

Review

Humusica 2, article 13: Para humus systems and forms[☆]

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A B S T R A C T

Planet Earth is covered by very common Terrestrial (not submersed), Histic (peats) and Aqueous (tidal) humipedons. Beside these typical topsoils there are other more discrete humipedons, generated by the interaction of mineral matter with microorganisms, fungi and small plants (algae, lichens and mosses). In some cases roots and their symbionts can be a driving force of litter biotransformation, in other cases a large amount of decaying wood accommodates particular organisms which interfere and change the normal process of litter decomposition. Particular microorganisms inhabit submerged sediments or extreme environments and can generate specialised humipedons with grey-black or even astonishingly flashing colours. We describe all these common but still unknown humipedons, defining diagnostic horizons and proposing a first morpho-functional classification, which still has to be improved. At the end of the article, the hypothesis of evolving and interconnected Cosmo, Aero, Hydro, Humi, Co, Litho and Geopedons (related to the microbiota) is formulated as a speculative curiosity.

1. Introduction to Para humus systems

Beside Terrestrial and Histic humus systems and intergrades, it is possible to notice other humus systems in natural or artificial environments. Their ecological determinants are different from those of the main systems and are strongly related to specific habitats and/or plant covers. Labelled “Para” (from the ancient Greek παρά, aside), these novel humus systems and their main characters are reported in Table 1. We know that we are not in the mainstream of soil science, by extending the concept of soil (and humus by the same way) to environments such as hot springs, sea floors and even air columns (see Sections 7 and 8) and we are conscious that some readers will be surprised, if not shocked by such a venturesome position. Shorthill et al.

(1976) wrote the word “soil” between brackets in their first publication on the soil of Mars. Mars-like soils are now described in deserts and other inhospitable environments of the Earth (Navarro-González et al., 2003). Mickol and Kral (2016) tested the survivability of four methanogen species under low pressure conditions approaching average Martian surface pressure in an aqueous environment and each of the species survived exposure of varying length (3 days–21 days) at pressure down to 6 mbar. We urge people to read this article with naive eyes, being thus prone to observe the universe in a versatile manner. We intend to classify things still poorly known and far from being characterized on scientific grounds because putting names on things may help to better understand them: if a moss cushion is not only a plant but also a microcosm inhabited by a myriad of bacteria, fungi and animals

[☆] Black Rebel Motorcycle Club-Weight of the World <https://www.youtube.com/watch?v=ueIdcyZ2m6o&index=1&list=RDueIdcyZ2m6o><https://www.youtube.com/watch?v=ueIdcyZ2m6o&index=1&list=RDueIdcyZ2m6o>

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<http://dx.doi.org/10.1016/j.apsoil.2017.09.043>

Received 10 February 2017; Received in revised form 29 August 2017; Accepted 28 September 2017

Available online 07 November 2017

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Table 1
Para humus systems: description, diagnostic characters and dynamic considerations.

Humus system	Description	Diagnostic characters	Dynamic considerations
CRUSTO	Complex mosaic of cyanobacteria, algae, lichens, bryophytes, microfungi, and heterotrophic bacteria. Filamentous microorganisms cover the outer surface of rock/soil, agglomerating organic residues, mineral particles and microbial necromass. On rock, airborne sediments may be trapped and incorporated in the rock crust. Crusto organisms form a matrix that stabilizes and protects soil surfaces from erosion. Additional explanation: basics and principles are the same for rock surfaces and stone/sand soil surfaces. The difference is more in the available energy sources and the dominant physiological group: phototrophic on rock, heterotrophic on soil. Cyanobacteria, green algae and fungi (including lichens) can be in the form of filaments, which are unnecessary if the surface is not exposed to erosion. On horizontal flat surfaces or finely structured surfaces (most soils) or in micro-cavities, etc., microbes can adhere and be retained on the substrate without building filaments.	Soil and organisms form an inseparable three-dimensional living aggregate. Crusto break out like inelastic layers. The presence of underlying mineral soil material is a discriminant factor and distinguishes biological rock crusts (rather micro crusts), established on rocks, from biological soil crusts (macro crusts, established on organic, mineral-organic or mineral soil material/horizons. Rock crusts may evolve into soil crusts according to soil development.	Pioneer ecosystems of arid and polar deserts, rocky outcrops and buildings; harsh climate conditions, permanent or periodic lack of water, nutrients or soil; phases of incipient pedogenesis.
BRYO	Bryophytes or arbuscular lichens or small stoncrop plants totally covering the soil and forming a stratified carpet or cushion with living (green) parts overgrowing a layer of dead stems and leaves.	Humus systems where more than 70% of the volume (estimated in the field by the naked eyes) of the cumulated OL, OF and OA horizons is made of mosses or other minute plants.	Pioneer ecosystems succeeding to biological crusts in cold, arid or wet environments (peat formation); also in mosaic on boulders or under forest trees on eroded soil.
RHIZO	Organic and/or mineral-organic diagnostic horizons almost entirely made of root material (living and dead).	Humus systems where more than 70% of the volume (estimated in the field by the naked eyes) of the cumulated humus profile is made of roots or other subterranean plant parts.	Heathland and grassland ecosystems built by grasses, sedges, ferns, ericaceous and other suffrutescent or scrub vegetation, with very active vegetative within-soil development.
LIGNO	Organic diagnostic horizons almost entirely made of wood decayed by fungi and tunnelled by invertebrates. Additional explanation: degradation residues can be either sugars and organic acids (in case of white rot fungi) or lignin (in case of brown rot fungi) providing widely different substrates for further humus formation.	Humus systems where more than 70% of the volume (estimated in the field by the naked eye) of cumulated organic horizons is made of more or less decomposed wood.	Specific ecosystems exploiting the energy released during wood decomposition. The process of decomposition takes place on the ground or on stems and branches of standing dead trees. Very common in old-growth forests, particularly in unmanaged temperate and tropical forests.
ANAERO	Humus systems under prominent influence of bacteria and archaea in permanently flooded sediments. While the surface of the water column may be still aerobic, deeper layers are strictly anaerobic. Additional explanation: sinking residues are degraded rapidly (shortage of oxygen but not of water and nutrients) and form (together with insoluble minerals) the sediment layer. In Lake Baikal, the sediment layer may be up to 11 km in depth. Each millimetre of this sediment underwent a short period of aerobic degradation followed by a long period of slow anaerobic decomposition. That's the reason why more than 95% of all biomass on Earth is bound to marine and lake sediments. Extremophiles (in common sense) should all be classified under the Archaeo system. Anaero embrace all submerged humus system not fitting with Histic or Aqueous systems.	River-, lake- marsh- and sea-beds, sewages, submerged anoxic habitats, in photic zone. Parts of seas, oceans, lakes, other water parts inhabited by planktonic systems.	As a concept, only the heterotrophic part of a plankton system could be assimilated to a "humus system". A column of plankton may raise hundreds of meters and continuously move and change in dimension and form. Even if phytoplankton deposited in sediments is fully recognized as belonging to Anaero humus systems, the idea that floating phytoplankton belongs to the Anaero humipedon still is not shared by the authors of this table.
ARCHAEO	Humus systems under prominent influence of archaea, anaerobic bacteria and cyanobacteria; biofilms of fungi, algae, sometimes associated with heterotrophic bacteria.	Extremophile habitats without plants, in aphotic zone; highly saline, acidic, or alkaline water; hot springs; wet surfaces of any type, supporting organic matter or other sources of energy.	Phototroph, lithotroph and organotroph microorganisms living in extremophile emerged or submerged habitats. Pioneer organic humus systems starting the development of soil. In dry sunny habitats they may evolve into Crusto, in moister shady habitats into Bryo systems.

which derive their food from its living and dead parts, and built minute horizons beneath it, why not to call and classify this micro-humus system as Bryo humus system? And if this microcosm is influenced by the surrounding environment, stemming in the existence of several variants, why not to add qualifiers to better identify such a Bryo humus system?

A large (perhaps the largest?) number of humus systems are invisible to the naked eye. Virtually on every surface of our planet one can find inconspicuous microorganisms living in and transforming invisible layers of organic matter. Although undetectable to the naked eye, these micro humus systems can initiate pedogenesis everywhere on

planet Earth, today, e.g. biofilms, as in the fossil record, e.g. stromatolites (Krumbein et al., 2003). Nonetheless pedogenetic processes taking place at this microscale are not well understood. Even if we do not treat "invisible humus systems" in this manual, they are very important and we need to fill this gap in a near future.

A dynamic relationship between Para systems is observable in the field. For example, a long-term sequence of terrestrial pedogenesis may start with Crusto systems, continues with Bryo, then Rhizo and finishes in main Terrestrial units. In Histic environments, progressing from river-, lake-, marsh- or sea-beds toward the water edge, Anaero gradually evolve to main Histic units. The same can be observed in

extremophile habitats where Archaeo are progressively replaced by Anaero or Histic units. A mosaic or a gradient of humus systems is very common in large and ecologically variable landscapes. Intergrades between Terrestrial, Histic and Para units are possible and at the end of this article we will give some information for describing humus system mosaics with the help of prefixes.

We know that the knowledge on Para forms and systems is still incipient, and the present article, written by scientists having included them in their own research frame, does not cover the whole range of Para humus systems. Among others, we did not take into account suspended soils, a key biological component of rain forest canopies (Lindo and Winchester, 2006), and faecal deposits by birds and bats (guano), an invaluable source of life in by elsewhere inhospitable environments (Gagnon et al., 2013). We encourage people to describe them, testing the conceptual and practical tools we make at their disposal in this field manual.

2. Field assessment of Para humus systems

Specific diagnostic horizons allow the identification of each Para humus system. As listed below, Para systems are presented together with their associated prefixes. The adopted classification principle is to use the name alone (Crusto, Bryo, Rhizo, Ligno, Anaero, Archaeo) when the absence of more evolved horizons does not allow assigning them to the main classical Terrestrial or Histic humus systems or forms. Unless arrested in their development by erosion or climatic constraints, they correspond to initial dynamic phases of vegetation-soil development (Crocker and Major, 1955) and can be identified when peculiar plant material occupies more than 70% (decidedly more than 50%, nearly 2/3) of the volume of humus diagnostic horizons. The case of Rhizo systems associated with alpine grasslands does not necessarily represent an initial dynamic phase but a stable stage of soil-vegetation imposed by climatic limits. Nevertheless, the upward movement of upper treelines, observed on many mountains as a consequence of global warming, may endanger alpine grasslands and their associated Rhizo systems (Theurillat et al., 1998).

In the case of many humus systems occurring in a single area, the adopted principle of classification is to use the single name (Crusto, Bryo, Rhizo, Ligno, Anaero, Archaeo) when more than 70% of the humipedon volume is characterized by the activity of particular agents of humus system formation (Table 1). If these activities characterize less than 70% and more than 30% of the humipedon volume, a double attribution is possible, setting the prevailing system in second position in the compound name, names being separated with hyphens (Fig. 1a). If two humus systems coexist side by side and none is prevailing on the other, the hyphen is replaced with the sign “=” between the system names. A third name may be used in rare cases where three humus systems occupy each one nearly 1/3 of the investigated volume.

Surface or volume occupied by humus systems may be estimated during field investigations. It is possible to distinguish horizontal mosaics of humus systems (side-by-side, juxtaposed systems) from superposed systems. Main (Mull, Moder, Mor, Amphi and Tangel) and Para (Crusto, Bryo, Rhizo, Ligno) humus systems can cover a given area or be juxtaposed or superposed. Names of co-existing systems are separated with a hyphen “-” in case of juxtaposition (horizontal mosaics, example Bryo-Moder mens that protruding rocks are covered with a Bryo system, in a surrounding forest floor covered by a Moder system) and with a slash sign “/” in case of superposition (vertical mosaics, example Bryo/Moder means that a Bryo system developed over and in the organic horizons of a Moder system, even if it is still independent from the Moder). Sometimes it is really difficult to interpret the co-existence of humus systems, because they tend to dynamically form more complex systems at a higher scale of observation. For instance, a Mor system can have at its top a Bryo system developing independently from it (a phenomenon observable in many acid forests where small moss cushions punctuate the forest floor); but a Bryo system can have a Mor

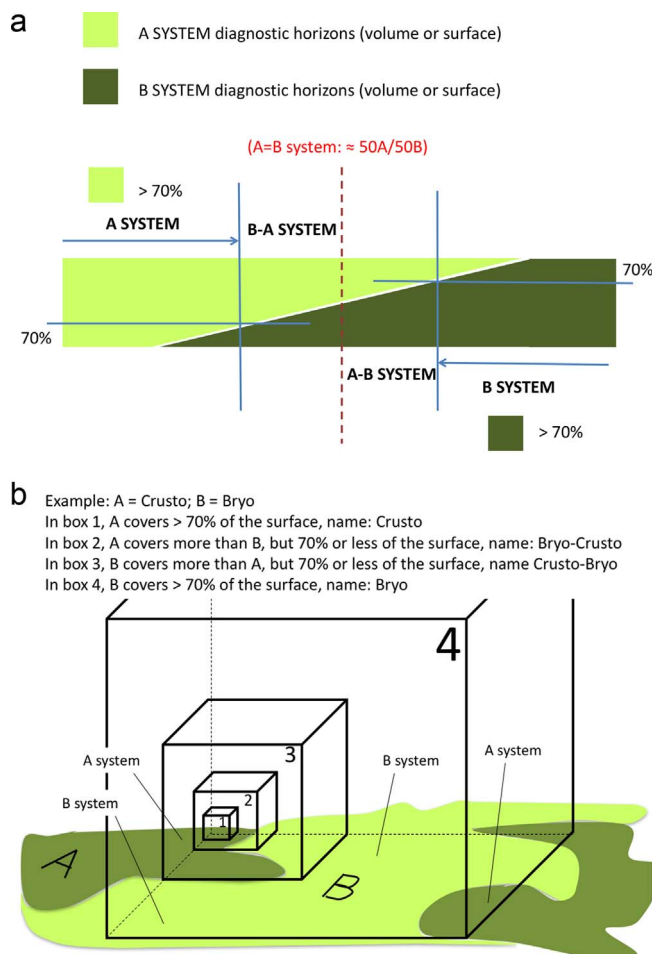


Fig. 1. (a) Rules followed to attribute a name to a humus system when two systems occupy the same investigated volume (or area in case of approximation of volume by surface). When a system occupies a volume or a surface larger than 70% of a given volume (or area), we can say that this volume (or area) is characterized by a single humus system. With more than 30% of surface occupied by co-existing systems, their names are separated with a hyphen if disposed side-by-side horizontally, or with a slash if separated vertically, or without any sign between them if the distinction is unclear or undetermined. The last name is the more represented in the given area/volume (example: Crusto-Bryo system means that a considered humipedon is made of juxtaposed Bryo and Crusto systems, and that the surface covered by Bryo is larger than the one occupied by Crusto systems). If two humus systems coexist in a given area/volume and none seems to prevail on the other, as estimated by naked eye in the field (red line), the sign “=” can be set between the two system names (A = B system). (b) Enclosing investigated areas in imaginary boxes helps better circumscribing the object of research. In Fig. 1b, the small size of cube number 1 allows to investigate the humus system at detailed scale. If the aim is to investigate a larger area, cubes 2 to 4 should be preferred (see Humusica 1, article 7). A “mosaic-reference” is attributed following the principles illustrated in Fig. 1a. If relationships between A and B systems are of no interest, imaginary boxes can be placed in the central part of the picture where system B is large enough to be investigated alone, without any interference of other systems.

system evolving in and below it, progressively becoming a Mor system. A regression process is possible from Mor to Bryo humipedons, when mosses colonise the organic horizons of a Mor in a degraded forest evolving toward open grassland, the process ending with a mosaic of Bryo Mull under bryophytes and Rhizo Mull under grasses.

For these reasons, we recommend to use hyphen and slash signs with prudence, preferring to write the two names in sequence without any sign between them in case of doubt. Progressive or regressive evolutions are typical expressions of living natural ecosystems. Try to understand them is certainly the most interesting and fruitful aspect of an ecological investigation.

As explained in Humusica 1, article 7, enclosing a pointed system in

an imaginary cube (Fig. 1b) may help to circumscribe Para systems and to understand/describe the relationships occurring between different humus systems occupying a same site. The imaginary box can be large enough to include not only a small area of the ecosystem but a large mosaic of plant assemblages and its corresponding mosaic of humus forms. For practical reasons (mapping purposes, for instance) it is possible a) to circumscribe a single plant community (or plant assemblage) and its humus form or b) to consider a heterogeneous mosaic. In the latter case, instead of the volume (which could be difficult or too long to be measured) the ratio of surface covered in the box by each single unit of the mosaic can be evaluated to assign a double name to the mosaic (Fig. 1b). This reference is called 'mosaic-reference' in order to distinguish it from the humus form reference attributed to a single humipedon. A surface ratio can be easier to evaluate for carpet-like Crusto and Bryo than for Rhizo and Ligno systems, because the diagnostic characters of the latter are hidden in the soil and less evident from a cursory examination of the ground. More precise indications are given below for each Para system.

A specific contribution for Ligno systems is proposed in Humusica 3 by D. Tatti and collaborators. For field investigations needing more detailed and expert characterisation of Crusto and Archaeo humipedons, we suggest to freely download detailed keys of classification and precise descriptions and photographs/data reported in Pietrasiak (2015) and Belnap et al. (2001a) for Crusto systems, and Ball et al. (2010) and Rothschild and Mancinelli (2001), for Archaeo systems: Wikipedia is also an immense source of information (see https://en.wikipedia.org/wiki/Biological_soil_crust for Crusto and <https://en.wikipedia.org/wiki/Archaea> for Archaea).

Short overviews are given below for all Para systems, with some references of diagnostic horizons, which help in understanding the functioning of these important but still badly known humus systems with underestimated ecological functions.

3. Crusto humus systems

Crusto humus systems are strongly controlled by the presence of bacteria, cyanobacteria, algae, lichens, bryophytes, and microfungi living in extremophile, aerated or periodically watered habitats (Evans and Johansen, 1999; Elbert et al., 2012). These organisms may form monospecific (microbial communities with a visible dominant member and many invisible associated members) or plurispecific (microbial communities with numerous invisible microscopic members) covers, from micrometric biofilms to millimetric microcrusts or thicker (1–5 cm) crusts. Aeration is mandatory for stable biofilms and crusts. They can even float (Declerck et al., 2007) or be submerged over short periods of time (Bowker, 2007). However, fully submerged anaerobic humus systems are classified into other units called Anaero and Archaeo, which are described in separate sections. In illuminated habitats, photoautotrophic organisms and their symbionts are the usual living constituents of Crusto communities. However, Crusto can be formed even in dark aerobic environments if necessary nutrients and energy are supplied from above (Garcia-Pichel and Belnap, 2001). In these dark habitats, organo- or lithotrophic electron acceptors may be necessary for utilizing the energy input.

It is possible to recognize two-dimensional- and three-dimensional-biological crusts. Two-dimensional crusts are formed by organisms tightly appressed to the substrate such as cyanobacteria, bacteria, algae, short mosses (*Bryum* spp.), liverworts, crustose, leprose, squamulose, or gelatinous lichens, with a thickness less than 2 mm (Fig. 2a–f). Three dimensional crusts have a distinctly visible thickness (> 2 mm) and can be composed of fruticose (or arbuscular), foliose and taller bryophytes (e.g. *Grimmia* on rock; *Syntrichia* spp., *Crossidium* spp., or *Pterygoneurum* spp. on soil; Fig. 3a–d). Among these organisms, cyanobacteria are particularly noticeable. They are very diverse (physiologically, morphologically and genetically) and grouped in several subclasses (Hoffmann et al., 2005). As a group of very old (and still persisting)

bacteria they share some common survival strategies, such as exocellular slime formation, dual phototrophic pathways (anoxygenic and oxygenic), nitrogen fixation, antibiotic production and, finally, in contrast to algae, formation of glycogen and PHB for energy storage (Herrero and Flores, 2008). These properties provide them with remarkable persistence and survivability in unfavourable habitats. Salt-tolerant species (not halophiles as archaea) are quite common, as well as thermophile cyanobacteria. Cyanobacteria live even in harshest environments and are present in Archaeo humus systems described at the end of this article.

3.1. Nos (Not On Soil) Crusts and Soil crusts

In this guide, we consider the presence of mineral soil material/horizon as a discriminant factor and we differentiate biological crusts between those developed without or with soil. We call these two categories Nos (Not on soil, bi-dimensional) and Soil (tri-dimensional) crusts, respectively. Some soil crusts (algal crusts) can appear as thick two-dimensional ones as well. Separating rock crusts (Nos crusts) from Soil crusts is easier to practice in the field than the two- versus three-dimensional diagnostic characteristics.

Nos crusts are generally established on unweathered rock while Soil crusts develop on mineral soil material (evolved from weathered rock). Soil crust communities actively change the properties of the parent mineral soil through losses, addition, transportation and transformation of minerals and organic matter (Belnap et al., 2001b). Nos crusts represent primary humipedons in terrestrial ecosystems. In fact, lichens, epi and endolithic free-living bacteria, cyanobacteria, algae, and fungi living on and within rocks initiate rock weathering and pedogenesis (Büdel, 1999; Adamo and Violante, 2000; Chen et al., 2000). Fungi, bacteria and algae colonize and deteriorate even other structural material like concrete, plastic and metal (Burford et al., 2003). Rock crusts may evolve into Soil crusts once enough mineral soil material has accumulated, or dust material has been trapped, for example in rock pockets/bowls (Souza-Egipsy et al., 2004). Nos crusts, in literature also called cryptogamic covers, may appear even on non-rocky solid substrates, like bark (Elbert et al., 2012), building and historical monuments (Gadd, 2007), human manuscripts or painting (Sterflinger and Pinar, 2013), plastics (Crispim et al., 2003), or even liquid substances (mud, oil, dirty water, Höpner et al., 1994). With the help of a knife it is possible to remove the largest humipedons from the substrate like a carpet or a stiff crust aggregate (< 3 cm), corresponding to thick Nos crusts (example in Fig. 2e) or Soil crusts (Fig. 3a–c).

When observed in vertical section, Soil Crusto shows a sandwich setup (Fig. 3d). The structure is made of organic, organic-mineral and mineral elements, which form an interconnected crust/soil aggregate which persists in harsh climates as a whole (Vačulík et al., 2004). Fracturing the crust or separating it from the substrate (for instance by trampling) may severely damage the fragile equilibrium between this complex living structure and its habitat (Cole, 1990).

3.2. Crusto diagnostic horizons

To the naked eye, Soil crusts are made of separable organic (cruO) and organic-mineral A horizons, often laying on a thin AC horizon as a miniature of classical humus systems. One can distinguish:

- cruO = mixed organic horizon with more than 70% of the volume (estimated in the field by the naked eye) made of visible lichen/algal/fungal remains; detectable to the naked eye only in macro-crusts;
- cruOA = organic-mineral horizon in which it is not possible to distinguish a homogeneous layer. It corresponds to living and dead organisms, mixed with thin organic-mineral and mineral material. The symbol "OA" has been selected because it often looks like a very organic, mixed O (organic material) and A (organic-mineral material) horizon.



Fig. 2. (a) Nos Crusto (“not on soil” Crusto) system on cliffs of Dolomitic mountains (Trento, Italy). The grey areas covering the rocky walls are biofilms mostly made of cyanobacteria forming Crusto humus systems. Rain washing down the rocky wall, enriched with mineral elements, supplies this micro-ecosystem in water and nutrients. The organic matter photosynthetically produced by cyanobacteria and algae supports heterotroph microorganisms such as fungi and bacteria, which find the energy necessary for their life even in such extreme environments. (b) Nos Crusto system on a purple shale in French Brittany. A cruOA horizon is noticeable as a coating whose colour depends on the type of organisms living on and in the rock and on the debris/dust which they retain and/or chemically fix on the rock. (c) Nos Crusto systems in mosaic. Single species dominate the small squares and are combined in a unique community in the larger square. As for larger ecosystems, the scale of investigation influences the quality and the number of discerned objects. (d) Nos Crusto system on a purple shale in French Brittany. A cruOA horizon is noticeable as grey-white patches corresponding to living lichens and debris/dust which these organisms retain and/or chemically fix on the rock (see also Fig. 2e). (e) Evolved Nos Crusto (still two-dimensional). Thin cruO (3 mm) and a still thinner (1–2 mm) cruOA organic-mineral horizon are detectable when turning over a crustose lichen. The rock itself is covered with grey stains and brown marks, the thickness of which is quite undetectable with the naked eye, corresponding to micro crusts (cruOA horizon < 1 mm). (f) Nos Crusto system on tree bark, made of microalgae, fungi and lichens. It corresponds to a cruO horizon, made of a mixture of living and dead microorganisms.

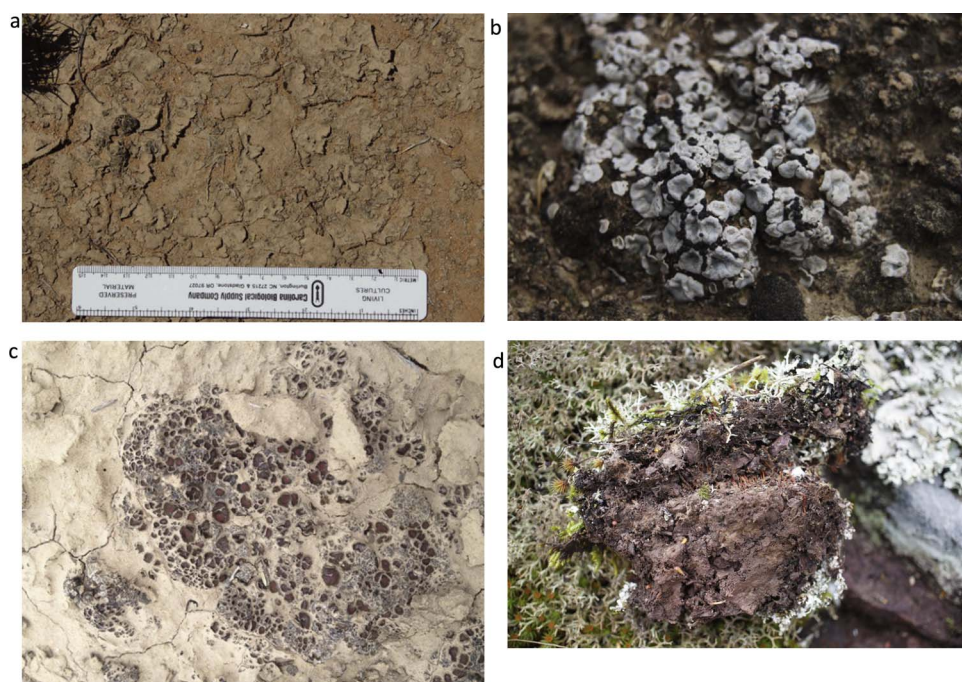


Fig. 3. (a) Soil Crusto on desert sediment (Regosol) found in the Jornada Experimental Range, Chihuahuan Desert, Chile. (b) Soil Crusto system, with funnel-like apothecia of foliose lichen, on gypsum soil in the Chihuahuan Desert, Chile. (c) Soil Crusto system of a crustose lichen showing brown thalli with red apothecia on a clay loamy, dry-crack desert soil. (d) Soil Crusto system on rock. When turned over, the crust shows a lichen layer at the top, anchored with red rhizoids to the fragmented rock at the bottom, intricate in the medium part with dead organic matter and mineral particles. Black cruO (in this case could be rather a lichen-made bryo) horizon is noticeable at the surface, overlying a reddish cruA and rocky AC.

To the naked eye, Nos crusts may be described using a single cruO or cruOA horizon, comprising organic (dead and living organisms) and mineral matter (or not), lying or being fixed on a hard substrate (rock, bark, artefacts...).

3.3. Definition and classification of Crusto systems

A Crusto system corresponds to a humipedon where Crusto diagnostic horizons (cruO and/or cruOA) cover more than 70% of its volume (estimated in the field by the naked eye). When diagnostic horizons of Crusto occupy between 30% and 70% of the volume, the rules reported in the introduction are adopted (Fig. 1a and b), i.e. both names of co-existing systems will be used for characterizing the humipedon. A larger area than the examined soil profile can be characterized with a “mosaic-reference” and, to this purpose, the soil surface occupied by the Crusto system has to be estimated (Fig. 1b and also see Humusica 1, article 7).

Nos or Soil Crusto systems correspond to small but relatively independent humipedons. Crusto systems often develop in patches, sometimes among other main terrestrial humus systems. Pioneer patches of Crusto systems may grow on and between coarse rock debris, sometimes also called “crevice crusts”. Bryo or Rhizo systems, or even both these intricate systems may supersede Crusto systems in the same area and form a mosaic of pioneer systems within a forest ecosystem. From the point of view of vegetation such systems have been called “enclaves” by Lemée (1994). When characterizing forest humus system as a whole, Crusto will be used as a prefix only if the surface covered by the Crusto system raises at least 30% of the surface of the whole forest floor.

3.4. Open question: are there Crusto systems even at the soil bottom?

Even if covered by the overlying soil material, endolithic fungal communities can live and weather rock minerals in the subsurface (Hoffland et al., 2004). Can these communities be considered as buried Crusto humipedons? Can we consider that a Crusto system might be present even in a Lithopedon? This doubt confirms the necessity to share the soil in three parts to be studied separately, at least in a first approach to soil functioning (see Humusica 1, article 1). The lithopedon might well be subdivided in a more “biological” part at the top and a more “geological” part at the bottom.

4. Bryo humus systems

Bryo are humus systems strongly influenced by dominant mosses or arbuscular lichens (mosses and lichens are often associated) or small stonecrop plants (Figs. 4–9). These organisms may form mono- or multi-specific covers. Aeration is a mandatory prerequisite even if they prefer wet environments where they may form peatland (sphagnum bogs). These plants may grow on remains of a previous stem and when looking through a Bryo humipedon profile, old and new plants are recognizable by the naked eye, forming the diagnostic horizons of these particular humus systems. Anaerobic humus systems built by mosses (some among main Histic systems) display at the top of the profile an oxygenated part where growth of the living part of the Bryo system takes place. A Bryo system corresponds to a moss cushion growing more or less independently from the underlying substrate. Mosses grow on their own dead bodies, which are slowly biodegraded and still belong to the same moss cushion. Mosses do not have a real root system to the exception of rhizoids, mainly used for anchorage, and their green leaves and stems directly absorb water and nutrients from rain and throughfall, capillary rise through dead parts being possible within limits (Ketcheson and Price, 2014). A moss cushion taken in a forest and transplanted to a garden in similar climatic context will continue to grow as an independent system, a property which is used in the rehabilitation of cutover peatland (Cagampan and Waddington, 2008).

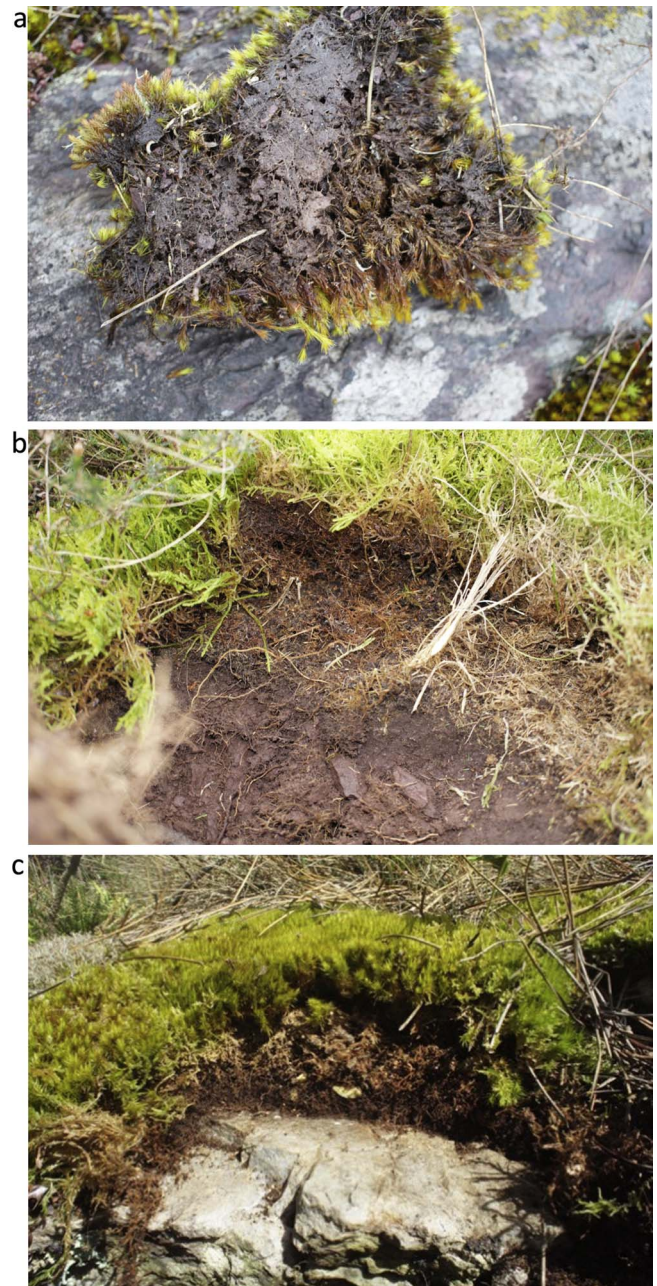


Fig. 4. (a) Bryo system on rock. Visible horizons under the living greenish moss layer (from periphery to centre): orange bryOL, brown half-decayed bryOF, brown-grey bryOA (even with living encytraeids). (b) Bryo system with green living parts of mosses covering an orange bryOL horizon, lying on a bryOF gradually stemming in a reddish bryOA; here and there pieces of A and AC horizons. (c) Bryo system on rock or lithic Leptosol (WRB). The green living parts of mosses are growing over an orange bryOL, lying on brown bryOF to bryOA horizons the base of which abruptly lies on the rock. bryOL = 4 cm, bryOF = 1.5 cm, bryOA = 0.7 cm.

4.1. Bryo diagnostic horizons

- bryOL = OL horizon with more than 70% in volume of recognizable remains (estimated in the field by the naked eye) made of moss or arbuscular lichen or succulent plant remains (on rocks: Fig. 4a–c; on tree trunks: Fig. 5a and b; on soil: Fig. 6); diagnostic characters of a general OL horizon are present, too: humic component less than 10% by volume (recognizable remains $\geq 90\%$);
- bryOF = OF horizon with more than 70% in volume of recognizable remains (estimated in the field by the naked eye) made of moss or



Fig. 5. (a) Bryo system at the base of a tree trunk. Only the living green part of the system is visible from the outside. Bryo system on wood. Structure of the humus system: living green parts of mosses + beige bryOL + brown bryOF and darker ligOF horizon (Ligno horizon). This system may be studied as a complex Bryo-Ligno system.



Fig. 6. Bryo system on organic horizons and albic E horizon of a Podzol in an open forest of *Pinus sylvestris*. Under the living green part of mosses: beige bryOL, yellow and brown bryOF and brown OH. Two interpretations of this humipedon are possible: 1) the Bryo system develops independently over and partly in the organic horizons of a Mor humus system, in this case the right name that can be assigned to the humipedon is Bryo/Mor (Bryo system superposed to Mor system); 2) the Bryo is undistinguishable from the Mor system, the name being Bryo Mor, meaning that the humus system corresponds to a Mor influenced by moss organic remains. Considering the rules expressed in Figs. 1a and b, the name Bryo Mor must be used when the volume of bryOL + bryOF is far less than that of OH, which could be the case in this picture.

arbuscular lichen or succulent plant remains (Fig. 4a–c, Fig. 5a and b, Fig. 6); diagnostic characters of a general OF horizon are present, too: the proportion of humic component is 10% to 70% in volume;



Fig. 7. (a) Mosaic of humus systems: Crusto develops on and around protruding rocks, Bryo on soil. Bryo horizons may develop among rock debris and form new soil. The Bryo system is composed of mosses and arbuscular lichens and even a little succulent plant (the reddish *Sedum anglicum*). As the Bryo system covers here more than 70% of the investigated surface (i.e. the whole picture), the whole mosaic is considered as a Bryo system. Under living plant cover: orange bryOL, dark bryOF, and more mineral bryOA in contact with rock. (b) Bryo system are generally generated in pioneer circumstances, lying directly on a lithopedon (rock) or on incipient soils. Here the bryOA is made side-by-side of pieces of an organic OH horizon and clumps of organic-mineral A horizon. Epigeic earthworms find enough soil and water even in very harsh situations (pH_{water} of bryOA horizon < 4.5). (c) Epigeic earthworm living in organic horizons of a Bryo system, the darker parts of it corresponding to a bryOA with many earthworm faeces.

- bryOA = mixed O and A horizons, organic and organic-mineral aggregates juxtaposed in micro-patches (Fig. 4a–c, Fig. 8a and b).

Because of the difficulty of recognizing in the field the original plant components of OH and A horizons, these horizons cannot be considered as diagnostic horizons for Bryo systems.

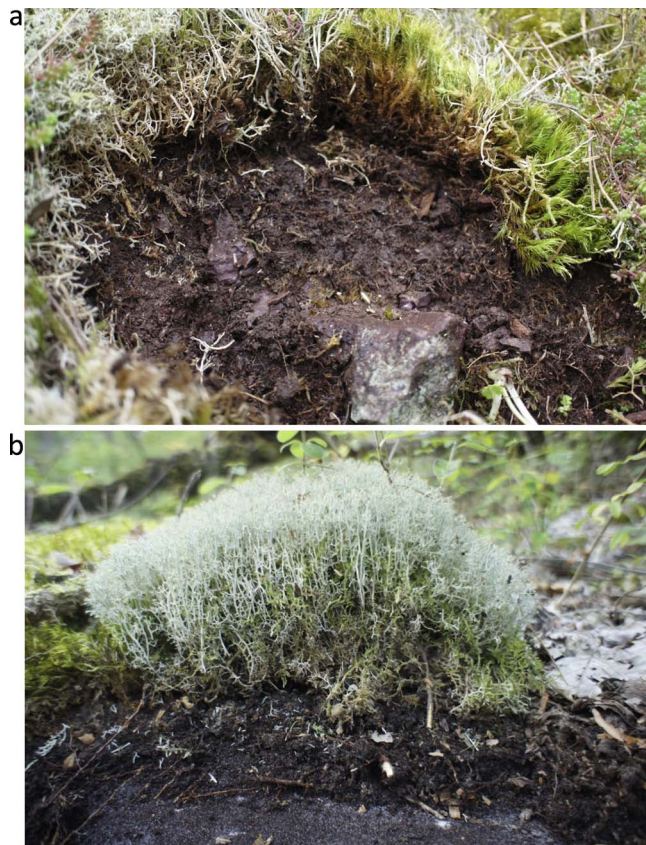


Fig. 8. (a) Bryo system: bryOL, bryOF and bryOA are visible and overlie a biomesostructured A horizon. This small Bryo system was growing on a rock and was not included in a larger ecosystem. (b) Bryo system under arbuscular lichens, with common (not Bryo) OH and miA horizons, lying abruptly on a sandstone boulder (grey acid sandy rock). bryOL (from lichens), bryOF (from lichens) and bryOA are visible over the OH horizon. This small Bryo system is an independent unit.

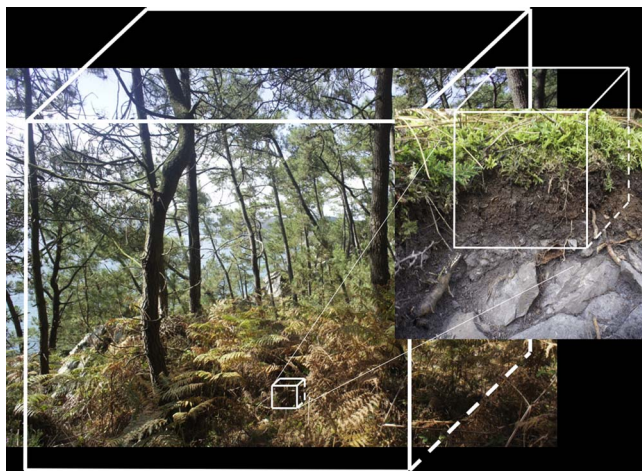


Fig. 9. A Bryo system included in a larger forest ecosystem under pine (*Pinus maritima*) and fern (*Pteridium aquilinum*) cover, on a Leptosol (WRB) with sandstone Lithopedon (French Brittany). bryOL and bryOF overly thick (ca. 7 cm) OH (brown, dark grey) and A (organic-mineral, grey, in contact with the rock) horizons. The volume occupied by (bryOL + bryOF) being between 30 and 70% of the volume of the humus profile, Bryo must be used as prefix. The profile is assigned to a Bryo Moder, meaning a Bryo system partially occupying the organic horizons of a Moder. We think that under oceanic climate, facing the sea (the blue background through pine stems) and because of the protection offered by the fen cover, mosses find a particularly favourable habitat.

4.2. Definition and classification of Bryo systems

A Bryo system corresponds to a humipedon where Bryo diagnostic horizons (bryOL, bryOF, bryOA) cover more than 70% of the volume of the humipedon (estimated in the field by the naked eye). When Bryo diagnostic horizons are present and their cumulated volume is important ($\geq 30\%$) but does not overwhelm 70% of the volume of the humipedon, another humus system co-exists with the investigated Bryo system. In this case, the rules reported in the introduction will be adopted (Fig. 1a), i.e. names of co-existing systems will be used to characterize the humipedon. A larger area than that of the examined soil profile can be characterized with a “mosaic-reference” and, to this purpose, the soil surface occupied by the Bryo system has to be estimated (Fig. 1b and see Humusica 1, article 7, section 6).

An example of a Bryo system in mosaic with a Crusto system is shown in Fig. 7a: here the humipedon is classified as Bryo system both at fine scale (top right corner of the picture) and at coarse scale (the whole picture), since the co-existing Crusto System covers less than 30% of the investigated area.

4.3. Examples of classification of Bryo systems included in larger ecosystems

- **CASE 1: Vertical mosaics of Bryo and forest humipedons.** In a forest, the volume of Bryo diagnostic horizons is less than 70% of the volume of the forest humipedon. Example: the soil of a pine forest covered with pine needles and a continuous moss carpet under a dense fern cover. The humus profile (Fig. 9) presents a bryOL, a bryOF and thick OH and A horizons. As Bryo diagnostic horizons represent between 30% and 70% of the volume of the humipedon, a Bryo system name cannot be attributed and Bryo will be used only as prefix to the predominant humus system. In this example, the presence of an OH horizon thicker than 1 cm gradually passing to the underlying A horizon allows assigning the humipedon to a Dysmoder humus form, corresponding to a terrestrial Moder humus system. The humipedon can thus be classified as a Bryo/Moder system (dash symbols conventionally used instead of hyphens in case of superposed humus systems). However, the two humus systems are so integrated that it can seem difficult to identify a superposition. The simple succession of the names Bryo and Moder is preferred (Bryo Moder), letting unsolved the relative position of the co-existing systems. Note that in the present case, when considering the forest ecosystem as a whole, even if the surface covered by mosses overwhelms 70% of the forest floor surface, the humus system must be classified as Bryo Dysmoder, because of the presence of OH and A horizons, which are part of the humus system of the forest, with a combined volume larger than 30% of the humipedon. A forest humus system can be classified as a Bryo system only if Bryo diagnostic horizons occupy a volume larger than 70% of the forest humipedon, which is very rare, a forest humipedon being generally larger in thickness and volume than a superficial Bryo humipedon;
- **CASE 2. Side-by-side mosaics of forest and Bryo humipedons.** When Bryo diagnostic horizons occupy more than 70% of the volume of the humipedon, a Bryo system is in place as an independent system. This can be the case in a forest landscape with rocky areas covered by mosses dispersed here and there. Let's imagine an important surface covered with mosses ($\geq 30\%$) but not overwhelming 70% of the studied landscape area. Now let's imagine the rest of the surface covered with a forest characterized by a Mull humus system. The mosaic reference name given to the landscape (forest Mull plus Bryo systems) depends on the relative proportion of the two systems: Bryo-Mull system if the Mull system associated to the forest dominates or Mull-Bryo system if the Bryo system dominates. A landscape with less than 30% of Bryo is a Mull system. A landscape with $> 70\%$ of Bryo is a Bryo system.



Fig. 10. Rhizo system in a moss-fern rocky land area. Thick rhiOL and rhiOF horizons, and the high content in roots, rhizomes and rhizoids even in the A horizon (rhiA), allow classifying this humipedon as a Rhizo system.

5. Rhizo humus systems

Rhizo humus systems occur when roots are the driving factor of humus system development (Figs. 10–16). This humus system is not easy to detect because root-built aggregates are similar to other soil aggregates and, in addition, roots may penetrate and modify earthworm aggregates (Pouville et al., 2008). The humipedon is systematically assigned to a Rhizo system where more than 70% of the volume of the cumulated humus horizons is made of roots or other subterranean plant parts (living and dead). In the presence of roots and organic-mineral aggregates and in the absence of any other sign of biological activity (except invisible microorganisms), a Rhizo system is present, even if the volume of roots is less than 70%. This is often the case in sandy soils covered with grasses (Fig. 12c and d) in semi-arid climates (savannas, pampas). Rhizo humipedons are strongly influenced by roots and their exudates, which represent a noticeable contribution to soil organic matter (Martinez et al., 2016; Yang et al., 2016) and play an important role in the formation of soil structure formation (Oades, 1984; Bais et al., 2006; Zhi et al., 2017), Oades 1984. Other factors are certainly involved in the functioning of the Rhizo humus system, but it can be difficult to share their relative contribution compared to the dominance of roots. Typically, Rhizo humipedons are associated with heathland and grassland ecosystems dominated by grasses, sedges, ferns, ericaceous and other suffrutescent plants.

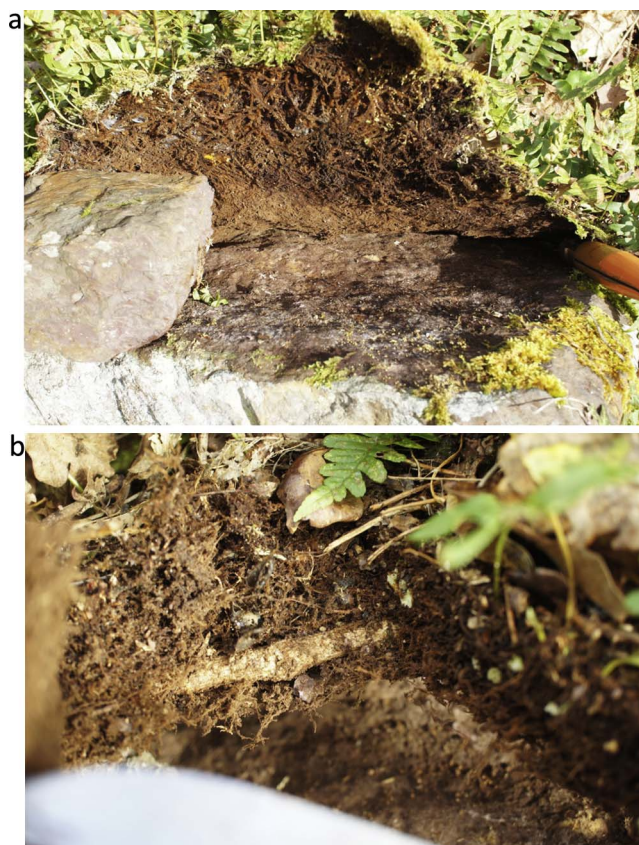


Fig. 11. (a) Rhizo system. Fern and moss rhizoids under a *Polypodium vulgare* population on acid rock. The humipedon, lying on a lithic Leptosol (WRB), has been lifted like a carpet. (b) Rhizo system under a fern population. rhiOF, rhiOH and rhiA are superposed in a humipedon, they were made apparent by transversally sectioning the carpet described in Fig. 11a.

5.1. Rhizo diagnostic horizons

- rhiOL = OL horizon with more than 70% of the volume (estimated in the field by the naked eye) made of thin roots (diameter ≤ 2 mm) and other active subterranean plant parts (rhizomes) (Fig. 10); the remaining part of the horizon is mainly composed of recognizable remains ($\geq 90\%$) and the humic component is less than 10% in volume;
- rhiOF = OF horizon with more than 70% of the volume (estimated in the field by the naked eye) made of thin roots (diameter ≤ 2 mm) and other active subterranean plant parts (rhizomes) (Fig. 10, Fig. 11a and b); the remaining part of the horizon (30%) is made of 10 to 70% humic component and 30 to 90% recognisable remains;
- rhiOH = OH horizon with more than 70% of the volume (estimated in the field by the naked eye) made of thin roots (diameter ≤ 2 mm) and other active subterranean plant parts (rhizomes) (Fig. 10, Fig. 11a and b); the remaining part of the horizon is made of more than 70% humic component and less than 30% recognisable remains;
- rhiA: A horizon with more than 70% of the volume (estimated in the field by the naked eye) made of thin roots (diameter ≤ 2 mm) and other active subterranean plant parts (rhizomes) (Figs. 10–12), or A horizon with roots and aggregates linked to roots in the absence of other visible biological agents of soil aggregation (e.g. animals, fungi).

5.2. Definition and classification of Rhizo systems

A Rhizo System corresponds to a humipedon where a) Rhizo diagnostic horizons (rhiOL, rhiOF, rhiOH, rhiA) are present and fill more

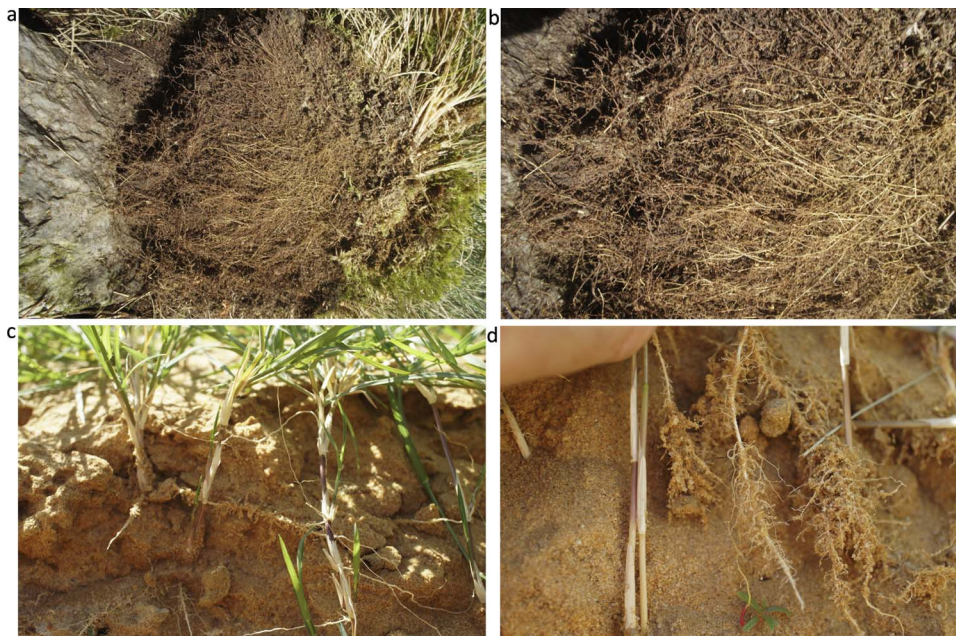


Fig. 12. (a) Rhizo system under a grass tuft, with well-expressed rhiOF and rhiA horizons. The volume of rhiA is larger than 70% of the volume of the whole humipedon. (b) Detail view of Fig. 12a: the rhi A horizon of a Rhizo system under a grass tuft. (c) The rhi A horizon of a Rhizo system under grasses in a sandy dry soil (sub-tropical semi-arid climate). (d) Detail view of Fig. 12c: various aggregates in the sandy rhi A horizon (sub-tropical semi-arid climate).



Fig. 13. Rhizo system in an acidophilic lawn. OL and OF are not “rhi” horizons, however, the volume occupied by rhiOH and rhiA allows assigning this humipedon to a Rhizo system. There are no earthworms in the AC horizon, organic matter recycling being strongly and indirectly influenced by grass roots.

than 70% of the volume (estimated in the field by the naked eye), or b) roots and aggregates linked to roots are present in the absence of other visible biological agents of soil aggregation. This means that a) more than 70% of the cumulated humus profile is made of thin roots (diameter ≤ 2 mm) and/or other subterranean plant parts (rhizomes), or b) soil aggregates cannot be assigned to biological agents other than roots.

In a Rhizo system, roots strongly influence the functioning of the humipedon. When Rhizo diagnostic horizons occupy between 30% and 70% of the volume of the humipedon, the rules reported in the introduction are adopted (Fig. 1a), i.e. both names of co-existing systems are used for characterizing the humipedon. When Rhizo diagnostic horizons cover less than 30% of the humipedon volume, the Rhizo prefix is omitted, and only the predominant humus system is mentioned. If no Rhizo diagnostic horizons are present, and even if the volume of large roots (diameter > 2 mm) is very important, Rhizo cannot be used as a prefix.

5.3. Examples of classification of Rhizo systems included in larger ecosystems

In the case of a Rhizo Mull (Fig. 14), locally (often the top first 2–3 cm of soil in a meadow), the volume of thin roots may be high but

the thickness of this particular layer is not sufficient for strongly influencing the functioning of the whole humipedon, which remains functionally a Mull and admit “Rhizo” as a qualifier. Rhizo systems are often superposed to other main humus systems. It is often difficult to use the symbol “/” between Rhizo and a subjacent system for subdividing the entire complex system in two distinct superposed systems. The simple succession of the names is generally preferred.

Examples of Rhizo used as qualifier are illustrated in the following figures:

- Rhizo Mull: Rhizo Mesomull Fig. 14a and b; Rhizo Dysmull Fig. 14c;
- Rhizo Moder: Rhizo Eumoder Fig. 15a; Rhizo Dysmoder Fig. 15b;
- Rhizo Mor: Rhizo Humimor Fig. 16.

Frame and scale used for describing the humipedon intervene in the process of classification. A larger area than the soil profile examined can be characterized with “inferred references” (superposed systems) or “mosaic references” (side by side systems) and the soil surface occupied by the Rhizo system has to be estimated (Fig. 1b and see Humusica 1, article 7).

6. Ligno humus systems

Ligno are humus systems made of dominant wood under transformation by wood-feeding animals and/or wood-rotting fungi.

6.1. Ligno diagnostic horizons

- ligOL = OL horizon with more than 70% of the volume (estimated in the field by naked eye) made of decaying wood, still compact (not friable between fingers) (Fig. 17); diagnostic characters of a general OL horizon are present, too: humic component less than 10% by volume (recognizable remains $\geq 90\%$);
- ligOF = OF horizon with more than 70% of the volume (estimated in the field by naked eye) made of more or less fragmented wood (friable between fingers) (Fig. 18); diagnostic characters of a general OF horizon are present, too: the proportion of humic component is 10% to 70% in volume;
- ligOH = OH horizon with more than 70% of the volume (estimated in the field by naked eye) made of decaying wood in an advanced stage of decomposition (wood humus, Fig. 19); the diagnostic

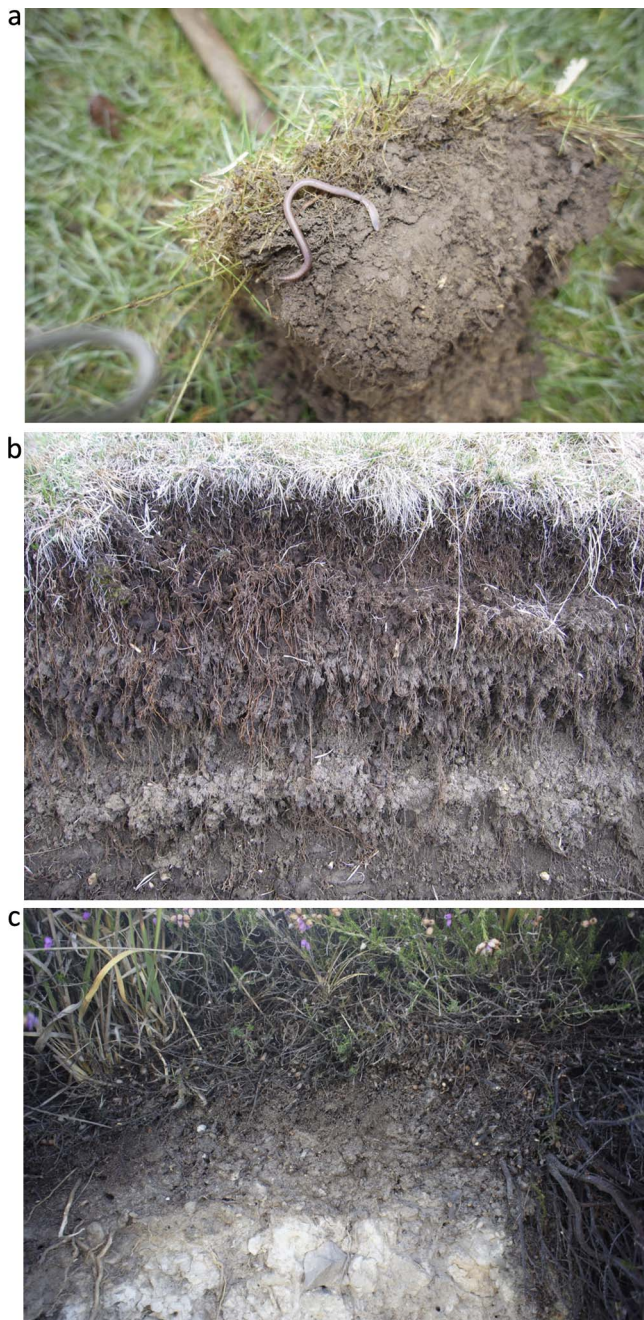


Fig. 14. (a) Rhizo Mesomull system (presence of a discontinuous rhiOL) in a grassland, with a nice healthy anecic earthworm (*Lumbricus terrestris*), easily recognizable by its red pointed head and its flat clear tail. Presence of a discontinuous rhiOL on a rhiA followed in depth by a typical biomacrostructured maA. Roots are dense only at the top of the A horizon (rhiA), which is current in most temperate grasslands. rhiOL and rhiA covers between 30 and 70% of the volume of the humipedon, therefore Rhizo is only used as a prefix before the name of the main humus form (here Mesomull). (b) Rhizo Mesomull system under Alpine grassland. The volume of roots occupies more than 70% of the soil volume at the top (rhiA) but the volume of rhiA is less than 70% when considering the whole humipedon. The humipedon is a Rhizo Mesomull because of the presence of a discontinuous rhiOL. It could be called Rhizo/Mesomull, the first system (Rhizo) occupying the top darker part of the profile. (c) Rhizo Dymull system. Roots occupy a large volume of the rhiOF horizon but the rhiOF horizon represents less than 70% of the total volume of the humipedon: Rhizo Dymull (rhiOF continuous).

characters of a general OH horizon are present, too: humic component amounting to more than 70% in volume.

Other humus horizons are not considered as Ligno diagnostic horizons.

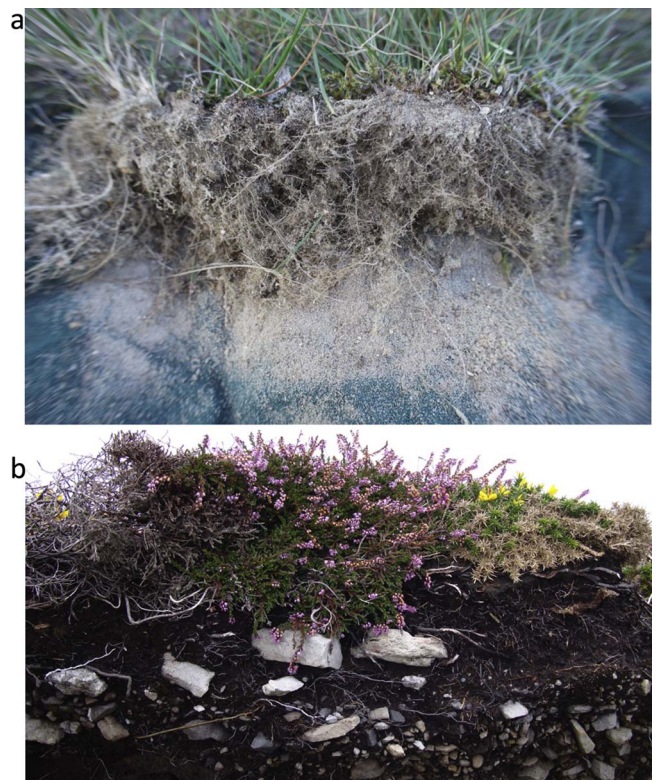


Fig. 15. (a) Rhizo system in a lawn on sandy soil, with a microstructured rhiA horizon. A discontinuous bryOL is also present. Roots occupy less than 70% of the volume of the humipedon: Rhizo Eumoder (presence of miA, absence of OH). (b) Rhizo Dymoder in an oceanic heathland. The volume of thin roots is less than half the volume of the whole humipedon, presence of a thick OH horizon.



Fig. 16. Rhizo system in an acidophilic lawn, mixed with Bryo organic layers, in a pine forest on a lithic Leptosol (WRB). Detectable horizons: OL, bryOF, rhiOH, zoOH, the whole lying on a siliceous hard bedrock. rhiOH is less than 70% but higher than 30% of the volume of the humipedon: Rhizo Humimor (thick zoOH). bryOF, being less than 30% of the volume of the humipedon, is not mentioned.

6.2. Definition and classification of Ligno systems with examples of Ligno systems included in larger ecosystems

A Ligno system corresponds to a humipedon where all organic horizons are Ligno diagnostic horizons (ligOL, ligOF, ligOH). This means that: 1) the volume of decaying wood reaches a minimum of 70% of the volume of the humipedon; 2) the ratio humic component/recognisable remains follows the distinction between OL, OF and OH horizons of main terrestrial humus systems; 3) the process of wood biodegradation is detectable as in “classical” horizons and reaches an



Fig. 17. ligOL, horizon with more than 70% of the volume (estimated in the field by the naked eye) made of decaying wood (as remains of white rot activity).



Fig. 18. ligOF, horizon with more than 70% of the volume (estimated in the field by the naked eye) made of decaying wood. Here many fine roots have invaded the ligOF horizon, like in the OF horizon of a forest floor.



Fig. 19. ligOH, horizon with more than 70% of the volume (estimated in the field by naked eye) made of strongly decayed wood (wood humus). This horizon may have a flashing orange colour, depending on the composition of the wood-destroying fungal community. With ongoing degradation it is turning to brown-black when fully humified and transformed into faeces by wood-eating fauna. Brown rot fungi and many bacteria degrade cellulose while lignin remains, turning the colour towards orange, red or brown. In contrast, a pale yellow or white colour is the result of the activity of white rots, which degrade both lignin and cellulose in various proportions or selectively degrade lignin (see Fig. 17). The remaining substrate is slowly degraded by a diverse microbial and animal community, forming humic substances comparable to those of “normal” soil.



Fig. 20. A Ligno system (small imaginary box and its enlargement) in a *Quercus-Fagetum* forest ecosystem (large imaginary box) punctuated by an artificial plantation of conifers (*Abies grandis*, *Pseudotsuga menziesii* and *Pinus strobus*). These exotic trees are now dying and undergo a natural recycling process thanks to localized Ligno systems.

equivalent intensity considering the ratio humic component/recognizable remains assigned to Ligno diagnostic horizons. An accumulation of undecomposed wood lying on the soil is a potential Ligno system, not a real Ligno system. A humus system becomes a Ligno system when all its horizons fall into the category of Ligno diagnostic horizons (Fig. 20).

Ligno is used as qualifier when one or more Ligno diagnostic horizons (ligOL, ligOF, ligOH) are present and the volume of decaying wood is important ($\geq 30\%$) but does not overwhelm 70% of the whole organic horizons. The frame and scale used for describing the humipedon intervene in the process of classification:

- A humipedon (Fig. 20) is a Ligno system if investigated at local scale (i.e. in an imaginary cube centred on the humipedon) when all horizons are Ligno diagnostic horizons (ligOL, ligOF, ligOH);
- Ligno is used as a qualifier when in the forest floor the volume of decaying wood is important ($\geq 30\%$) but does not overwhelm 70% of the total volume of organic horizons. Examples: Ligno Eumoder (Fig. 21); intergrade between Ligno Moder and Ligno Mor (Fig. 22);



Fig. 21. Diagnostic horizons of a Ligno system: OL and ligOL, orange ligOF (recognizable remains until 70%) and ligOH, gradually passing to a more mineral A horizon. This Ligno system corresponds to a punctual reality in a generalized Eumoder. When wanting to underline the presence of a lot of decaying wood in this forest ecosystem, it is possible to use Ligno as a qualifier. The name of Ligno Eumoder is proposed when, by observing a given surface of forest floor, decaying wood reaches more than 30% but does not overwhelm 70% of the volume of organic horizons. When decaying wood overwhelms 70% of the volume of organic horizons in a given area, it is possible to classify the humipedon of this area as a Ligno system. This occurs in a forest when restricting the surveyed surface to that occupied by a fallen trunk at some stage of biodegradation.

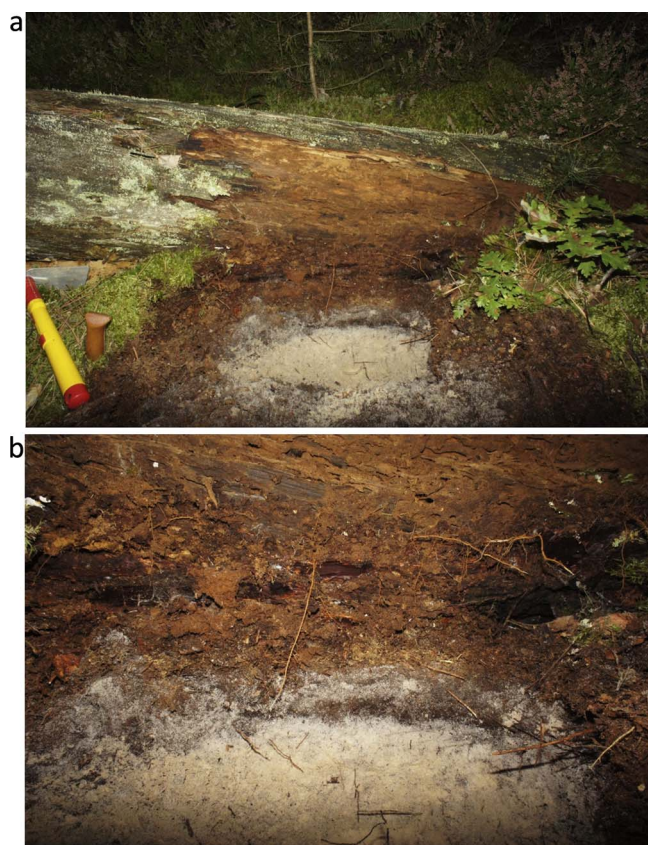


Fig. 22. Diagnostic horizons of a Ligno system. From top to bottom: ligOL (undecomposed part of the fallen trunk), orange ligOF (recognizable remains until 70%) and ligOH down to a grey beige AE horizon then a bleached sand layer (E horizon). The Ligno system occurs punctually in a generalized Dysmoder. For the classification of this humipedon we hesitate between Ligno Mor and Ligno Moder. Points favourable to a Mor denomination: the AE horizon is a nozA, the soil is a Podzol (WRB), which implies a process of podzolization, with an increasing separation (abrupt transition) between organic and mineral horizons; points favourable to a Moder denomination: the gradual transition from organic and organic-mineral horizons. Thereby we classify it as an intergrade between Ligno Humimor and Ligno Dysmoder.

- The humipedon of a forest stand cannot be classified with Ligno as qualifier if the estimated volume of decaying wood is less than 30% of the volume of organic horizons in the whole stand. Note that we enlarge the observation to the whole forest floor, which may include Ligno systems punctually (thereby generating a mosaic of humus systems). In other words, if the decaying wood accumulated in these “Ligno punctual areas” does not reach 30% of the volume of organic horizons of the surveyed forest floor, Ligno cannot be used as a prefix.

7. Anaero humus systems

Here the concept of humus system is extended to environments where water is the matrix. This should be considered as an innovation, which is proposed to the scientific community as a possible extension of names and concepts coined for terrestrial environments to aquatic environments. Although undergone by specialists of different disciplines, using different methodologies and different vocabularies, soil and sediment studies show that both environments ensure similar functions, such as for instance carbon storage, and exhibit quite comparable trophic networks including a wide range of producers and decomposers (Groffman and Bohlen, 1999). This urged us to tentatively erect suspensions and deposits of more or less humified organic matter to the range of humus system in an endeavour to embrace the whole reality of planet Earth. However, we cannot embrace the whole water column of



Fig. 23. Forest stream, St. Petersburg region, Russia. The dark brown colour of the water is due to humic substances, which were formed in nearby peat soil and washed out with groundwater flow.

fluvial and marine environments in the Anaero category because water flows and eddies (i) feed water with oxygen and (ii) make the fate of suspended organic particles more spatially complex than in stagnant waters, despite evident parallels in decomposition processes between rivers and soils (Wagener et al., 1998).

Anaero humus systems are under the prominent influence of bacteria and archaea living in submerged anoxic or anaerobic habitats. The top layer, consisting of freshly deposited organic debris, has undergone an aerobic process of degradation. In the course of time, as it becomes more and more covered by new sediment, the considered layer becomes anaerobic. Such humipedons correspond to river-, lake-, marsh-, and sea-beds, sewages and other habitats for lithotroph and organotroph anaerobic microorganisms (Fig. 23).

The main feature of Anaero is a predominance of water in which the most labile humus form is dispersed and/or floating. Basin dimensions and shape as well as water flow largely determine the persistence of this dispersed organic matter. Mineral and organic parts are in a low amount, but have a high ecological value (Figs. 23 and 24). Organic particles of different sizes represent a “floating litter” which may decant or be transported by water. The process is related to the dynamics of water and knows seasonal variations. It is very difficult to circumscribe

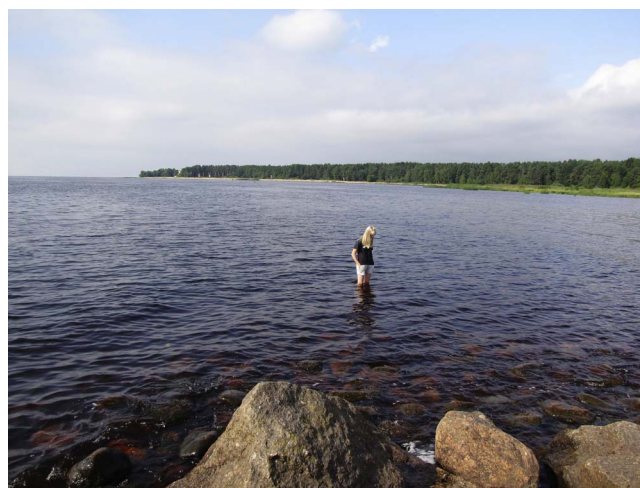


Fig. 24. Where the Black River (Черная речка) flows into the Finland Gulf, St. Petersburg region, Russia. Waters of the Gulf are associated with those of the Black River, the colour of which is lighter.



Fig. 25. Voronka River, St. Petersburg region, Russia. The water of the river contains humic substances and dispersed mineral particles eroded from the surrounding land. The water is fawn-coloured.



Fig. 26. A drainage ditch in a swamp forest, Lisino, St. Petersburg region, Russia. The dark brown colour of the water is due to humic substances.

the functioning of these strange humus systems characterized by such a “dissolved and floating” top layer.

The mineral part of Anaero is represented by soluble mineral components and small-size (colloidal) suspended mineral particles. Dissolved organic matter (DOM) can be autochthonous or allochthonous. Autochthonous DOM is in greater amount in temperate streams (Figs. 25 and 26) compared to tropical streams (Kim et al., 2006).

Autochthonous DOM has an algal and macrophytic origin. Algal DOM prevails in large lakes and marine waters, while macrophytic DOM prevails in small lakes with a dominant littoral zone. Autochthonous DOM consists of individual substances and products of their interaction with the water solution (Bertilsson and Jones, 2002). Allochthonous DOM comes from the surrounding terrestrial ecosystems and its quality depends of landscape, soil, vegetation, hydrology and climate. Humic substances with prevailing fulvic acids (ratio FA to HA 10:1 in light coloured water and 5:1 in highly coloured water) make up 50% of dissolved organic carbon (DOC). Large portions of lakes in temperate and boreal regions are stained brown due to dissolved humic substances (Aitkenhead-Peterson et al., 2002).

The input, storage, transformation and decomposition of humic substances in aqueous systems are important ecological processes. The nature and timing of DOM inputs influence both community organization and metabolism of Anaero.

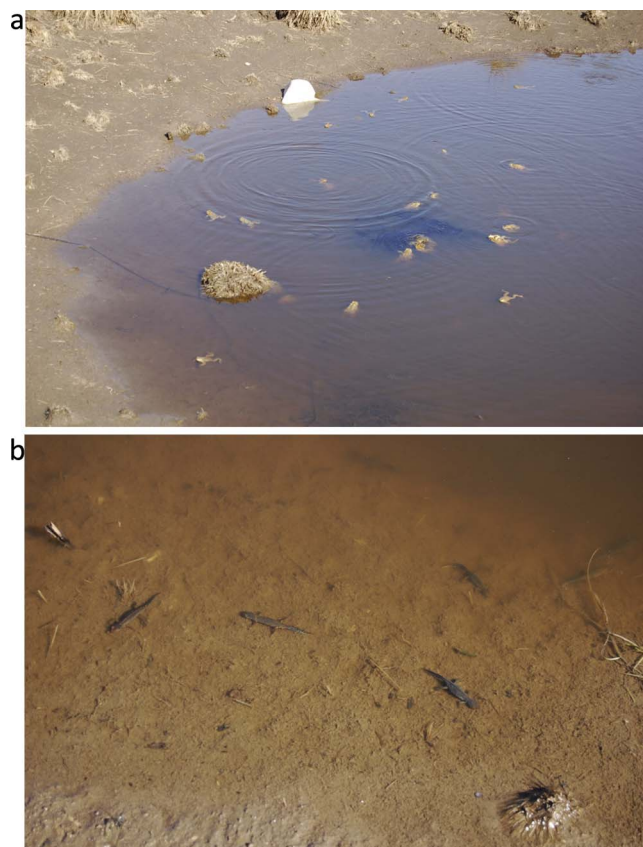


Fig. 27. (a) Anaero system at the edge of a little Alpine lake: surface water without vegetation. (b) Anaero system at the edge of a little Alpine lake: anaOA horizon corresponding to a brown reddish mud deposit. Alpine newts (*Ichthyosaura alpestris*) abund during summer time.

To define more precisely what can be “humus” in running-water conditions and if it’s still relevant to talk about humus form describing those ecosystems (and be able to share running water from stagnant water), we suggest to refer to Wagener et al. (1988), Gessner et al. (2010) and Treplin and Zimmer (2012). The equivalence between the step-by-step decomposition of organic matter along a humus profile would appear along the course of a river, from the source to the estuary.

7.1. Anaero diagnostic horizons

At present time, the floating “OL horizon” is not considered as part of the ANAERO humus system, even though a debate is on the road and generates very discordant opinions among the authors of this article.

anaOA = submerged organic and/or organic-mineral horizon [ana = anaerobic, from Greek an (without), aer (air) and bios (life)] formed by the deposition of organic and mineral particles suspended in water (Fig. 27a and b). Never emerged OA horizon (when emerging, the horizon undergoes a process of oxic biodegradation and is generally integrated in a gA or anA horizon). Observed in the first phases of biological formation of sea and ocean floors, and river beds. Possible in Aqueous systems (see Humusica 2, article 12) over an anaA horizon. Plant roots (seagrasses) and zoological activities of benthic organisms (crustaceans, molluscs and aquatic worms) are possible.

7.2. Definition and classification of Anaero systems

Anaero humus systems are still under investigation. It is difficult to distinguish horizons in sediments even if Kristensen and Rabenhorst (2015) tried to clarify the question. We were oriented in distinguishing photic (exposed to sunlight and permitting photosynthesis; usually less

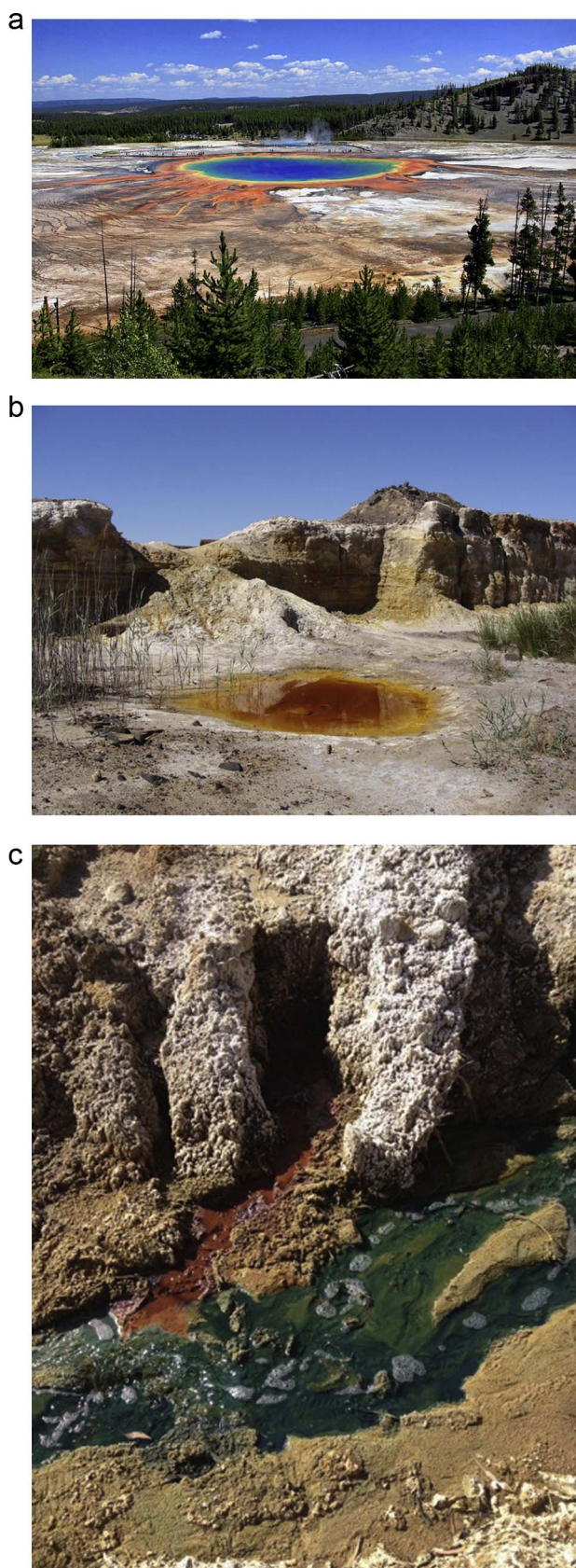


Fig. 28. a) Grand Prismatic Spring (Yellowstone National Park, USA). The vivid colors in the spring are the result of pigmented archaea in the microbial mats that grow in and around the edges of the mineral-rich water. Available at https://en.wikipedia.org/wiki/Grand_Prismatic_Spring#/media/File:Grand_Prismatic_Spring_and_Midway_Geysers_Basin_from_above.jpg. b) Acid mine drainage (pH 1.5). Goldmine in Stilfontein (South Africa). Photograph: Jaco Koch, professor at North-West University; c) Goldmine tailings

located at the Crown Mining complex in Johannesburg. The white color on the rock is gypsum resulting from sulfuric acid neutralisation; the red color in the drainage is due to Iron hydroxide precipitating from the same reaction; the blue/green in the other drainage is due to an organic polymer used for dust suppression that breaks down in the acidic conditions. The fact that the whole looks like an Italian flag is casual. Description: Jaco Koch; photograph: Hermano Taute, MSC student at North-West University.

than 100 meters in depth) and aphotic zones: a) in the photic zone, Anaero (only with anaOA) and Aqueous systems (with anaOA and/or anaA) can be present, with Anaero considered as an incipient stage in the development of Aqueous; b) in the aphotic zone, only anaerobic Archaeo systems (extremophiles in deep seas, barophiles, etc.) are observed. We hope being able to strengthen the information on all these submerged systems in a near future.

8. Archaeo humus systems

Archaeo humus systems are under the influence of archaea or anaerobic bacteria living in extremophile submerged and emerged habitats without plants: highly saline, acidic or alkaline waters, hot springs among many others. These micro-ecosystems are formed by phototroph, lithotroph and/or organotroph microorganisms living in extremophile habitats (Fig. 28).

8.1. Archaeo diagnostic horizons

arcOA = organic and/or organic-mineral horizon without plants roots and formed by a mass of dead and living microorganisms mixed with a mineral mass which can display bright colours.

8.2. Definition and classification of Archaeo systems

The Humus group is attracted to soil ecosystems because it is the ecosystem as a whole that creates the biological essence of soil, that is, humus as opposed to regolith. It is the appearance of humus that allows the further development, growth and expansion of the ecosystem, and is the driving force of the recycling of essential nutrients. From the harsh environment that appears in the aftermath of volcanic eruptions, that is the eruptive rock devoid of organic matter, or the initial regolith of the just accreted land, the influx of organic matter and the concomitant formation of humus are a key to the evolution of life on land (Ponge, 2003).

A key question is what role extremophile systems play in creating soil humus? To answer this question, we must take a look at life on Earth. Essentially everywhere life is present, and that life is tenacious. From the dry cold deserts of Antarctica to the hot acid and alkaline springs of Yellowstone there is life. What we call an extreme environment is dominated by microorganisms. Hot alkaline springs are mainly inhabited by thermophilic archaea, while hot acid springs are inhabited by bacteria and some single-cell eukaryotes (Kristjansson and Hreggvidsson, 1995). Even solid salt is inhabited by microbes. In these extreme environments, the basic functions of microbes are the same as in more mesic environments, i.e. recycling nutrients, increasing organic matter content, and where soil exists creating a humus layer. Although extreme and mesic environments may differ at the organismal level they function similarly at the ecosystem level. Although we think of extremophile systems as isolated systems they do influence the biosphere as a whole through water run-off and gaseous outputs (e.g., CO₂, and N₂).

Rothschild and Mancinelli (2001) provide a review of extreme environments and their inhabitants. These environments range from hot springs and geysers, deep sea hydrothermal vents, hypersaline environments, deserts, ice, permafrost, snow, the atmosphere and even space extreme environments. Within all of these environments microbes create organic material made from microbial metabolites and dead

Table 2
Classification and examples of extremophiles (from Rothschild and Mancinelli, 2001).

Environmental parameter	Type	Definition	Examples
Temperature	Hyperthermophile	Growth > 80 °C	<i>Pyrolobus fumarii</i> , 113 °C
	Thermophile	Growth 60–80 °C	<i>Synechococcus lividis</i>
	Mesophile	15–60 °C	<i>Homo sapiens</i>
	Psychrophile	< 15 °C	<i>Psychrobacter</i> , some insects
Radiation	–	–	<i>Deinococcus radiodurans</i>
Pressure	Barophile	Weight-loving	Unknown
	Piezophile	Pressure-loving	For microbes, 130 Mpa
Gravity	Hypergravity	> 1 g	None known
	Hypogravity	< 1 g	None known
Vacuum		Tolerant of vacuum (space devoid of matter)	Tardigrades, insects, microbes, seeds
Desiccation	Xerophile	Anhydrobiotic	<i>Artemia salina</i> , nematodes, microbes, fungi, lichens
Salinity	Halophile	Salt-loving (2–5 M NaCl)	Halobacteriaceae, <i>Dunaliella salina</i>
pH	Alkaliphile	pH > 9	<i>Natronobacterium</i> , <i>Bacillus firmus</i> OF4, <i>Spirulina</i> spp. (all pH 10.5)
	Acidophile	pH < 2	<i>Cyanidium caldarium</i> , <i>Ferroplasma</i> sp. (both pH 0)
Oxygen tension	Anaerobe	Cannot tolerate O ₂	<i>Methanococcus jannaschii</i>
	Microaerophile	Tolerate O ₂	<i>Clostridium</i> spp.
	Aerobe	Requires O ₂	<i>Homo sapiens</i>
Chemical extremes	Gases	Can tolerate high concentrations of gases or	<i>Cyanidium caldarium</i> (pure CO ₂) <i>Ferroplasma acidarmanus</i> (Cu, As, Cd, Zn);
	Metals	metals (metalotolerant)	<i>Ralstonia</i> sp. CH34 (Zn, Co, Cd, Hg, Pb)

cells. This detritus material serves as food for other organisms. A pioneer trophic network is thereby generated, assuming the typical pyramidal structure of a soil foodweb (see Humusica 1, article 8). As illustrated in Rothschild and Mancinelli (2001), the structure and function of these confined ecosystems strongly depend on many environmental parameters (Table 2).

In extreme environments, a single parameter may dominate and select for a few very specialized organisms in localized sites. Generally, many parameters intervene at the same time and the natural expression of an extremophile ecosystem can be the fruit of different colonies of micro-organisms, which sometimes confer to the site an astonishing aspect (Fig. 28). From the hot blue center to the cooler red edges, mineral composition and microbial communities vary along a mineral and temperature gradient, creating a spectacular “rainbow” in spring water and surrounding ground. These colored halos can be compared to the horizons of a natural soil profile. Natasha Geiling (<http://www.smithsonianmag.com/travel/science-behind-yellowstones-rainbow-hot-spring-180950483/?no-ist>) explains this phenomenon as follows: “The archaea produce colors ranging from green to red; the amount of color in the microbial mats depends on the ratio of chlorophyll to carotenoids and on the temperature of the water which favors one archaea over another. In the summer, the mats tend to be orange and red, whereas in the winter the mats are usually dark green. The center of the pool is sterile due to extreme heat. The deep blue color of the water in the center of the pool results from the scattering of blue light by particles suspended in the water. This effect is particularly visible in the center of the spring due to the lack of archaea that live in the center and the depth of the water”.

We always teach students that the brown-orange color of the soil is due to iron oxides. Is this always true? No. It is actually a combination of minerals and organisms. For example, when looking at photos of Octopus Spring (http://www.lpi.usra.edu/education/fieldtrips/2007/explorations/octopus_springs/index.html), one can see that the hot area is dark blue (due to minerals dissolved in hot water) then when water flows from the source a pinkish film appears on the rocks, due to pigments of *Thermocrinis ruber*, and as water becomes cold a yellowish color is followed by a brown and finally a green color, all primarily due to microbial pigments.

In general, focusing our attention from main humus systems (Terrestrial, Histic and Aqueous: Humusica 1 and 2, articles 1–12) to

Para systems here presented, we get the impression of a travel through time. By observing Crusto and Archaeo we approach the primeval microbial world, although we cannot see by the naked eye the million bacterial cells living in a gram of soil or a milliliter of water where their biomass exceeds by far that of animals and plants. The bacterial cells inhabiting the human body are ten times more numerous than the cells of the body itself. Readers interested in this aspect can find in the next pages some other matter of thought.

9. Can a column of plankton have humus inside? Is there humus even in the intergalactic space?

If we admit that the main components of a humus form are its specialized colonies of biodegrading and organic matter transforming microorganisms, we can say that there is humus in a column of plankton and even in the air. Soil microorganisms disperse out of the soil. Like pollen they are transported everywhere through the air in a kind of “microscopic dusty-misty-soil” represented by mineral and organic and/or organic-mineral particles, water, air and microorganisms.

A new more realistic concept of living soil rises from these assertions. Soil is not only what is expressed in classical definitions, even if shared in three new sub-units (Humi-, Co- and Lithopedon, see Humusica 1, article 1), but can be found even out of the soil profile, in rocks (Geopedon, alive or fossil) (Baudin et al., 2007; Wright and Cherns, 2016), rivers, lakes and oceans (Hydropedon, plankton and mineral/organic suspended particles), air (Aeropedon, microorganisms and mineral/organic suspended dust), or in the space and provisionally out of Planet Earth gravitational field (Cosmopedon, cosmic soil, even still unknown and part of exoplanets, generally out of our planet gravitational field but historically and potentially related to Earth soil) (Kwok and Zhang, 2011). The soil of our planet is even connected with the microorganisms we have on our skin and inside our body (Nih Hmp Working Group, 2009) (Symbiopedon: symbiotic microorganisms, microbiota) (Fig. 29a and b). Microorganisms are everywhere and in dynamic evolution: on one side colonies of large ecological amplitude interconnected by wind and water movement; on the other side, specialized colonies in less accessible sites, such as deep seas and high rocks or other harsh environments like deserts, hot springs, wastes..., containing specialized microbial communities that are physically or

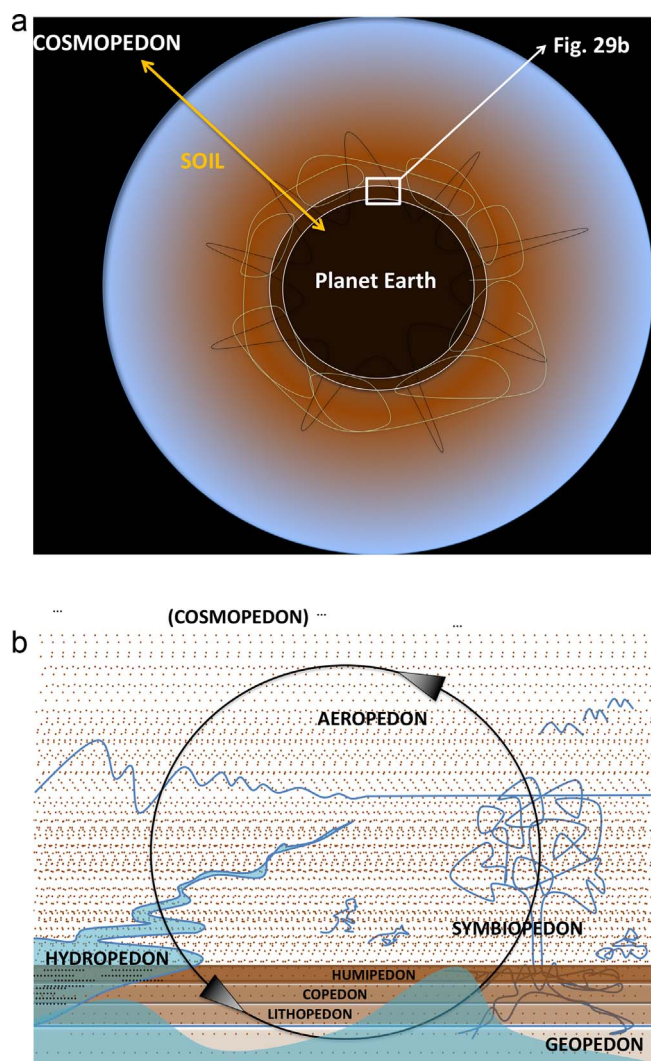


Fig. 29. (a) What's soil? If microorganisms are the most important living components of the soil, then the latter is not confined to what is under our feet but embraces our whole planet as a biotic cover in which microorganisms diffuse and are dynamically interconnected. (b) Soil microorganisms and mineral particles are present even in the air. We tentatively propose the existence of Humi-, Co- and Lithopedon (the three parts of a classical Pedon, as explained in Humusica 1, article 1), but even Cosmopedon, Aeropedon, Hydripedon, Geopedon and Symbiopedon as interacting parts of a new ecological and functional concept of soil.

climatically segregated (Nagler et al., 2016). It could even be possible that these islands of specialized bacteria might act as reservoirs of life, from which new life can be regenerated on Earth when global ecological crises overcome and destroy larger, more exposed and sensitive organisms (mass extinction phenomena), like it might have happened after the collapse of the Ediacara and the Cambrian explosion of life, 542 Ma ago (Xiao and Laflamme, 2008). V Paul Wriath (see also in Humusica 3, his article titled “An early carboniferous humus form South Wales preserved by marine hydromorphic entombment”) in a recent letter: “I do appreciate scientists looking at the bigger (cosmic) picture. I have been working with a Martian lake expert at Oxford University (Nick Tosca) to help me understand the giant oil and gas fields offshore Brazil hosted in Cretaceous lake deposits, and also the feedback between diagenesis and biodiversity during one of the key biodiversity spikes in the early Palaeozoic (attached). The more I study especially carbonate sediments the more similarities there are between them and soils, in terms of very early biological and chemical re-organisation.”

Medicine should be more interested in the relationship between humans and humus. In fact, we live in a cloud of microorganisms dynamically connected to soil microbiota. We are living in a “biological soil” diffuse in air, water and biological vectors all over our planet. The consequences of this statement are of crucial importance. Photosynthesis, for instance, becomes a secondary process compared to the primary one which is based on microbial metabolism. Photosynthesis becomes a process rooted in humus and not vice-versa as we have been taught, i.e. that plants produce organic matter then store it in humus and form the latter. A more realistic eco-evolutionary process would be that microorganisms formed plants that in turn produce organic matter for feeding them. Microorganisms thereby stay not only at the base of the tree of evolution but also at its top, occupying the place some persons generally reserve to humans. An ecosystem is not made of organisms each with an individual purpose, but a mass of organisms that have a common purpose, like a large “amoeba-shaped” cloud maintaining a tight connection between its constituents. This “amoeba” is rooted in humus and, in some sense, is humus. There are many aromatic-aliphatic organic particles in the space (Kwok and Zhang, 2011). This idea would help humans to better consider their relative position in terms of natural processes, and be more careful in forecasting the future of our living planet (in Humusica 2, articles 17 to 19; in Humusica 3: Humans, humus and universe, or Have you never seen an infrared humus/human profile?).

With the model depicted in Fig. 29 in mind, it is easier to understand the series of Para humipedons we presented in this article. Their dynamic and spatial relationships with the main humus systems become evident. Initial phases of Crusto humipedons are microorganisms “fixed” on rocks or mineral substrates. Microorganisms form biofilms floating on water and living in very thin layers on any type of physical support. These colonies do not need a photosynthetic process as founder mechanism. They simply “arrive” on a substrate transported air and/or water. Evolution toward other more complex systems is possible. During their development, coordinated photosynthetic and biodegrading processes take place, increasing the energetic demand for sustaining larger and larger systems (Fig. 30):

1. Crusto (bacteria, fungi and lichens, cyanobacteria and algae on mineral particles in aerated environments);
2. Bryo (arbuscular lichens, bryophytes and small plants on mineral and/or organic and/or organic-mineral soil horizons);
3. Rhizo (fern, grass, ericaceous roots and rhizomes on soil horizons);
4. Ligno (wood-destroying animals and fungi on woody remains);
5. Anaero (anaerobic microorganisms, in always submerged environments: 5a, river bottoms, lake; 5b, sea, ocean floors);
6. Archaeo (archaea living in very harsh environments, 6a out of water, 6b in photic submerged zone, with photosynthetic organisms, 6c in aphotic zone, in deep seas).
7. Main terrestrial humus systems (all on evolved soil horizons; Mull = dicots, in temperate climates; Mor = conifers, in cold rainy climates; Moder = mixed forests, in half mountain, half continental climates; Amphi = sclerophyllous vegetation, in contrasted climates (mountain, mediterranean); Tangel = conifers, in contrasted dry climates);
8. Main histic humus systems (all in semi-terrestrial more or less anoxic environments; Fibrimoor = base-poor soils, in brook valley systems and bogs; Mesimoor = moderately base-poor soils, in brook valley systems and bogs; Amphimoor = moderately moist base-rich soils, in brook valley systems or in half-drained fens; Saprimum = base-rich soils, in brook valley systems or fens; Anmoor = base-rich soils or soils enriched by base-rich groundwater, in brook valley systems and floodplains, never in dynamic floods with fast currents);
9. Aqueous = tidal ecosystems (Oxitidal = Fe_2O_3 dominant; Reductitidal = Fe_2O_2 dominant; Eusubtidal = only Fe_2O_2).

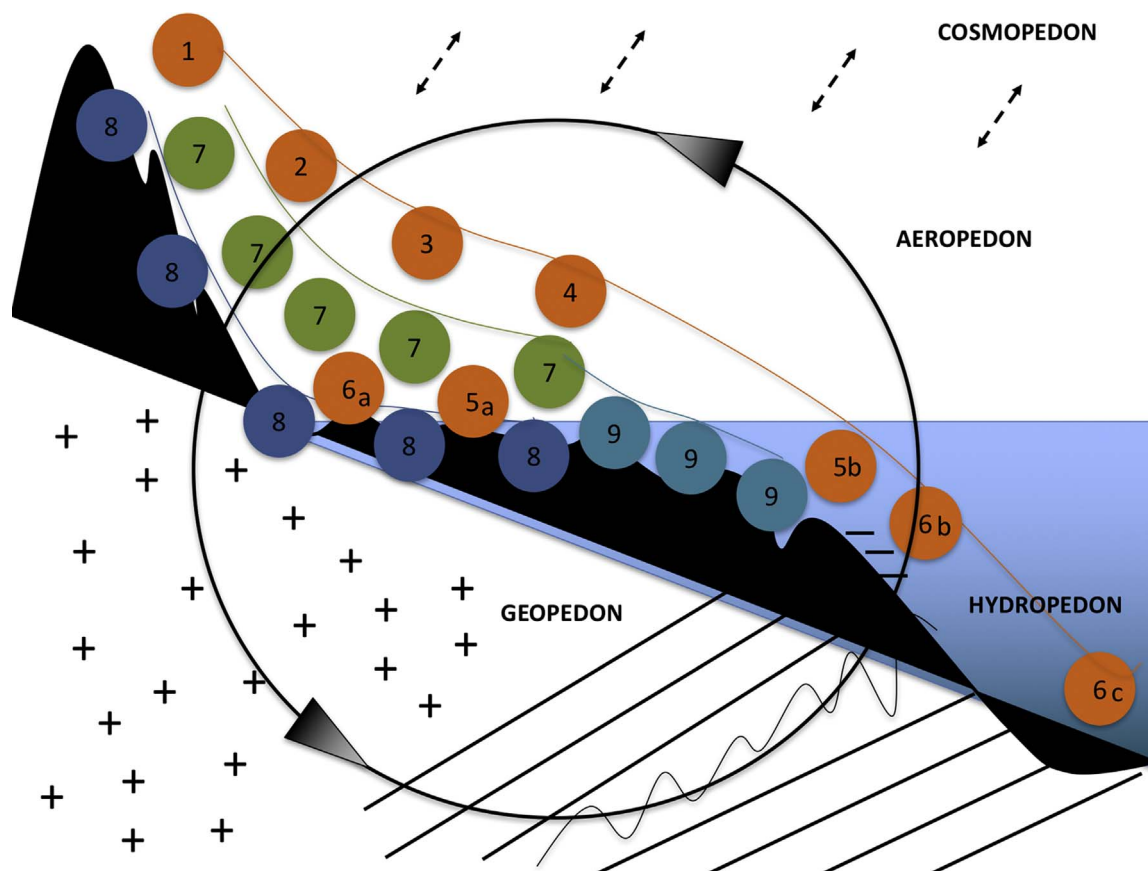


Fig. 30. Distribution of humus systems along a geomorphologic gradient: 1. Crusto; 2. Bryo; 3. Rhizo; 4. Ligno; 5. Anaero; 6. Archaeo; 7. Main terrestrial (Mor, Tangel, Moder, Mull, Amphi); 8 Main histic (Anmoor, Saprimoor, Amphimoor, Mesimoor, Fibrimoor); 9 Aqueous (Tidal, Subtidal).

Advertisement to the reader

As for other articles of Humusica 2, the reader must be informed that some knowledge of Humusica 1 (especially articles 1 and 7) is necessary for knowing what we mean by “humus form”, “humus system”, “humipedon”, “diagnostic horizon”, etc., and the same for the use of qualifiers, mosaic references, and most basic principles of our classification.

We must admit that Section 9 is largely speculative, and needs more developments in a paper specifically devoted to this topic. However, we think that it is important that the reader could be informed on our aim to enlarge our concept of humus form to every kind of environment where organisms, mineral/or organic matter are tightly interconnected from a functional point of view. This is the essence of “Para humus forms”, as better explained in the introductory part of this article. We do not intend to discuss the leading or subordinate role of bacteria compared to other organisms (there is a dearth of literature on “bottom-up” versus “top-down” control of trophic networks, without clear “winner” in the debate). Bacteria are here just an example of life which can be found everywhere on our planet, from deep rocks to the stratosphere, where they contribute to exchanges of matter and energy between biotic and abiotic compartments of air, water and earth. As a special issue of ASE, Humusica is, among others, a place where novel ideas can be presented to a wide audience, stimulating a debate about what soil is and what soil could be in our mind in a near future.

Authors' contributions

Zanella A. and Ponge J.-F.: coordination of authors, structure of the article, redaction of the first draft of text, tables and figures, re-elaboration, final presentation; Zanella A.: non-cited author of photographs.

Others Authors: collaboration to the redaction of the article in specific domains and punctual corrections in other parts. Introduction and Field assessment: Matteodo M., Fritz I., Pietrasiak N.; Crusto: Pietrasiak N., Fritz I.; Bryo: Matteodo M.; Rhizo: Juilleret J., Matteodo M.; Ligno: Tatti D., Le Bayon R.-C.; Anaero: Nadporozhskaya M., Fritz I.; Archaeo: Rocco M., Rotschild L., Fritz I.

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