHS and HM or HF, zoHS dominant, nozHS absent; humus forms of moderately moist base-poor soils in brook valley systems, or partly base-rich soils in half-drained fens;

Mesimoor: within the control section (40 cm below the surface), HF possible but never dominant, HM or nozHS present and thicker than other horizons; organic-matter degradation more active/efficient than in Fibrimoor; humus forms of wet, moderately base-poor organic soils in brook valley systems, or base-enriched soils of drained, previously base-poor fens or bogs;

Fibrimoor: within the control section (40 cm below the surface), presence of a thick HF horizon, HM possible but never thicker than HF, degradation of organic matter slow or inhibited; wet, very base-poor soils in brook valley systems and bogs, rain-fed moors, bogs, isolated parts of fens and brook valleys, base-poor, rain-fed soils. For details on the classification and in-depth information, consult the Supplementary Materials 2 (articles 9, 10 and 11).

Aqueous semiterrestrial humipedons are still under investigation [65]. They are distinguished from the Histic semiterrestrials by the more direct dependence on the sea (salt water and above all regular periodic dynamics of the tide). The diagnostic horizons are organic gO and organo-mineral anaA (anaerobic A) and gA (g = with hydromorphic features). In this particular medium, humus systems that form below the highest tide level and systems that develop above this level show different diagnostic horizons (Figure 4C). For the modality of interaction with plants, the former are more similar to Histic semiterrestrial systems, while the latter are more similar to Terrestrial ones. For details on the classification and in-depth information, consult the Supplementary Materials 2 (article 12).

Terrestrial (A):

- one Mull system without OH horizon, which corresponds to a rapid disappearance of litter from the topsoil;
- four systems with OH (or with organic horizons not or little-attacked by pedofauna), which corresponds to a slow process of litter biodegradation:
 - o two influenced by calcareous (or basic) parent material systems: (a) A horizon dominates in thickness (Amphi); (b) OH horizon dominates (Tangel);
 - o two influenced by siliceous parent material systems: (a) presence of biological interchange between organic and mineral horizons (Moder); (b) no interchange, no or very few pedofauna (Mor).

Semiterrestrial Histic (B):

- three long-time submerged systems (Saprimoor, Mesimoor, and Fibrimoor), with progressive submerged duration and characteristic dominant horizons;
- one disrupted system, with horizons showing a varying dynamic of submersion in time and duration, without a dominance of functioning revealed by a specific horizon (Amphimoor);
- one rather organomineral Anmoor system, in areas with long periods of flood or dryness (6 months), earthworms arriving when the soil becomes aerated.

Semiterrestrial Aqueous (C):

- one Tidal system that develops between the high and low tide levels. This system contains two humus forms which differ in the length of the submersion period. The “kinship” of the Tidal system with the Terrestrial systems can be highlighted by using suitable prefixes;
- one always-submerged Subtidal system lying under the lowest tide level.

Tested in various environments, this new key appears to work quite well. Examples of application of the classification are presented in Supplementary Materials 3. For the precise

distinction of Terrestrial (non-submerged land) from other humipedons (submerged, young soils, anthropic systems), we suggest the reader to refer to dedicated articles [31,56,66]. Here, we present a freely downloadable iOS and Android application that allows an investigator to bring information connected to Terrestrial and Semiterrestrial Histic humus systems into the field, and to obtain some clues about common Para systems.

5. TerrHum: Humusica in Your Phones and Tablets

The TerrHum name assembles the abbreviated words Terra (planet Earth in Italian) and Humipedon (organic and organomineral humus horizons). With this application, a user can classify the Terrestrial and Histic semiterrestrial humipedons of our planet. It also contains some information on the diagnostic horizons of Para systems, such as the Bryo, Rhizo and Ligno, and on horizons disrupted by wild mammals. The application is built on the indications on the diagnostic horizons reported and illustrated in articles 4, 5, 6, 9, 10, 11, and 13.

The App is freely available on the iOS (App Store) and Android (Google Play) platforms in English, French, and Italian. TerrHum makes use of many figures that are stored in a cloud and downloaded on cellphones the first time the users recall them. Once all figures (about 140) have been opened, devices do not need to be connected to run the application.

Instead of describing the App, we show some figures that illustrate how it works (Figures 5–7).

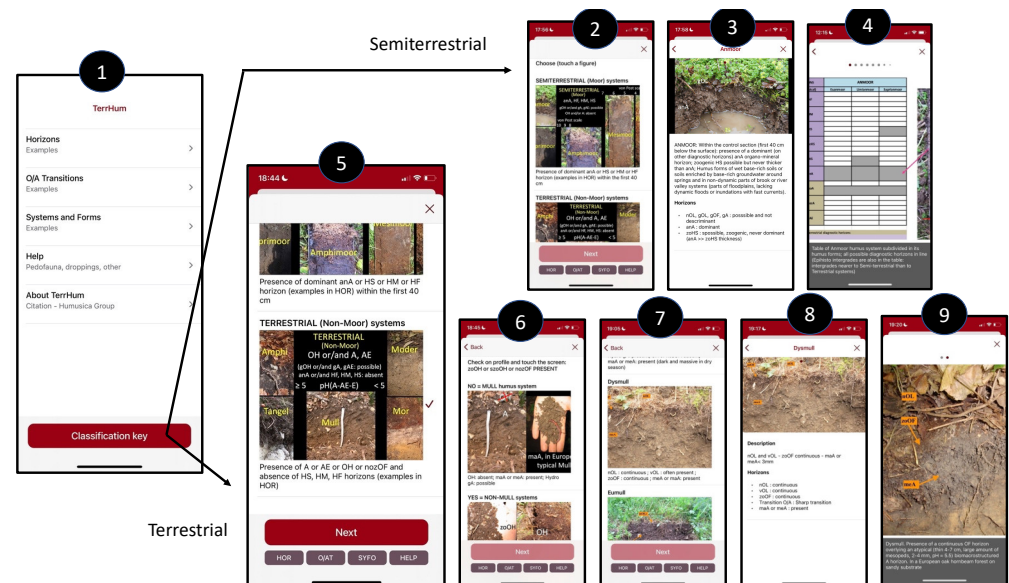


Figure 5. TerrHum is the result of a collective work and allows us to classify Terrestrial and Histic systems and forms. Indications are provided to also consider the Hydro transitions between Terrestrial and Histic, and also the complexifications of Terrestrial systems with Bryo, Ligno, and Rhizo systems. (1) Starting screen, iOS version (similar to the Android one). By clicking on the red button ‘Classification key’, the screen on the right opens; observing the profile to be classified, the user must choose between Semiterrestrial (2) and Terrestrial systems (5). To achieve this, they must search for the diagnostic horizons indicated on the screen. For example, to belong to the Semiterrestrial systems (2), a profile must show at least one of the following horizons: anA, HF, HM, HS; to belong to the Terrestrial systems (5), the profile must show OH, A, or AE horizons. If the user is a beginner, they can see photographic examples by tapping at the bottom of the screen (the four small brown rectangles at the bottom of screens 2, 5, 6, 7): HOR = diagnostic horizons, O/A T = O/A transitions; SYFO = systems and forms; HELP = tables, diagrams, other. These same commands correspond to the ones of the starting screen (1). Semiterrestrial example: By touching the screen at the “Semiterrestrial” level (2); ‘Next’ appears in red, which allows one to move forward and scroll among examples of th-

ese humus systems; for example, by choosing ‘Anmoor’ between them, one can display some photographs of these system profiles (3). By touching the photo, one can zoom in by spreading one’s fingers on the screen. One can view more Anmoor examples, bringing the photo to the smallest size and sliding it to the left. Tapping the photo again brings up a legend. A table (4) with the details of the humus forms of this system can be viewed by pressing “systems and forms” on the screen (1), or the equivalent command “SYFO” at the bottom of other screens (2, 5, 6, 7). As with each image, the table can be enlarged by spreading the fingers on the screen. Terrestrial example: Terrestrial horizons are present on the real profile, the operator taps the Terrestrial figure (5); ‘Next’ appears in red, which allows one to move forward (6). Now the operator has to choose between Mull or non-Mull systems. If there is an absence of OH horizon in the field profile, then the NO = MULL humus system figure should be selected, followed by ‘Next’, to obtain examples of Mull forms (7). Then, it always works in the same way: by touching the screen at the level of the chosen figures, examples and legends appear that can be enlarged (8, 9). If in doubt, one can ask for information by clicking on the commands on the home screen (1) or at the bottom (small brow rectangles) of the other screens (2, 5, 6, 7).

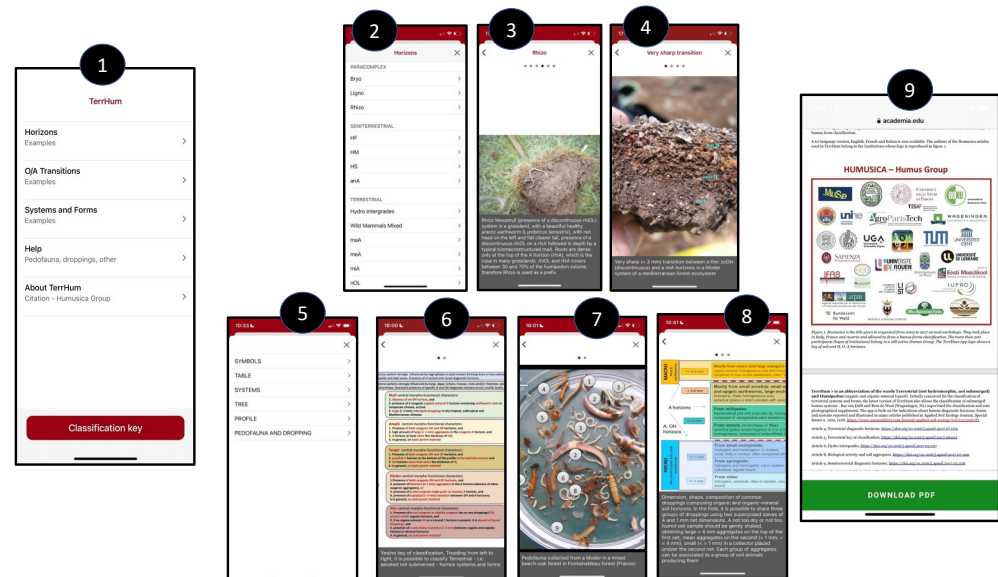


Figure 6. Main screen commands (1): ‘horizons’, ‘O/A transitions’, ‘systems and forms’, ‘help’ and ‘about TerrHum’. ‘Horizon’ command opens screen (2). To list available horizons, just touch a horizon code on the screen and scroll for examples of this horizon. The user selected ‘Rhizo’ (3); the dots above the figure indicate the number of possible views, and the 4th view corresponds to that of a Mesomull A horizon. A thin Rhizo system occupies the top. By spreading one’s fingers on the figure, one can zoom in. Touching the figure displays a legend. To go back, just touch the cross at the top right. ‘O/A Transition’ button allows one to see examples of gradual, sharp, and very sharp transitions between O and A horizons. The one enlarged on the screen (4) is a very sharp transition. ‘Systems and forms’ command is a shortcut for experts. It gives direct access to all the Semiterrestrial humus systems (to have the details of the Semiterrestrial humus forms, it is necessary to activate the ‘Help’ command and view the corresponding tables) and to all the Terrestrial humus forms, in alphabetical order. Just touch the name of a system or a form of humus to obtain examples of them. ‘Help’ button leads to a list of new commands (5): SYMBOLS = a list of symbols to be used in the field for the description of the diagnostic horizons (they were used in the field a few years ago; today we prefer to take a photo and write on it; however, sometimes batteries run out . . .); TABLE = humus systems classification tables and schemes; SYSTEMS = humus forms classification tables; TREE: dichotomous classification schemes (6); PROFILE = graphs on the soil structure in horizons; PEDOFAUNA AND DROPPING: photographs of animals (7) and droppings photographs and classification keys (8). ‘About TerrHum’ leads to a web page with information on the Humus Group and on the articles from which the information presented with the app is taken. Researchers

from all the Institutes cited in the figure (9) were called to contribute. Once at a congress, someone objected that it is too complicated to classify humipedons. The answer was that the functioning of natural ecosystems is very interesting but complex.

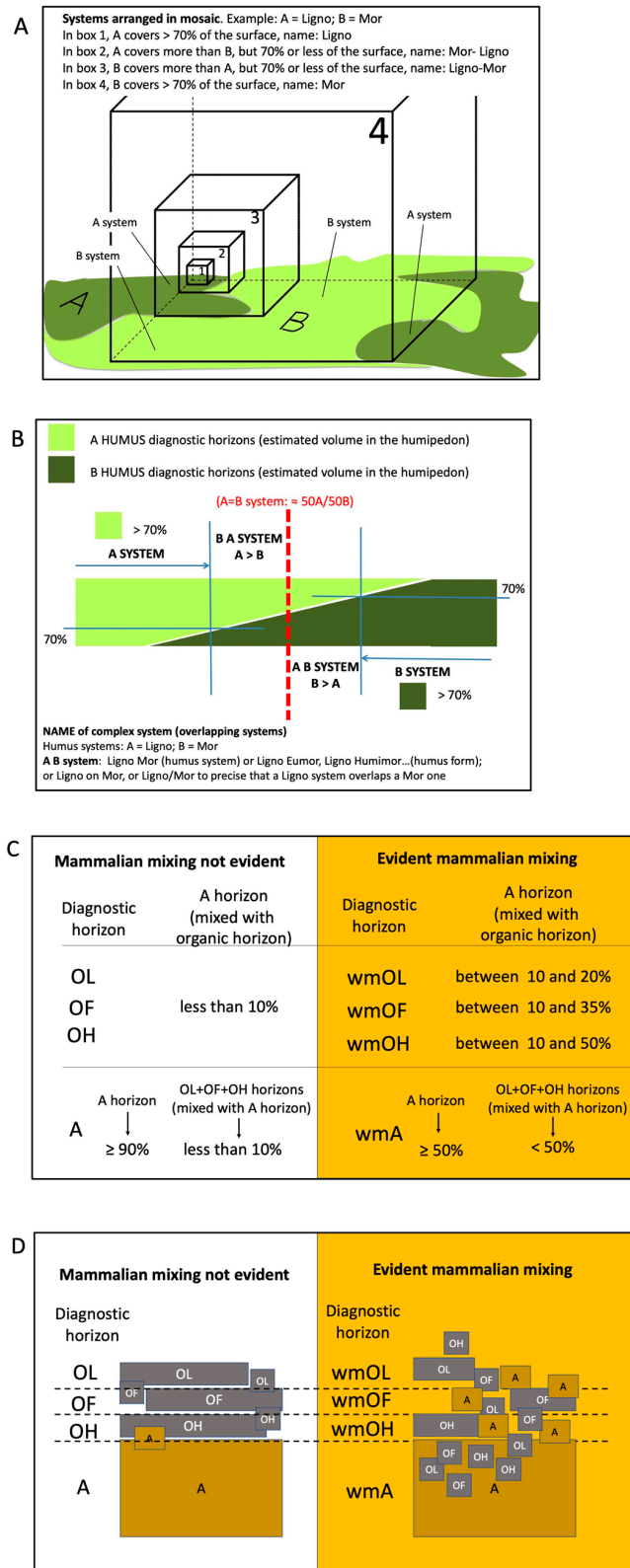


Figure 7. To simplify complexity: humus systems arranged in mosaic (A) or overlapping (B); diagnostic horizons broken down by wild mammals, definition (C) and schematic drawing (D). Generally, hum-

us systems juxtapose like pieces of a puzzle (A). To perceive this reality, it is necessary to investigate the environment at different scales and recognize the elementary humus systems. The interpretation of the landscape that follows depends on the observation scale. The figure shows an example of two humus systems, Ligno (dark green = a decaying stump) and Moder (light green = area without dead wood). In the smaller cube, there is only the Ligno system, in all the other larger cubes there are two systems. The name assigned to the system found in the studied environment depends on the dominance of one system over the other in the cube that contains that environment. Overlapping humus systems (B). This happens when studying series of soils along a large time gradient. In general, new systems arise under older systems. The genesis is recognized thanks to the presence of diagnostic horizons typical of different systems. The name that can be assigned to the humipedon analyzed depends on the thickness in the horizon profile typical of each system. TerrHum path: Main screen > Horizons > Ligno > Second (A) and third (B) pictures. Mammals, such as mice, moles, wolves, foxes, deer, wild boars, etc., can break down the horizons of a humipedon. These are based on the mixture of organic horizons with the organomineral A horizon (C,D). It is simply tolerated that in the event of obvious and localized turmoil caused by these animals, an organic horizon may contain more horizon A than usual, and that an A horizon may contain more organic material than usual. TerrHum path: Main screen > Horizons > Wild Mammals Mixed > First (C) and second (D) pictures.

6. Conclusions

TerrHum enables a standardized morpho-functional classification of the Humipedon (topsoil). The full citation reference for this application is as follows:

Humusica Group, 2022. TerrHum application 2022. From: Humusica Applied Soil Ecology Special issues vol. 122a and 122b, <https://www.journals.elsevier.com/applied-soil-ecology/special-issues> (accessed on 27 June 2022). Classification updated in December 2021. Android version (2022): Bronner T., Zanella A., Pousse N., TerrHum, Google Play, Education; original iOS application (2018, updated 2022): Zanella G., Zanella A., TerrHum, App Store, Education. Translated in French and Italian by: Tatti D., Ponge J.-F., Le Bayon R.-C., Chersich S., Stanchi S., Carollo L., Zanella A.

Advice for beginners:

- (1) Humipedon classification cannot escape a part of subjectivity. Direct classification experience is an important component of diagnostic ability. The novice investigator should call on the knowledge of an expert, even if the key horizons are few: it is precisely necessary to know these fundamental landmarks with certainty. It only takes one outing to catch a glimpse and touch these horizons. In a terrestrial environment (= out of water), it is necessary to see the OH organic horizon and the maA and miA organo-mineral horizons; in a semiterrestrial environment (= more or less in water), the HF and HS organic horizons, and the anA and anaA organomineral horizons are crucial; to define the humipedons of the first stages of soil development, it is necessary to recognize at least the Crusto, Bryo, and Rhizo systems.
- (2) In the field, humus systems and forms are distributed horizontally and vertically as in a mosaic (Figure 7A,B) [18]. It is therefore normal to be “lost” at the beginning. Before embarking on a localized and precise diagnosis, it is necessary to survey the ground, and determine the eventual main lines of the mosaic coverage. It is relatively easy to separate the Para systems from the others, for example, a Bryo systems on outcropping rocks. If in a phytocoenosis the vegetation is fairly homogeneous, the investigator will often be in a single humus system composed of a hidden mosaic of humus forms. In the forest, this often depends on the appearance of and increase in the OH horizon (localized increase in the volume of litter, microconcavity, change of coverage or exposure), or conversely on the decrease until the disappearance of this same OH horizon.
- (3) The questions which the investigator is called upon to answer are the following: (1) Is there an OH horizon? (2) How is the transition between the organic and the mineral parts of the humipedon? (3) Is the parent material (rock that directly or indirectly influences the formation of the diagnostic horizons of the humipedon) acidic or basic?

- (4) What is the water dynamics in the profile and how long does a given horizon remain submerged? (5) Am I in a tidal zone? (6) What are the main living actors of litter biodegradation and why? (7) What is the importance of the impact of human action on the system?
- (4) “Well-defined and easily recognizable” diagnostic horizons are associated to “central, typical” humus forms or systems. Cases of atypical horizons (but assignable to a diagnostic horizon defined by estimating the percentages of its components), or humipedons that mark the passage from one system to another, are common in geomorphologically and floristically varied environments. There is usually a dominant humus form, and others are in ecological corollary. Once the investigator understands how to work, it becomes an interesting game to interpret the dynamics of the forest soil.

To define all the variations of the “disturbances” that humipedon horizons may encounter is useless. We contented ourselves with describing those of wild mammals reported in Figure 7C,D), and which ultimately remain connected to the original natural horizons.

TerrHum: a way to standardize classification at the planet level.

Young Italian climbers investigated the humus systems that generate on the rocky mountain ledges, trying to understand the process of soil formation [67–70]. Other authors linked the humus systems to soil pollution [14,49], others to soil nutrition [71], biodiversity [72,73], or organic carbon content [74]. If nature and soil lovers began to classify humipedons in a coordinated and standardized way, it would be possible to map the morpho-functional state of the world’s biotic soil. Management that respects the soil biodiversity would be much easier. Humans could even seriously plan far-sighted land use and mitigate global warming (Supplementary Materials 4).

Supplementary Materials: The following supporting information can be downloaded at: 1: Special Issues published in Applied Soil Ecology, 2018: Humusica 1–Terrestrial Natural Humipedons, <https://www.sciencedirect.com/journal/applied-soil-ecology/vol/122/part/P1> (accessed on 27 June 2022); 2: Humusica 2–Histic, Para, Techno, Agro Humipedons, <http://www.sciencedirect.com/science/journal/09291393/122/part/P2> (accessed on 27 June 2022); 3: Humusica 3–Reviews, Applications, Tools, <https://www.sciencedirect.com/journal/applied-soil-ecology/vol/123> (accessed on 27 June 2022); 4: Video: Humipedon Critical Zone (Conference held on 28–29 September at IUFRO World Day—Digital Forest Science iForum 2021, and then renewed on 12 October 2021 at the Luxembourg Institute of Science & Technology) <https://datacloud.tesaf.unipd.it/index.php/s/qMgtlYj1KeEJ2i7> (accessed on 27 June 2022).

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References

1. Certini, G.; Scalenghe, R.; Amundson, R. A view of extraterrestrial soils. *Eur. J. Soil Sci.* **2009**, *60*, 1078–1092. [[CrossRef](#)]
2. Zanella, A.; Ponge, J.-F.; Gobat, J.-M.; Juilleret, J.; Blouin, M.; Aubert, M.; Chertov, O.; Rubio, J.L. Humusica 1, article 1: Essential bases—Vocabulary. *Appl. Soil Ecol.* **2018**, *122*, 10–21. [[CrossRef](#)]
3. Ponge, J.F. Humus: Dark side of life or intractable ‘aether’? *Pedosphere* **2022**, *32*, 660–664. [[CrossRef](#)]
4. Paul, E.A. The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biol. Biochem.* **2016**, *98*, 109–126. [[CrossRef](#)]
5. Churchland, C.; Grayston, S.J. Specificity of plant-microbe interactions in the tree mycorrhizosphere biome and consequences for soil C cycling. *Front. Microbiol.* **2014**, *5*, 261. [[CrossRef](#)]
6. Tecon, R.; Or, D. Biophysical processes supporting the diversity of microbial life in soil. *FEMS Microbiol. Rev.* **2017**, *41*, 599–623. [[CrossRef](#)]
7. Dwivedi, D.; Riley, W.; Torn, M.; Spycher, N.; Maggi, F.; Tang, J. Mineral properties, microbes, transport, and plant-input profiles control vertical distribution and age of soil carbon stocks. *Soil Biol. Biochem.* **2017**, *107*, 244–259. [[CrossRef](#)]
8. Rumpel, C.; Kögel-Knabner, I. Deep soil organic matter—A key but poorly understood component of terrestrial C cycle. *Plant Soil* **2011**, *338*, 143–158. [[CrossRef](#)]
9. Pombubpa, N.; Pietrasiak, N.; De Ley, P.; Stajich, J.E. Insights into dryland biocrust microbiome: Geography, soil depth and crust type affect biocrust microbial communities and networks in Mojave Desert, USA. *FEMS Microbiol. Ecol.* **2020**, *96*, fiae125. [[CrossRef](#)]
10. Hao, J.; Chai, Y.N.; Lopes, L.D.; Ordóñez, R.A.; Wright, E.E.; Archontoulis, S.; Schachtman, D.P. The Effects of Soil Depth on the Structure of Microbial Communities in Agricultural Soils in Iowa (United States). *Appl. Environ. Microbiol.* **2021**, *87*, e02673–20. [[CrossRef](#)]
11. Frey, R.W. Concepts in the Study of Biogenic Sedimentary Structures. *J. Sediment. Res.* **1973**, *43*, 6–19.
12. Freppaz, M.; Pintaldi, E.; Magnani, A.; Viglietti, D.; Williams, M.W. Topsoil and snow: A continuum system. *Appl. Soil Ecol.* **2018**, *123*, 435–440. [[CrossRef](#)]
13. Berg, B.; McClaugherty, C. *Plant Litter*; Springer International Publishing: Cham, Switzerland, 2020.
14. Korkina, I.; Vorobeichik, E. Humus Index as an indicator of the topsoil response to the impacts of industrial pollution. *Appl. Soil Ecol.* **2018**, *123*, 455–463. [[CrossRef](#)]
15. Kukuļs, I.; Nikodemus, O.; Kasparinskis, R.; Žigūre, Z. Humus forms, carbon stock and properties of soil organic matter in forests formed on dry mineral soils in Latvia. *Est. J. Earth Sci.* **2020**, *69*, 63. [[CrossRef](#)]
16. Büks, F.; van Schaik, N.L.; Kaupenjohann, M. What do we know about how the terrestrial multicellular soil fauna reacts to microplastic? *Soil* **2020**, *6*, 245–267. [[CrossRef](#)]
17. Bani, A.; Pioli, S.; Ventura, M.; Panzacchi, P.; Borruso, L.; Tognetti, R.; Tonon, G.; Brusetti, L. The role of microbial community in the decomposition of leaf litter and deadwood. *Appl. Soil Ecol.* **2018**, *126*, 75–84. [[CrossRef](#)]
18. Zanella, A.; Ponge, J.-F.; Matteodo, M. Humusica 1, article 7: Terrestrial humus systems and forms—Field practice and sampling problems. *Appl. Soil Ecol.* **2018**, *122*, 92–102. [[CrossRef](#)]
19. Lovelock, J.E.; Margulis, L. Atmospheric homeostasis by and for the biosphere: The gaia hypothesis. *Tellus* **1974**, *26*, 2–10. [[CrossRef](#)]
20. Barlow, J.; França, F.; Gardner, T.A.; Hicks, C.; Lennox, G.D.; Berenguer, E.; Castello, L.; Economo, E.P.; Ferreira, J.; Guénard, B.; et al. The future of hyperdiverse tropical ecosystems. *Nature* **2018**, *559*, 517–526. [[CrossRef](#)]
21. Ripple, W.J.; Wolf, C.; Newsome, T.M.; Barnard, P.; Moomaw, W.R. World scientists’ warning of a climate emergency. *Bioscience* **2019**, *70*, 8–12. [[CrossRef](#)]
22. Ali, A.; Chen, H.Y.; You, W.-H.; Yan, E.-R. Multiple abiotic and biotic drivers of aboveground biomass shift with forest stratum. *For. Ecol. Manag.* **2019**, *436*, 1–10. [[CrossRef](#)]
23. Frazão, J.; Goede, R.; Brussaard, L.; Faber, J.H.; Groot, J.; Pulleman, M.M. Earthworm communities in arable fields and restored field margins, as related to management practices and surrounding landscape diversity. *Agric. Ecosyst. Environ.* **2017**, *248*, 1–8. [[CrossRef](#)]
24. Ponge, J.-F. Biodiversité et biomasse de la faune du sol sous climat tempéré. *Comptes Rendus De L’académie D’agriculture De Fr.* **2000**, *86*, 129–135.
25. Blakemore, R.J. Critical Decline of Earthworms from Organic Origins under Intensive, Humic SOM-Depleting Agriculture. *Soil Syst.* **2018**, *2*, 33. [[CrossRef](#)]
26. Fournier, B.; Samaritani, E.; Frey, B.; Seppely, C.V.; Lara, E.; Heger, T.; Mitchell, E.A. Higher spatial than seasonal variation in floodplain soil eukaryotic microbial communities. *Soil Biol. Biochem.* **2020**, *147*, 107842. [[CrossRef](#)]
27. European Commission. *The Factory of Life: Why Soil Biodiversity Is so Important*; Office for Official Publications of the European Union: Luxembourg, 2010; Available online: https://ec.europa.eu/environment/archives/soil/pdf/soil_biodiversity_brochure_en.pdf (accessed on 27 June 2022).

28. Joergensen, R.G.; Wichern, F. Alive and kicking: Why dormant soil microorganisms matter. *Soil Biol. Biochem.* **2018**, *116*, 419–430. [[CrossRef](#)]
29. Eisenhauer, N.; Antunes, P.M.; Bennett, A.E.; Birkhofer, K.; Bissett, A.; Bowker, M.A.; Caruso, T.; Chen, B.; Coleman, D.C.; de Boer, W.; et al. Priorities for research in soil ecology. *Pedobiologia* **2017**, *63*, 1–7. [[CrossRef](#)]
30. Zanella, A.; Ponge, J.-F.; Jabiol, B.; Sartori, G.; Kolb, E.; Gobat, J.-M.; Le Bayon, R.-C.; Aubert, M.; De Waal, R.; Van Delft, B.; et al. Humusica 1, article 4: Terrestrial humus systems and forms—Specific terms and diagnostic horizons. *Appl. Soil Ecol.* **2018**, *122*, 56–74. [[CrossRef](#)]
31. Zanella, A.; De Waal, R.; Van Delft, B.; Ponge, J.-F.; Jabiol, B.; De Nobili, M.; Ferronato, C.; Gobat, J.-M.; Vacca, A. Humusica 2, Article 9: Histic humus systems and forms—Specific terms, diagnostic horizons and overview. *Appl. Soil Ecol.* **2018**, *122*, 148–153. [[CrossRef](#)]
32. Dampney, F.G.; Birkhofer, K.; Nsiah, P.K.; De La Riva, E.G. Soil Properties and Biomass Attributes in a Former Gravel Mine Area after Two Decades of Forest Restoration. *Land* **2020**, *9*, 209. [[CrossRef](#)]
33. Keke, H.; Bo, Z. Leaching is the dominant route for soil organic carbon lateral transport under crop straw addition on sloping croplands. *Plant Soil Environ.* **2018**, *64*, 344–351. [[CrossRef](#)]
34. Moroni, M.T.; Hagemann, U.; Beilman, D.W. Dead Wood is Buried and Preserved in a Labrador Boreal Forest. *Ecosystems* **2010**, *13*, 452–458. [[CrossRef](#)]
35. Sofo, A.; Ricciuti, P.; Fausto, C.; Mininni, A.N.; Crecchio, C.; Scagliola, M.; Malerba, A.D.; Xiloyannis, C.; Dichio, B. The metabolic and genetic diversity of soil bacterial communities depends on the soil management system and C/N dynamics: The case of sustainable and conventional olive groves. *Appl. Soil Ecol.* **2019**, *137*, 21–28. [[CrossRef](#)]
36. Yang, Z.; Wullschleger, S.D.; Liang, L.; Graham, D.E.; Gu, B. Effects of warming on the degradation and production of low-molecular-weight labile organic carbon in an Arctic tundra soil. *Soil Biol. Biochem.* **2016**, *95*, 202–211. [[CrossRef](#)]
37. Chen, S.; Wang, W.; Xu, W.; Wang, Y.; Wan, H.; Chen, D.; Tang, Z.; Tang, X.; Zhou, G.; Xie, Z.; et al. Plant diversity enhances productivity and soil carbon storage. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4027–4032. [[CrossRef](#)]
38. Batjes, N.H.; Batjes, N.H. Technologically achievable soil organic carbon sequestration in world croplands and grasslands. *Land Degrad. Dev.* **2019**, *30*, 25–32. [[CrossRef](#)]
39. Ping, C.L.; Jastrow, J.D.; Jorgenson, M.T.; Michaelson, G.J.; Shur, Y.L. Permafrost soils and carbon cycling. *Soil* **2015**, *1*, 147–171. [[CrossRef](#)]
40. Chiti, T.; Gardin, L.; Perugini, L.; Quarantino, R.; Vaccari, F.P.; Miglietta, F.; Valentini, R. Soil organic carbon stock assessment for the different cropland land uses in Italy. *Biol. Fertil. Soils* **2012**, *48*, 9–17. [[CrossRef](#)]
41. Zhao, Z.; Dong, S.; Jiang, X.; Zhao, J.; Liu, S.; Yang, M.; Han, Y.; Sha, W. Are land use and short time climate change effective on soil carbon compositions and their relationships with soil properties in alpine grassland ecosystems on Qinghai-Tibetan Plateau? *Sci. Total Environ.* **2018**, *625*, 539–546. [[CrossRef](#)]
42. Bojko, O.; Kabala, C. Organic carbon pools in mountain soils—Sources of variability and predicted changes in relation to climate and land use changes. *Catena* **2017**, *149*, 209–220. [[CrossRef](#)]
43. Zanella, A.; Katzensteiner, K.; Ponge, J.; Jabiol, B.; Sartori, G.; Kolb, E.; Le Bayon, R.; Aubert, M.; Ascher-Jenull, J.; Englisch, M.; et al. TerrHum: An iOS Application for Classifying Terrestrial Humipedons and Some Considerations about Soil Classification. *Soil Sci. Soc. Am. J.* **2019**, *83*, S42–S48. [[CrossRef](#)]
44. Zanella, A.; Ponge, J.-F.; Jabiol, B.; Sartori, G.; Kolb, E.; Le Bayon, R.; Gobat, J.-M.; Aubert, M.; De Waal, R.; Van Delft, B.; et al. Humusica 1, article 5: Terrestrial humus systems and forms—Keys of classification of humus systems and forms. *Appl. Soil Ecol.* **2018**, *122*, 75–86. [[CrossRef](#)]
45. Zanella, A.; Ponge, J.-F.; Briones, M.J. Humusica 1, article 8: Terrestrial humus systems and forms—Biological activity and soil aggregates, space-time dynamics. *Appl. Soil Ecol.* **2018**, *122*, 103–137. [[CrossRef](#)]
46. Cesário, F.V.; Balieiro, F.D.C.; Mazzei, L. Humipedon dynamics in lowland Amazonian forests: Are there Amphihumus forms even in tropical rain forests? *Geoderma* **2022**, *418*, 115849. [[CrossRef](#)]
47. Waez-Mousavi, S. Humus systems in the Caspian Hyrcanian temperate forests. *Appl. Soil Ecol.* **2018**, *123*, 664–667. [[CrossRef](#)]
48. Jafarisarabi, H. *Effects of Tree Species Diversity on Leaf Litter Decomposition and Recognizing the Humus Forms in the Central Zagros Forests, Iran*; Lorestan University: Khorramabad, Iran, 2019.
49. Colombini, G.; Auclerc, A.; Watteau, F. Techno-moder: A proposal for a new morpho-functional humus form developing on Technosols revealed by micromorphology. *Geoderma* **2020**, *375*, 114526. [[CrossRef](#)]
50. Zanella, A.; Ponge, J.-F.; Topoliantz, S.; Bernier, N.; Juilleret, J. Humusica 2, Article 15: Agro humus systems and forms. *Appl. Soil Ecol.* **2018**, *122*, 204–219. [[CrossRef](#)]
51. Burrow, C.; Pernin, C.; Lepretre, A. Influence of connectivity & topsoil management practices of a constructed technosol on pedofauna colonization: A field study. *Appl. Soil Ecol.* **2018**, *123*, 416–419. [[CrossRef](#)]
52. Zanella, A.; Ponge, J.-F.; Juilleret, J.; de Waal, R.; Le Bayon, R.-C.; Vacca, A.; Andreetta, A. Humusica 1, Article 6: Terrestrial humus systems and forms—Hydro intergrades. *Appl. Soil Ecol.* **2018**, *122*, 87–91. [[CrossRef](#)]
53. Zanella, A.; Ponge, J.-F.; De Waal, R.; Van Delft, B.; De Nobili, M.; Ferronato, C.; Antisari, L.V.; Vianello, G.; Jabiol, B. Humusica 2, article 11: Histic humus systems and forms—Epihisto intergrades and dynamics. *Appl. Soil Ecol.* **2018**, *122*, 162–169. [[CrossRef](#)]
54. Zanella, A.; Ponge, J.-F.; de Waal, R.; Ferronato, C.; De Nobili, M.; Juilleret, J. Humusica 1, article 3: Essential bases—Quick look at the classification. *Appl. Soil Ecol.* **2018**, *122*, 42–55. [[CrossRef](#)]

55. Zanella, A.; De Waal, R.; Van Delft, B.; Ponge, J.-F.; Ferronato, C.; De Nobili, M.; Le Bayon, R.-C.; Andreetta, A.; Kölli, R. Humusica 2, article 10: Histic humus systems and forms—Key of classification. *Appl. Soil Ecol.* **2018**, *122*, 154–161. [[CrossRef](#)]
56. Zanella, A.; Ponge, J.-F.; Fritz, I.; Pietrasiak, N.; Matteodo, M.; Nadporozhskaya, M.; Juilleret, J.; Tatti, D.; Le Bayon, C.; Rothschild, L.; et al. Humusica 2, article 13: Para humus systems and forms. *Appl. Soil Ecol.* **2018**, *122*, 181–199. [[CrossRef](#)]
57. Markiewicz, M.; Hulisz, P.; Charzyński, P.; Piernik, A. Characteristics of soil organic matter of edifisols—An example of techno humus system. *Appl. Soil Ecol.* **2018**, *123*, 509–512. [[CrossRef](#)]
58. Zanella, A.; Ascher-Jenull, J. Editorial. *Appl. Soil Ecol.* **2018**, *122*, 1–9. [[CrossRef](#)]
59. Zanella, A.; Ascher-Jenull, J. Editorial. *Appl. Soil Ecol.* **2018**, *122*, 139–147. [[CrossRef](#)]
60. Zanella, A.; Ascher-Jenull, J. Editorial. *Appl. Soil Ecol.* **2018**, *123*, 297–298. [[CrossRef](#)]
61. Baritz, R. *Humus Forms in Forests of the Northern German Lowlands*. 2003. Available online: http://www.schweizerbart.de/publications/detail/isbn/9783510959082/Sonderheft%5C%5C_SF%5C%5C_3%5C%5C_Geol%5C%5C_Jahr%5C%5C_Reihe%5C%5C_F (accessed on 27 June 2022).
62. Chertov, O.; Nadporozhskaya, M. Development and application of humus form concept for soil classification, mapping and dynamic modelling in Russia. *Appl. Soil Ecol.* **2018**, *123*, 420–423. [[CrossRef](#)]
63. Bernier, N.; Ponge, J.-F. Humus form dynamics during the sylvogenetic cycle in a mountain spruce forest. *Soil Biol. Biochem.* **1994**, *26*, 183–220. [[CrossRef](#)]
64. Hugelius, G.; Bockheim, J.G.; Camill, P.; Elberling, B.; Grosse, G.; Harden, J.W.; Johnson, K.; Jorgenson, T.; Koven, C.D.; Kuhry, P.; et al. A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region. *Earth Syst. Sci. Data* **2013**, *5*, 393–402. [[CrossRef](#)]
65. Zanella, A.; Ferronato, C.; De Nobili, M.; Vianello, G.; Antisari, L.V.; Ponge, J.-F.; De Waal, R.; Van Delft, B.; Vacca, A. Humusica 2, article 12: Aqueous humipedons—Tidal and subtidal humus systems and forms. *Appl. Soil Ecol.* **2018**, *122*, 170–180. [[CrossRef](#)]
66. Zanella, A.; Schad, P.; Galbraith, J.; Ponge, J.-F. Humusica 2, Article 14: Anthropogenic soils and humus systems, comparing classification systems. *Appl. Soil Ecol.* **2018**, *122*, 200–203. [[CrossRef](#)]
67. Carollo, S. Studio Preliminare di Suoli di Cengia; Esempi di Forme di Humus su Roccia Madre Basica [Preliminary Study of Ledge Soils, Examples of Humus Forms on Basic Parent Material]. Ph.D. Thesis, Università degli Studi di Padova, Padova, Italy, 2020.
68. Brandolese, A. Studio Preliminare di Suoli di Cengia; Esempi di Forme di Humus su Roccia Madre Acida [Preliminary Study of Ledge Soils, Examples of Humus Forms on Acidic Parent Material]. Ph.D. Thesis, Università degli Studi di Padova, Padova, Italy, 2020.
69. Bertelle, M. Suoli Alpini di Cengia: Indagine Preliminare Sui Fattori Che ne Determinano la Formazione (Trentino e Veneto, Italia) [Alpine Ledge Soils: Preliminary Investigation of the Factors that Determine its Formation (Trentino and Veneto, Italy)]. Ph.D. Thesis, Università degli Studi di Padova, Padova, Italy, 2021.
70. Zaminato, N. Gli Indici di Biodiversità Come Strumento Per Comprendere gli Effetti dei Cambiamenti Climatici: Un Caso di Studio nel Parco Naturale Adamello Brenta [Biodiversity Indices as a Tool for Understanding the Effects of Climate Change: A Case Study in the Ada]. Ph.D. Thesis, Università degli Studi di Padova, Padova, Italy, 2019.
71. Aubert, M.; Trap, J.; Chauvat, M.; Hedde, M.; Bureau, F. Forest humus forms as a playground for studying aboveground-belowground relationships: Part 2, a case study along the dynamics of a broadleaved plain forest ecosystem. *Appl. Soil Ecol.* **2018**, *123*, 398–408. [[CrossRef](#)]
72. Hellwig, N.; Tatti, D.; Sartori, G.; Anschlag, K.; Graefe, U.; Egli, M.; Gobat, J.-M.; Broll, G. Modeling Spatial Patterns of Humus Forms in Montane and Subalpine Forests: Implications of Local Variability for Upscaling. *Sustainability* **2018**, *11*, 48. [[CrossRef](#)]
73. Hellwig, N.; Gómez-Brandón, M.; Ascher-Jenull, J.; Bardelli, T.; Anschlag, K.; Fornasier, F.; Pietramellara, G.; Insam, H.; Broll, G. Humus Forms and Soil Microbiological Parameters in a Mountain Forest: Upscaling to the Slope Scale. *Soil Syst.* **2018**, *2*, 12. [[CrossRef](#)]
74. Bonifacio, E.; Falsone, G.; Petrillo, M. Humus forms, organic matter stocks and carbon fractions in forest soils of northwestern Italy. *Biol. Fertil. Soils* **2011**, *47*, 555–566. [[CrossRef](#)]