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CHAPTER 2

FUNCTIONAL CONSIDERATIONS

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- **Energetic considerations:** Chapter 2.3.
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- Attempt to consider the conclusions of the book ***Plant Litter, Decomposition. Humus formation. Carbon sequestration*** (Berg B. and McClaugherty C., 2014) **in the frame of existing specialized humus systems:** 2.4.2. Allocation of net primary production and humus system strategies
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- ✓ Berg Björn: Limit values and stable fractions vs influencing factors
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CHAPTER 2

FUNCTIONAL CONSIDERATIONS

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2.1. A FUNCTIONAL CLASSIFICATION

Classifying has sense only if the established categories of objects correspond to a few references allowing us to better understand the observable real world. We have named these references Humus forms (= theoretical groups of humus profiles displaying the same series of diagnostic horizons) and Humus systems (= theoretical groups of humus forms sharing the same biological/functional properties). If we want to use these references for understanding the real world, some theoretical/practical principles have to be considered:

1. Things of the real world are organized in systems with a strange property: they encompass smaller systems and are themselves embedded in larger systems. The humus system concept has this fractal structure, too. The scale of the model has to be expressed clearly. Our purpose is to observe and classify the humus profiles observable in the field by the naked eye or with a 10X-magnifying lens. This scale allows us to detect objects whose smallest dimension is 1/10 mm (when magnified 10 times with a lens it becomes 1 millimetre large, which is visible by the naked eye).
2. Admitting a fractal structure means that we accept to discover “models” of functioning, not “real processes”. We find these models at each scale, they are interconnected and influence each other. Obviously these models are only “historical steps”; they help us to understand; they translate things from a concrete world into human “brain-models”.
3. The process of comprehension needs to start from a large-scale model, easy to understand, and in a second step include more detailed questions at a finer resolution, until reaching the limit of a personal (historical) knowledge. The inverse way has to be taken too, from smaller to larger scales, and the movement in both senses has to find a final relative harmony in a functional model that could be observed at the same time at both large and small scales. A detective (Sherlock Holmes, Miss Marple, Maigret,...) feeling, perhaps comes along with this harmony in progress.

The final functional model presented to other minds cannot satisfy everybody. It has not to satisfy everybody. It only admits the largest and relatively tolerant agreement; it helps us to understand things; if crowned by success, it represents a new starting point for further search. The final agreement cannot be different from an anthropomorphic statement.

2.2. WHAT IS A HUMUS SYSTEM?

The humipedon - the upper part of a soil made of organic and/or organic-mineral horizons - is directly under the influence of the aboveground parts of an ecosystem. The humipedon constitutes an interaction system born to manage a functional transition between organic and mineral worlds. This humus system has the possibility to degrade structured organic matter and use it as a source of energy. Further, it may act as a sink and a source of energy. On the one hand, due to the process of photosynthesis, plant activity produces organic matter, which feeds a complex system of consumers. On the other hand living organisms lose mineralised compounds such as water, carbon dioxide, ammonia, nitrate, and organic matter (urea, organic waste products) in order to renew their structures, thereby creating a substrate rich in energy, which can be utilized by numerous interconnected decomposers. Both processes (production and mineralisation of organic matter) are interdependent and can or cannot be well shared. All this activity is organized like a chain from the largest to the tiniest organisms. At each step, part of the energy is extracted from the substrate. Curiously, the result of the process of biodegradation is not a complete mineralisation of the previously built organic matter, but a new “body”, a new functional complex, an organic, organic-mineral and mineral interacting “being” (Fig. 2.1). On one side this new structure is able to form and/or retain vital elements while on the other side it can release these elements both in mineral form and in more sophisticated molecules (humic acids, hormone-like substances...). This new substrate behaves like a biological matrix in which microorganisms as well as meso- and macro-organisms live and evolve in tight association. The result seems helpful for the

producing photosynthetic system (aboveground), which finds in it water and nutrients in relatively equilibrated association all along its lifetime. We suggest that such systems of interactions between biotic and abiotic components taking place in the humipedon be called “humus interaction systems” or in short “humus systems”. They are designed to provide a name for still imperfectly known conditions for the common life and evolution of the immense variety of organisms which ensure, in a coordinated manner, the sustainability of terrestrial ecosystems. Since a limited number of strategies were selected in the course of Earth’s history, taking into account the variety of conditions (climate, nutrient availability, vegetation types...) prevailing in terrestrial environments, several humus systems have been described, featuring the bulk of existing variation (Ponge, 2003).

2.3. ENERGETIC CONSIDERATIONS IN TERRESTRIAL SYSTEMS

The large-scale approach (point 2 of section 2.1) has to consider the most important parameter while discussing ecosystem functioning: energy. No energy, no life. Sun sends high amounts of energy to Earth. Ignoring clouds, the average insolation for the Earth is approximately 250 watts per square meter (= 6 kWhm⁻² day⁻¹). In fact, over the course of a year the average solar radiation arriving at the top of the Earth's atmosphere is roughly 1366 watts per square meter of ground. Sun rays are attenuated as they pass through the atmosphere, thus reducing the insolation at the Earth's surface to approximately 1000 watts per square meter for a surface at right angle to sun rays at sea level on a clear day. Then, taking into account the lower radiation intensity in early morning and in evening, the sun angle at different seasons of the year and the fact that only half of the Earth spherical surface receives sun radiation - the other half being in night - the average insolation per square meter reduces itself to 250 W (1 W = 1 J s⁻¹). Still, this represents (250x60x60x24=21 600 000 = 21 MJ day⁻¹) about twice the power necessary to cover the daily energy expenditure of an adult human being (nearly 10 MJ day⁻¹, in Roberts & Dallai, 2001).

On a clear day, at noon (universal time), in a temperate zone, the carbon flux absorbed by a plant mass shifts from 10 to 40 µmol carbon m⁻² s⁻¹. As for the insolation, considering the night/day cycle and the changing height of the sun in the sky during the year, only a quarter of this value measured at noon may be taken as average over the course of a year. This means 2.5 to 10 µmol m⁻² s⁻¹. Then, on each meter square of terrestrial green Earth, a flux of 0.2 to 0.8 mole of carbon could be assimilated every day, corresponding to 2.4-10 g C m⁻² day⁻¹, or 876 to 3650 g C m⁻² year⁻¹. Taking in account the respiration of the photosynthetic mass (wasting 50% of the fixed C), the estimated net primary production (NPP) per square meter of terrestrial green Earth rises from 0.4 to 1.8 kg C m⁻² year⁻¹. Effectively, in a temperate climate, an annual production of biomass (biomass = 2 x C) of 1-3 kg m⁻² has been recorded.

In the Alps, data have been collected for some forest ecosystems:

- 1) Rodeghiero et al. (2003, 2010), InFoCarb (2007) (Italy):
aboveground total carbon (essentially in trees): 3.9 to 15.9 kg m⁻² ;
belowground total carbon (first 30 cm): 2.3 to 11.5 kg m⁻²;
total carbon of the system: 6.2 to 27.4 kg m⁻²;
litter carbon (freshly shed litter, aboveground): 0.21 to 0.65 kg m⁻².
- 2) Perruchoud et al. (1991ab) (Switzerland):
aboveground total carbon (essentially in trees): 7.6 to 13.5 kg m⁻²
belowground total carbon (first 20 cm): 4.8 to 7.4 kg m⁻²;
total carbon of the system: 12.4 to 20.9 kg m⁻²;
litter carbon (freshly shed litter, above- and belowground): 1.1 to 2.1 kg m⁻².

Figure 2.1: The place of the humus system in a terrestrial ecosystem. At the starting point there was a source of energy, a mineral planet and probably some small organic molecules. Using the available energy of a star (the sun), the mineral-organic world produced more complex structures occupying larger and larger space-time of the planet. Simplifying, the interaction between two components may explain how things are evolving. The photosynthetic unit is able to stock and restitute at the right moment/place a small but useful part of solar energy. The geological component stocks and delivers at the right moment/place the “grains of matter” necessary for the functioning of the first unit, which takes those mineral elements for building a new substance made of a carbon skeleton (instead of the preexisting silica skeleton of the rock), a certain amount of water and a low number of minerals. The interaction between the units is ensured by a web of consumers of the organic matter thus produced. Every structure exists and grows in a limited space-time. Each structure that originates in a point of the space-time grows, reproduces itself, dies, and is transformed into elements, which may be used for building new structures. Because of the gravity force, the residues of these aged structures fall and accumulate on the surface of the planet. Their transformation and reuse are influenced by environmental conditions. In cold, acid or anoxic situations biodegradation and reuse of organic residues progress slowly; besides, the more favorable the conditions for the decomposers, the faster the residues will be transformed and reused in new processes. Progressively, another component develops and grows between and with the two other ones: a humus system. Curiously, the result of the process of biodegradation is not a complete destruction (to mineral molecules) of the previously built organic matter, but a new “body”, a new functional complex, an organic, organic-mineral and mineral interacting “matrix” develops: humus.

Observing these data, and using a simple but realistic model, in an undisturbed forest ecosystem with all growth phases being in equilibrium. While an annual carbon mass of $0.5\text{--}1.5\text{ kg m}^{-2}$ is assimilated, an equal mass of carbon reaches the soil as litter, half above- and half belowground (root litter). All the “assimilated solar energy” is then cycling and feeds a “forest engine” such as gasoline fuels a car’s engine (Fig. 2.2). The main difference between forest ecosystems and cars is that the former produce their own gasoline in the form of litter by extracting energy from sunlight. The produced carbon mass, the “static mass” of this standard forest ecosystem, considering the roots living in the first 20-30 cm of soil, amounts to nearly 20 kg m^{-2} . In an Alpine environment, the biomass of living forest represents about 10 times the “turning dead mass”, i.e. the sum of above- and below-ground litter (Fig. 2.3).

Figure 2.2: Carbon balance. In an undisturbed forest ecosystem, the average annual net production of organic matter is used in the process of respiration by animals and microorganisms. Net primary production equals respiration + leaching and in an undisturbed Alpine forest ecosystem this amounts to $1\text{--}1.5\text{ Kg C m}^{-2}\text{ year}^{-1}$.

Going further in understanding our model, a useful way is to study - separately - the processes of production and respiration of glucose; in fact, though partially, Calvin and Krebs cycles represent the series of chemical reactions characterizing these processes that effectively occur in different times and spaces. They coexist at the level of ecosystems; they act together: no production without respiration. For understanding the functioning of an ecosystem, one has to consider both processes: production and respiration, or construction of bio-structures and their degradation. Concerning the evolution of terrestrial ecosystems, two kinds of dynamic changes have been well described:

- a LINEAR evolution: under favorable conditions, space-time is increasing, the system grows from an initial step of bare rock towards a better organized forest or grassland ecosystem, crossing a long series of intermediate levels of increasing complexity. The direction of the evolution may be inverted (collapse) in case of unfavorable conditions. More simply, when the biomass of the system is growing, the photosynthetic production has to be larger than the mass decomposed by respiration;

- a CYCLIC evolution: as for an individual life, each system comes into existence, develops, becomes adult, ages and finally dies. A forest, for example, knows innovation, aggradation, biostatic, and collapse phases (Oldeman, 1990). Observing attentively the formerly described linear evolution, it occurs that this process is made of a series of cyclic evolutions (Fig. 2.4). A force seems to push the natural systems along a space-time containing increasingly more complex structures, in response to a better use of solar energy. For the systems, this means being able to retain on Earth the largest part of energy coming from Space. Finally, adapting the topsoil to local constraints corresponds to a survival strategy, a need of parsimony in the use of a limited amount of energy.

Figure 2.3. Flux of mass and energy in a standard forest ecosystem. The flux of mass in a standard forest ecosystem concerns nearly 1/10 of the producing biomass. This **"travelling mass"** is composed of residues (dead organic matter lost by living organisms). The biodegradation takes place in the topsoil. This **"turning mass"** is necessary to maintain the system in a state of equilibrium. The static living mass is represented by a thin blue line, sharing above- and belowground "travelling biomasses".

Legend: E= energy (white arrow, electromagnetic waves at high frequency; red arrow, low frequency electromagnetic waves; the difference of energy becomes the "gasoline" that feeds the forest-engine); 1 = assimilation of water, mineral elements and energy; 2 = storage of energy in the soil.

Figure 2.4. As for the processes of production and respiration, it is hard to separate linear from cyclic evolution. Both interact at different space-time scales. Day-night cycles succeed within warm/cold seasons, influencing young/old stages, in warm/cold centuries and eras, on single/shared terrestrial crustal plates and seas... starting in high mountains from a bare rock point, in a medium cold climate, and stepping down through different ecosystems to join a more mesic plain, the natural history of a large territory has been crossed in a linear sequence (time step zero= bare rock; time 1 = crust and mosses carpet; time 2 = alpine grassland; time 3 =alpine heath; time 4= coniferous forest; time 5= broadleaf forest). However, stopping at one level and observing a given ecosystem, the cyclic evolution could be investigated. The more the system grows in complexity and biomass, the higher amount the “travelling mass” of carbon necessary for maintaining the system in good conditions. Quality and quantity of energy in the form of radiation, water, and mass of mineral elements limit the growth of the system.

2.4. CLIMATIC, PLANT LITTER, OR NUTRITIONAL CONSTRAINTS?

2.4.1. DARWIN, DOKUCHAEV, OR JENNY?

In an attempt to see further into the future, let us climb onto the shoulders of some fathers of soil science. There are two instructive articles that resume the debate in question since about a century ago, when scientific minds believed that they were able to understand the relationships between plants, soils, and animals. We have come further, but the question is still unresolved:

- ✓ Role of the plant factor in pedogenetic functions (Jenny 1958)
- ✓ Reflexions on the nature of soil and its biomantle (Johnson, Domier, and Johnson 2005).

The first article (Jenny 1958): “We shall set up models and imaginary experiments. Although they deviate from natural systems by an uncomfortable margin, these over-simplifications are most helpful in clarifying the independent and dependent aspects of the biotic factor and allied conceptual questions of system analysis.”

We report here three of Jenny’s imaginary sympathetic experiments. He wanted to illustrate the

influence of plants on soil development. The question is still under investigation (just a recent work: Andreetta et al. 2016).

First experiment: three boxes (climate-controlled) in which we may imagine: 1) bare soil; 2) 1+ grass seeds; 3) 1+ legume seeds.

Question: in the three boxes, how would be the soil be after 50 years?

Jenny's answer: only the "biotic factor" would change; climate, topography, and parent material would remain the same. Plants would grow and generate different soils, the one made by legumes (symbiotic fixation of N_2) would become richer in N and organic matter compared to the one made by grasses.

Second experiment: two boxes, the same loessic parent material: 1) ten per cent oak and ninety per cent pine seeds; 2) ten per cent pine and ninety per cent oak seeds; he reseeds annually but does not cut the trees.

Question: How will these two systems evolve?

Jenny's answer: If the two mixed-culture tanks are left to themselves for many centuries, their stands and proportions of species will become more and more alike, even if we keep adding annually the original seed mixture. Adult trees produce seeds and will self-determine the evolution.

Jenny's deductions: the soil under pine is different from the one under oak because of a species-specific effect. Plants make a specific soil: "if we cut the forest of one of the two boxes in the preceding experiment and replant it to an entirely new set of species, a new development cycle is instigated."

Third experiment: interaction between two large phytotrons, separated by a partition wall which prevents transfer of matter: 1) with a dense grass sod; 2) with a eucalyptus grove.

Question: after the partition wall is removed, how will the interacting system evolve?

Jenny's answer: "eucalyptus will move slowly into grass, along a narrow fringe, in which the grassland soil – in this case, a parent material – is transformed into a new soil, which is not necessarily identical to the original eucalyptus soil".

With the same spirit, Hans Jenny proposed analogous imaginary experiments for studying the influence of parent material, topography, climate, initial state, and time on soil formation and evolution. Supported by his examples, he presented the following fundamental function: $l, v, s, = f(cl, o, r, i, t)$, where: l = landscape, s = soil, v = vegetation and cl = climate, o = biotic factor, r = topography, i = initial state t = time. He concluded the article stating that:

- a) If in a given area, the five state factors (second part of the function) vary continuously, soil and vegetation very likely will vary continuously also. Larger systems would be expected to diffuse into each other.
- b) If, in a given area, one or more state factors vary in a discontinuous fashion, soil and vegetation very likely will also exhibit discontinuities. In the field there will be lines of demarcation.

In the second article, D.L. Johnson, J.E.J. Domier and D.N. Johnson (2005) oppose Darwin's animal-process and Dokuchaev's terrestrial five-factors, zonal approach.

A clarification, reported at the beginning of the article: Jenny's function, just presented in the preceding section was in fact proposed 70 years earlier in Russia by Dokuchaev (1883). Focusing on this function, we can see that it is not a real mathematical function. It simply says that vegetation or soil or the result of their co-evolution (the landscape) is dependent on climatic, biotic, topographic, initial state, and time factors: no mathematical formulas, no numbers, but graphic interpretations, like maps of soil and vegetation or points on a bi-plot considering two or three factors and showing a trend. The point raised by Johnson et al. (2005) is that, in soil formation, by "biotic factor" Dokuchaev (and Jenny) intended a

strong influence by plants, and this view might be opposed to that of Darwin for whom, on the contrary, animals (earthworms, in Darwin, 1881) are the biotic factor (named “vegetable mould” by Dokuchaev and Darwin) of soil formation.

Johnson et al. (2005) preferred the “animal” interpretation. In this guide we link specific humipedons to particular humus “systems”, avoiding the distinction between plant, animal and/or microbial influences: all organisms are in play and their activities are tightly interconnected in this concept.

We can state that climate (summarized in the combined yearly distribution of incident energy, air temperature, humidity, and precipitation) is the main factor that determines the type of terrestrial ecosystem occurring in a given point of our planet. Climate influences biotic activities and adaptations, on each given initial mineral substrate. Then, biotic (microbial, animal, and plant) activities modify the original natural frame, building an ecological dynamic system, changing with time, in equilibrium within a recognisable finite part of the planet, with structured plant-animal-microbial trophic networks, in a volume including aerial, photosynthetic-evapotranspiring and pedologic, biodegrading-recycling spaces.

Observing the topsoil of different terrestrial ecosystems in Europe, five main humus systems have been pointed out and called Mull, Moder, Mor, Amphi, and Tangel (Zanella et al. 2011ab, Jabiol et al. 2013). A key of classification, based on characters of diagnostic horizons, allows us to identify humus systems in the field. It has been well-established that the ecological attractors of these five “modalities of litter biodegradation” are to be found in the environment. In fact, litter quality, climate, and nutritional factors influence soil biological activity, the latter being directly responsible for the structures observed in the topsoil. A work hypothesis has been set down (Fig. 2.5) and needs a supplement of theoretical knowledge, involving the concepts of “humus system strategy” and “limit value” which are discussed below.

2.4.2. ALLOCATION OF NET PRIMARY PRODUCTION AND HUMUS SYSTEM STRATEGIES

Historical published data and well-known facts (very numerous works listed in Berg and McClaugherty 2014):

1. Litter quality varies with species. Coniferous trees in general have needle litter richer in lignin and poorer in nutrients than litter of broadleaf species (tables 2.1 and 2.2 are discussed in chapter 2.4.3);
2. Litter is produced above the soil (leaves, branches, bark....) and within the soil (roots, exudates) in equivalent quantities (in all about $\frac{3}{4}$ of annual NPP). In boreal forests, these quantities encompass $\frac{3}{4}$ of $20\text{--}30 \text{ t ha}^{-1} \text{ yr}^{-1}$ = about 10 t ha^{-1} above the soil and 10 t ha^{-1} within the soil = $2 \text{ kg m}^{-2} \text{ yr}^{-1}$, 1 kg above and 1 kg within the soil (synthesis of several papers, approximate values);
3. Half of the mineral elements are retranslocated by trees before shedding litter onto the ground;
4. The shed litter endures a selective attack (living organisms, physical, and chemical agents) and a progressive transformation until it has lost more than half its weight. During this transformation, we observe the formation of a complex organic matrix, which is richer in N and lignin and ligninlike compounds than the original litter, and more resistant to biodegradation (Berg and McClaugherty 2008, Berg and Cortina 1995; Berg and Dise 2004; Berg and Lundmark 1985; 1987).
5. Using solar energy a forest system produces organic matter by utilizing mineral matter in air (CO_2 , N_2) and in soil (H_2O , N, S, P, Mn,...). Quantifying the cycle, even approximately, we obtain the following data (Fig. 2.6):
 - a. $\frac{1}{4}$ of NPP is added to the living body (biomass) of the producing system,
 - b. $\frac{3}{4}$ end up outside of this living body as litter. Of these, 1 part is stored in the soil and 2 are biodegraded.

- c. Therefore, $\frac{1}{4}$ of this newly created organic matter is living organic matter, the other $\frac{3}{4}$ are “invested” out of the producing living body of the system. Of these latter, 1 quarter is fixed in the soil (transformed in an organic mass resistant to biodegradation = humus in a chemical sense) and 2 quarters are forced into a perennial cycle.

TERRESTRIAL HUMUS SYSTEMS and main ecological attractors

UNFAVOURABLE CONDITIONS for
ANECIC WORMS
but important MESOFAUNA like
Arthropods and Enchytraeids
Base-poor parent material

MODER

- 1-HEMI
- 2-EU
- 3-DYS

- 1-HEMI
- 2-EU
- 3-HUMI

MOR

VERY UNFAVOURABLE
CONDITIONS for animal activity,
Base-poor parent material

LOW CLIMATE and NUTRITIONAL
CONSTRAINTS
for biological activity

MULL

- 1-EU
- 2-MESO
- 3-OLIGO
- 4-DYS

PERIODICALLY
UNFAVOURABLE
CLIMATE CONDITIONS
for animal activity
Base-rich
parent material

AMPHI

- 1-LEPTO
- 2-EUMACRO
- 3-EUMESO
- 4-PACHY

TANGEL

1-LEPTO PERIODICALLY UNFAVOURABLE
2-EU CONDITIONS for animal activity
3-PACHY Base-rich parent material

Figure 2.5: Graphic model. The main “ecological attractors” in which a topsoil “falls” under the influence of climatic and nutritional constraints and as a consequence of its biological activity and connectedness.

Figure 2.6. Cycle of annually produced organic matter. 1/4 of the newly created organic matter is living matter, the other 3/4 are “invested” out of the producing living body of the system. Of these latter ones, 1 quarter is fixed in the soil (transformed in order to be resistant to biodegradation) and 2 quarters are forced into a perennial cycle.

Litter is attacked by microorganisms and pedofauna. The more important decomposers are fungi and bacteria. These living organisms have an “r” strategy (high reproductive rate) and are very sensitive to environmental factors that influence the development of them on Earth: temperature, water, nutrients such as C, N, P, as well as basic metal elements necessary for composing indispensable functional enzymes...). Everything that can limit the availability of these essential factors and elements necessary for the development/growth of fungi and bacteria inevitably influences the process of litter biodegradation (Berg et al. 1997; 2000; 2001; 2007); However, even if fungi and bacteria are mainly responsible for the mineralization of litter, they are far from being the chief agents of its transformation and fragmentation. Soil saprophagous animals ingest litter and transform it into fecal material, whether organic or organic-mineral. Thus, even if their direct impact on weight loss is far less than that of the microflora, their impact on litter disappearance from the ground surface and incorporation into underlying mineral matter is of paramount importance. Both microbial and faunal litter-processing chains are tightly interconnected and benefit from each other (Ponge, 2013a). In figure 2.7 we present the annual bi-phasic cycle of litter (nOL horizon) in a temperate broadleaved forest.

Figure 2.7. The bi-phasic cycle of litter production and biodegradation in a temperate broadleaved forest with the example from a very common European lowland namely *Quercus-Carpinetum*. At fall, all previously fallen litter has generally been integrated into the soil by anecic earthworms.

Following the main environmental factors, in terrestrial condition (aerated soils), five different main strategies of litter transformation are possible:

1. MULL HUMUS SYSTEM STRATEGY (FIG. 2.8)

- ecological conditions: temperate climate and/or base-rich siliceous or calcareous parent material and/or easily biodegradable litter ($C/N < 30$) and/or no major environmental constraint;
- dominant actors of biodegradation: anecic and large endogeic earthworms, fungi and bacteria;
- actors' action: fast biodegradation and consequent disappearance of litter from the topsoil (≤ 3 years), carbon mainly stocked in the A horizon;
- pH_{water} of the A horizon: generally ≥ 5 ;
- diagnostic characters (morpho-functional result of specific biological activities): OH never present, A biomacro or biomeso, very sharp transition (< 3 mm) between organic and organic-mineral horizons.

2. MODER HUMUS SYSTEM STRATEGY (FIG. 2.9)

- ecological conditions: mild to moderately cold climate, generally on base-poor substrate
- dominant actors of biodegradation: arthropods, epigeic earthworms and enchytraeids; bacteria and fungi;
- actors' action: slow biodegradation (2-7 years), carbon stocked in both organic and organic-mineral horizons;
- pH_{water} of the A horizon: generally < 5 ;
- diagnostic characters: OH always present, nozOF never present, A biomicro, massive or single grain, no sharp transition (≥ 5 mm) between organic and organic-mineral horizons.

Figure 2.8. Mull humus system strategy. The equilibrium point is a biomacrostructured A horizon, essentially generated by anecic and endogeic earthworms, which consume and incorporate all fallen litter in an organic-mineral horizon. The red arrow indicates that the disappearing organic matter is transported into the soil (in this specific humus system mostly by anecic and endogeic earthworms) and partially (the part not dissipated in the process of respiration) ends fixed in organic-mineral aggregates, forming a biomacrostructured A horizon, typical of a Mull system. This process allows stocking the energy needed for the future evolution of the system. It constitutes a sort of warehouse, a bank of energy, exploited first by the earthworms themselves when fresher aliments are no longer available, but also by plants, microorganisms and any organisms living in the soil, directly or indirectly linked to this durable resource.

3. AMPHI HUMUS SYSTEM STRATEGY (FIG. 2.9)

- ecological conditions: highly contrasting climate conditions with prolonged periods of biological inactivity (dry summer or cold winter) alternating with favourable (mild) seasons, generally on base-rich carbonated or siliceous substrate; an artificial substitution of vegetation, with a consequent shift from nutrient rich and palatable broad-leaf litter ($C/N < 20$) to recalcitrant coniferous litter ($C/N > 40$), leads generally to a transformation of the original Mull into Amphi. This dynamic process can also generate a Moder on base-poor substrate or in cold climate conditions.
- dominant actors of biodegradation: endogeic and anecic earthworms in the organic-mineral horizon; arthropods, enchytraeids and epigeic earthworms in the organic horizons; fungi;
- actors' action: slow biodegradation (2-7 years), high carbon content in both organic and organic-mineral horizons;
- pH_{water} of the A horizon: generally ≥ 5 ;
- diagnostic characters (morpho-functional result of specific biological activities): OH always present, nozOF never present, thickness of A horizon $\geq \frac{1}{2}$ OH; A biomacro and sharp transition (< 5 mm) between organic and organic-mineral horizons, or A biomeso (biomicro possible, but only in addition to A biomeso) and no sharp transition (≥ 5 mm) between organic and organic-mineral horizons.

Figure 2.9. Moder and Amphi humus form strategies. We observe the formation of a layer of undecomposed litter. The thickness of this layer depends of climate conditions, which periodically stimulate and arrest the biological activity of biodegradation. The Moder strategy has a point of equilibrium which shows transformed litter (zoOF and zoOH) accumulation and thin (< 5-7 cm) biomicrostructured organic-mineral A horizon. Amphi conditions generate a double humus system (the so-called "twin humus") with both well-developed organic and organic-mineral layers. Supposing a biodegradation that may "digest" half the yearly arriving litter, we would assist at a never-ending process of accumulation (theoretical accumulation). In the field in aerated soils we instead observe that the process raises a plateau. The process of biodegradation and integration of new litter in the soil increases (we tried to illustrate the collapsing litter with multi-lined teeth and dashed green arrows) with the thickness of the not biodegraded litter and reach an equilibrium dependent on climate and litter quality.

4. MOR HUMUS SYSTEM STRATEGY (FIG. 2.10)

- ecological conditions: cold climate, and/or base-poor siliceous substrate, poorly degradable litter (rich in resins, thick cuticle, C/N > 40);
- dominant actors of biodegradation: fungi (mostly mycorrhizal) and other non-faunal processes;
- actors' action: very slow biodegradation (> 7 years), highest carbon content in organic horizons;
- pH_{water} of E or AE or A horizon: < 4.5;
- diagnostic characters (morpho-functional result of specific biological activities): nozOF (**always present (always present)**); nozOH (not always present and often difficult to recognize especially in wet conditions), E horizon or A massive or single grain, very sharp transition (< 3 mm) between organic and organic-mineral (or mineral) horizons.

5. TANGEL HUMUS SYSTEM STRATEGY (FIG. 2.10)

- ecological conditions: mountain climate (subalpine or upper montane belts) on strongly carbonated substrates;
- dominant actors of biodegradation: epigeic earthworms, enchytraeids and arthropods within organic horizons; fungi;

- actors' action: very slow biodegradation (> 7 years), carbon stocked mainly in organic horizons;
- pH_{water} of the A horizon ≥ 5 ;

diagnostic characters (morpho-functional as a (??) result of specific biological activities): nozOF never present but thick organic horizons [(zoOF + OH) > 10 cm], if present, thickness of A horizon < $\frac{1}{2}$ OH; if present, A biomeso or A massive.

Figure 2.10. Mor and Tangel humus system strategies. In this case harsh climate conditions favor the formation of very organic soils, with a non-zoogenic OF horizon in very cold and humid aerated conditions where a fungal transformation of the litter dominates (Mor), or with very thick organic zoogenic layers, in cold climates with periodically more favorable conditions for litter biotransformation (Tangel). Supposing a biodegradation that may “digest” half the yearly arriving litter, we would assist at a never-ending process of accumulation (theoretical accumulation). In the field in aerated soils we instead observe that the process raises a plateau. The process of biodegradation and integration of new litter in the soil increases (dashed blue arrows) with the thickness of the not biodegraded litter and reaches an equilibrium dependent on climate and litter quality.

2.4.3. WHICH ARE THE MAIN FACTORS ARRESTING LITTER BIODEGRADATION?

2.4.3.1. THE CONCEPT OF LIMIT VALUE

Litter biodegradation is a biological process, depending on climate, substrate chemistry, and litter quality. Following biological laws, the process probably shows a logistic curve, beginning at a low rate, which increases when climate or litter chemical composition becomes progressively more favourable, increasing exponentially at optimum climate and/or chemical composition to decrease when conditions become unfavourable, for example due to limiting factors, such as subzero temperatures, summer drought, limited availability to nutrients, or when all litter has disappeared from the ground surface. The thick red descending line in figure 2.7 represents this process. There may be a

biodegradation even in winter (illustrated by the feeble slope of the top part of the thick red line), after which the process rate increases again with favourable conditions. In the figure this is represented as a commonly observed case of resource, when all available litter disappears before climate (or chemical) conditions arrest the natural biodegradation process. The rate of the process changes when climate conditions, or litter quality, e.g. nutrient availability, become limiting, as seen in figures 2.8 and 2.9. The process may last over several years and the annual cycle thus is repeated for several years. The curb of litter accumulation/disappearance looks like a saw-tooth line (Fig. 2.8).

The rate of the process changes and decreases when litter quality (nutrient availability) or climate conditions become limiting (concept of limiting value expressed in figure 2.11). Several successive years of the biodegradation process are represented in figures 2.9 and 2.10 and correspond to the genesis of Amphi or Moder and Tangel or Mor humus systems. In these cases, not all the yearly produced litter is consumed by biodegradation and we observe an accumulation of not decomposed litter (which stays on the soil even partially transformed: fragmented = OF horizon; humified = OH horizon). The system seems to produce more litter than it is able to degrade or “digest”. In figures 2.9 and 2.10 we represented both, a theoretical accumulation, hypothesizing a yearly biodegradation of half the new litter, and the observed accumulation, which continues until a plateau is reached. The harsher the conditions for decomposition, the higher the thickness of the organic horizons of the humipedon and the further in time the reached plateau. At the plateau level, the system degrades an amount of litter and organic matter which corresponds to the amount of new litter produced and the organic layer covering the organic-mineral and mineral soil maintains a constant thickness (stable fraction). This phenomenon is described in Berg and McClaugherty (2008, 2014) with the use of a function (figure 2.11). The growth of the stable fraction may be followed by summing the stable residues (100-limit value) of each year's litter fall. The simple formula $\sum(100\text{-limit value})$ over n years may give the accumulation. Such a calculation has been made for close to 3000 years ($n=2984$) (Berg et al. 2001; Berg and Dise 2004) for a boreal Mor system.

When the system reaches the plateau, the thickness of the organic horizons may remain stable even if new litter continues to fall onto the soil. This means that at this point, all the litter input is biodegraded and organic matter disappears not at the top but within the mass or at the bottom of the organic horizons. We think that at the plateau level, litter could have formed an enough temperature-insulating blanket that allows pedofauna and microorganisms activities for a litter biodegradation that compensates the annual addition of litter. We may point out that such a steady state has never been proven and with a humipedon still growing well after 2500 years (Berg et al. 2001), we may conclude that we deal with a concept which in practice is theoretical. Further, the equilibrium plateau may be different among ecosystems and vary with the litter components and climate.

The limit-value curve resembles the top lines that smooth out the toothed trend represented in figures 2.9 and 2.10. We can say that a limit value of 100% is raised in figures 2.7 and 2.8. In figures 2.9 and 2.10 the limit value is less than 100% and we observe an accumulation of litter year by year until raising a threshold value. In figures 2.8, 2.9, and 2.10 are also represented the results of litter transformation, i.e. different types of underlying A, OF, and OH (zoogenic or not) horizons. The evolution of the humipedon is arrested when the humus system has reached a point of dynamic equilibrium (a plateau). However, such an equilibrium has not yet been identified and may vary with dominant species and ecosystems. Above this plateau level there is the same annual amount of mineralised carbon (as CO_2) as is fuelled to the soil in the form of litter.

Although a plateau has been theorized, we must state that at present we know just part of what regulates the growth rate until the plateau.

It has been proven (many works collected and explained in Berg and McClaugherty 2014) that the limit value depends on litter quality and particularly its content in mineral elements and contents of lignin, nitrogen, and manganese.

The accumulation rate depends on (i) the amount of annual litter fall, which is related to climate, (ii) the size of the residual fraction estimated by (100-limit value), which determines the fraction of the annual litter fall that is accumulated. These aspects will be illustrated here with the help of selected data and figures extracted from Berg and McClaugherty (2014).

Figure 2.11. The limit value concept and its mathematical representation (from Berg and McClaugherty 2008, 2014).

2.4.3.2. LITTER QUALITY AND ITS CONTENT OF MINERAL ELEMENTS

Except for K and Mn, coniferous needle litter is generally poorer in mineral nutrients than the litter of broadleaf trees (e.g. Tab. 2.1). Coniferous needle litter is richer in cellulose and its woody litter is richer in lignin (Tab. 2.2); deciduous leaf litter is richer in water-soluble compounds, and its woody litter is richer in cellulose and pectin (component of primary cell walls).

The litter’s content in mineral elements mainly increases during the process of biodegradation. The litter’s organic matter is decomposed in a process known as “mineralization”. This process takes place in the soil (physical and biological attacks) and within living bodies of animals. Mineralization liberates both mineral elements into the soil and fine colloidal organic particles that can be leached out of the litter by percolating water. Further, delivered energy and minerals are invested in new living bodies and droppings, which in turn may be consumed in turn by other consumers. “Humification” is the process of storage in the soil of “organic matter other than fresh litter,” meaning organic (living and dead) and mineral products that remain in the soil and result from the two abovementioned processes of litter degradation: 1) physical and chemical mineralization by living organisms, whose bodies remain in the soil and 2) transformation inside living bodies and production of biomass and faeces, which may be consumed several times by other soil organisms. Humification may also result from the abiotic transformation of plant residues (mainly wood and cuticles, but also tannins), which slowly evolve by

incorporating oxygen (incomplete oxidation) and nitrogen (proteins, amino acids) without undergoing mineralization: lignin and polyphenol theories (Stevenson, 1994).

Table 2.1. Concentration of nutrients in coniferous needle and deciduous leaf litters. From Berg and McClaugherty (2008). Data: a) Johansson et al. 1995; b) Berg and Lundmark 1987; c) C. McClaugherty and B. Berg (unpubl.); d) Berg et al. 2000; e) Berg and Ekbohm 1991; f) Bogatyrev et al. 1983. In red the highest value, comparing average for mineral elements in coniferous and deciduous leaf litters.

Litter	Concentration of nutrient (mg/g)						
	N	P	S	K	Ca	Mg	Mn
Scots pine a)	4.8	0.33	0.55	1.07	4.4	0.49	0.79
Lodgepole pine b)	3.9	0.34	0.62	0.56	6.4	0.95	1.79
Maritime pine c)	6.8	0.54	1.01	1.95	3.1	1.9	0.59
Red pine c)	6	0.36	0.73	1.4	8.9	2	0.73
White pine c)	5.9	0.21	0.68	0.7	7.2	1.1	0.8
Jack pine c)	7.8	0.64	0.77	2.3	4	2.1	0.25
Limber pine c)	4.3	0.43	0.52	1.1	5.3	1.1	0.21
Norway spruce d)	4.9	0.45	0.73	0.72	17.9	0.65	na
AVERAGE Coniferous needle	5.6	0.41	0.7	1.23	7.2	1.29	0.7
Grey alder e)	30.7	1.37	6.12	15.6	12.3	2.32	0.1
Silver birch e)	7.7	1.05	0.8	4.7	11.8	3.3	1.23
Ash f)	8.6	1.96	Na	15.3	33.2	2.28	0.003
Mountain ash f)	7.1	0.31	Na	10.8	12.4	2.86	0.3
Trembling aspen f)	8.2	0.93	Na	5.1	29.9	4.69	0.53
European maple f)	5.1	3.15	Na	13.1	20.4	1.46	0.12
European beech d)	9.5	1.4	1.3	2.3	7.4	1.2	1.9
AVERAGE Deciduous leaves	10.9	1.45	2.74	9.6	18.2	2.59	0.6

Table 2.2. Compounds in coniferous and broadleaf litters (synthesis of many works: Berg 1998, 2000a, 2000b; Berg, and Meentemeyer 2002; Berg et al. 1982;1991;1995; Berg and McClaugherty 2008,2014)

Litter compounds	CONIFEROUS	DECIDUOUS
Water soluble compounds	10-15	20-25
Ethanol soluble compounds	5-10	5
Cellulose (needles and leaves)	20-30	10-15
Cellulose (wood)	10-15	35-45
Hemicellulose	1-2	1-2
Pectin	3-4	4-6
Lignin (needles and leaves)	20-30	15-25
Lignin (wood)	35-45	20-25

The process of mineralisation has been schematized in figure 2.12. Among the different compounds, gravimetric lignin shows a particular trend: its concentration increases and so does the concentration of new compounds due to incorporation of N in the litter's aromatic structures.

Figure 2.12. The process of mineralisation (y axis = sum of stable residues, viz. the residue when litter has reached the limit value. Litter compounds are transformed and mineral nutrients released. The picture does not show a parallel process of humification, which on the contrary builds new structures and living bodies in the soil.

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A process in which new stable compounds are formed from lignin and N has been described producing an increased concentration of these stable compounds. In the forest floor the concentrations of such stable compounds increase as does the amount due to the annual addition of a new undecomposed mass of lignin and 'reactive' N. In each given environment an equilibrium point will be raised where all components stabilize. This point corresponds to the stable formation of a humus system, with its specific horizons and living actors of biodegradation.

The humification process is much more complex and differs according to the humus system, each system being adapted to particular environmental conditions. The aim of the present guide is mainly to illustrate how to individuate and describe all these different humus systems. Plotting annual litter mass loss (= % of biodegraded and disappeared litter) versus litter lignin concentration at the start of each year Berg and McClaugherty (2008, 2014) discovered a strange "point of convergence" (Fig. 2.13): concentration of gravimetric lignin increases in the first years until a concentration of about 500 mg g⁻¹, which remains constant for the following years. The process is correlated to the actual evapotranspiration of the site in which the process occurs. High evapotranspiration also means high potential production of photosynthetic biomass. When the system is highly productive, the biological process of decomposition is also very active and the slope of the line of regression of litter mass loss

versus lignin concentration is steep. At the point of convergence the litter mass-loss rate is the same irrespective of the site's temperature, suggesting that litter chemistry may ensure a regulatory function.

Figure 2.13. Convergence of the regression lines of first-year litter mass loss versus concentration of gravimetric lignin to a point of about 500 mg g^{-1} at which litter decomposes at about the same rate irrespective of climate. The slope of the regression lines is well correlated to the actual evapotranspiration measured at the sites. High annual litter mass loss occurs at sites with high evapotranspiration which thus are well productive. The terrestrial humus systems described in this guide, from the most active Mull, in favourable climate conditions, to the less active Mor and Tangel, passing through intergrade Amphi and Moder, are indicated in the little graph on top right comparing actual ETP and slopes of regression lines.

2.5. HUMUS SYSTEMS AS AN ECO-DEVICE

Why are we interested in humus forms? Why are we trying to classify them? Why are we investigating processes of biodegradation? All these questions go back to the intuitive feeling that humus is useful for human beings. It might be useful as a source of 'free' nutrients needed for crop growth or timber production. It might provide a structure protecting soils from erosion. It might be an interesting sink for carbon sequestration in respect to the problem of climate warming. Also the humus system can be considered as a habitat for an abundant and diversified soil life highly contributing to global biodiversity. At the same time the heterogeneity of the soil might result in a broad niche differentiation providing a competition-free environment and consequently a blue print for plant biodiversity. Without being exhaustive it will be clear that the humus system has a manifold purpose character for human use. Depending on one's interest the humus system will be used in different ways. In this context the humus system can be considered as a tool, or better a device and still better an eco-device, the functional outputs (in terms of utility for humans) of which should be in line with the user's interest. In other words there are many ways to investigate the humus system. Trying to provide a common ground for these diverging interests, the eco-device concept will be introduced as a metaphor.

Analogous to an electric device an eco-device can only produce utility if connected to a potential field between a source and a sink. In this way house-keeping devices are connected to an electricity field and eco-devices to an ecological field. It will be clear that solar energy will be the main driving force for this ecological field. Other ecological fields may also occur, such as hydrological gradients between recharge and discharge areas.

It is the internal structure of the eco-device that determines its usefulness. An electric razor has quite another structure than a radio tuner although both use a difference of 230 V out of the same potential field. The internal structure of an eco-device is a function of local site factors (texture, pH, mineral composition, etc.), vegetation, and soil organisms. The main structures are known as Mor, Mull, Moder, Amphi, and Tangel. Each of these structures provides a distinct utility of the humus system: for example: a Mor is better equipped for carbon sequestration in cold climate than a Mull; but a Mull is better equipped in providing nutrients for plant or crop in temperate climate; an Amphi might generate favorable habitats for soil biodiversity and niche differentiation, in more contrasted climate conditions.....

The eco-device is founded on four main ecological functions: *supply* and *resistance* at the input side and *disposal* (release) and *retention* at the output side (Figure 2.14a). The eco-device makes use of these four functions to control its functionality for human beings or more specifically the operational environment for individual organisms, communities, habitats, ecosystems, landscapes and finally our Earth. Also the eco-device can be considered as a fractal structure: at each lower level the eco-device is embedded in a higher level with fundamentally the same fractal structure (Fig 2.14b). Conservation of energy is actually ensured by the chain of eco-devices. Disposal of energy from eco-device 1 will be a source (supply) of energy for eco-device 2. This approach even fits to the general ecosystem theory of Jenny in which the humus system clearly shows its dependent character (Figure 2.14b).

By its four main functions the eco-device is capable to maintain boundary conditions between maximally acceptable and minimally necessary energy and/or matter. Shortages can be prevented by supply or retention. Disposal or resistance protect against over-feeding. These functions can be applied to the humus system as well in a way that is preferred by the user, be it a human being, a soil organism or any plant species.

Some examples: a Mor humus system clearly displays its retention function for climate control by carbon sequestration, but also for hydrological control by its water holding capacity or nutrient retention by its low mineralisation rate. A Mull humus system on the other side has an excellent supply function for nutrients, which might be in favor of the activity of soil organisms and plant growth. In Agro Mull on arable land this function is overactive and disposal by leakage is necessary to prevent eutrophication. Mull also generates high nutrient cycling rates and consequently has an explicit disposal function for nutrient (N, P, K, Ca) release but a bad behavior with respect to climate control. Even in most Dutch natural fen meadows mowing and harvesting without manuring is a human measure to prevent an excess of nitrogen by atmospheric deposition. Actually this management replaces the ecosystem's disposal function. Without human aid these meadows should suffer from over-feeding, i.e. eutrophication. Resistance might finally play a role in the protection of seed banks, roots, soil organisms etc. by a thick OL or OF horizon acting as an isolator during cold or dry periods. Mull has a high resistance against the loss of nutrients by forest fire, as the main source of nutrients is in the endorganic part that is protected against fire. The same holds true most probably and for the same reasons for protection against climate warming. In contrast - mor humus forms has hardly any resistance against loss of nutrients in case of forest fires, as all nutrients are stocked in the ectorganic layer. Finally many other examples probably can be found to illustrate these distinct functions.

Figure.2.14. a) Concept of an eco-device that is composed of four main functions to control input and output of energy and to realize its functionality for potential users; b) the humus system can be considered part of a repeated structure of eco-devices at different hierarchical levels and is in its essence a fractal structure

Humus systems can also be seen as devices that convert energy into information. It is challenging to discuss the applicability of thermodynamic laws to eco-devices in general and to humus systems in particular. According to the First Law of thermodynamics energy cannot be lost and the Second Law states that open systems strive to the lowest energy levels and maximum entropy, corresponding to disorder and unpredictability (uncertainty sensu Heisenberg). In other words loss of energy coincides with increasing disorder. Order can only be achieved by input and storage of energy. According to thermodynamic laws the storage of energy in humus systems (by carbon sequestration) should therefore inevitably lead to decreasing entropy and subsequently to increasing organizational levels. Horizon differentiation mirrors this increasing degree of organization in humus systems. These highly ordered structures are reliable and predictable environments for organisms, including man, using any product of the humus system. By niche differentiation the competitive exclusion of organisms in their competition for nutrient resources is prevented. Many species will find a niche, which is a favourable condition for a high biodiversity.

Figure 2.15. The humus system (or more precisely the humus form) as a function of primary ecosystem factors and vegetation

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However the application of this law to the soil is not so simple. Following it, the more horizons there are, the more the living soil is organized, and the more it allows species to coexist. However, the higher level of biodiversity is actually achieved by Mull, not Moder or Mor (Ponge 2003, 2013a). Here the notion of stability takes place and should prevail when speaking about biodiversity. It is generally acknowledged that biodiversity first increases and then decreases with the level of disturbance according to a hump-shaped curve (Ponge 2013b). As most real objects, humus systems are the result of tradeoffs (compromises) between independent, opposed forces (the so-called “laws”, which are true only in theory, within a given set of conditions, rarely fulfilled in the real world, to the exception of man-made “devices”). The apparent “disorder”, visible in Mull is in fact the result of many disturbances such as temperature and moisture “highs” and “lows”, activities of burrowing animals, root growth pulses, etc., which counteract competitive exclusion (only demonstrated in artificial systems) and favor the coexistence of many species and functions. Despite and due to its “disorder” Mull maximizes biodiversity and associated functions such as high productivity (Ponge 2003). Energy is dissipated, according to the Second Law of thermodynamics, but this energy is not lost to the grassland or forest ecosystem, being rather circulated between plants, microbes, and animals: energy (and in the same way nutrients) is conserved, but in a state of permanent, or seasonal change. This is the force, but also the weakness of Mull, which is sensitive to any decrease in its integrity, such as when land-use changes, or when key organisms are killed or replaced by man (conifer plantation, hunting, etc.). Mull thus violates both the Second Law of thermodynamics and Darwin’s rule of species coexistence, the famous “struggle for life”. On the opposite side, Mor is strongly “organized” in the form of a variety of horizons, each inhabited by a specific assemblage of organisms, but Mor is much poorer than Mull from the point of view of biodiversity. This is not the result of competition, but - on the contrary - an effect of environmental factors which are detrimental to most organisms, namely harsh conditions: cold, acidity, sometimes

pollution (as in heavy metal-polluted sites). The Mor strategy is the best compromise between the need to ensure the sustainability of the ecosystem and an otherwise unfavorable context. In Mor the conservation of nutrients and energy is ensured by the soil, not by the vegetation. Moder is an intermediate between these two opposite strategies, allowing some level of nutrient and energy circulation between soil and vegetation, although at a lower level than Mull (Ponge 2013a). However, the all-round champion of compromises is Amphi. This humus system combines the advantages of Mull and Moder, by offering conditions of life for all types of organisms, while avoiding the main weakness of Mull, its lack of protection against climate hazards. By its dual nature, Amphi is able to sustain ecosystems through ecological crises such as present-day global warming and associated threats such as increased aridity (Ponge et al. 2011).

The organizational level of Agro Mull systems (see chapter 15 for a description of these anthropogenic humus systems) is low and close to a chaotic state. Homogenized “chaotic” humus profiles are illustrative for low organizational levels and poor biodiversity. The homogenization of the soil is obtained by the application of mechanical agricultural machineries (plows, rotating blades...) which mix the soil but cannot mimic organic-mineral and microbe-rich earthworm aggregates. By lack of organized (humus) structures the environment of Agro Mull is unpredictable and organisms have to compete for nutrient sources instead of relying on niche differentiation or repeated disturbances. Survival of the strongest is the adagio and monoculture the result. The most extreme example is an Anthropogenic poorly zoogenic massive A horizon (described in chapter 15). In this system a large part of the circulating energy is transferred to crop production, which is exported (thus lost) at the end of the cycle. Crops have also to compete with weeds, which try to counteract the Second Law and restore a more complex and ordered state. Accordingly to thermodynamics energy is needed to reduce entropy and to favor ordered structures like soil structures and more interactive ecosystem. In the same time an input of energy (fertilizers, pest control) is needed to maintain these poorly ordered and simplified systems, depend on humans for their maintenance. In other words, under temperate climate conditions, allowing a complex organization of the living network, simplified and poorly bio-diverse ecosystems, such as arable crops, are possible only at the cost of a high investment in energy inputs. On the other hand more ‘natural’ ecosystems such as forests, heathland or grassland (pastures, conservation grade agricultural crops and hay meadows being good compromises) try to organize themselves by conserving energy (First Law) but at the same time by converting it into an infinite number of localized structures (minimum level of entropy), rendering the whole compatible with the Second Law. Consequently, ecosystem development should be predictable. It is the task of ecologists and farmers to unravel the chaotic structures of these predictable systems and periodically restore the original complexity of the soil.

2.6. CAN TEMPERATURE INFLUENCE HUMUS DECOMPOSITION?

Björn Berg

Dear Augusto. This is the text you objected to:

We may point out that such a steady state has never been proven and with a humipedon still growing well after 2500 years (Berg et al. 2001), we may conclude that we deal with a concept, which in practice is theoretical. Further, the equilibrium plateau may be different among ecosystems and vary with the litter components and climate.

and your response:

I do not think we need to prove the existence of a plateau. If accumulation would have continued for 2500 years without raising a plateau, 1 cm/year of litter accumulation would have given 2500 cm = 25 metres

of organic layer, which is absurd. When litter reaches a given thickness, the process of accumulation continues at the top but biodegradation works under cover, imposing a given thickness to the organic cover. The system thus reaches a plateau. This plateau mostly depends of climatic conditions, litter quality certainly plays a master role too, the more we near the North pole, the lower the air temperature and the higher the thickness of not biodegraded litter, and probably the longer it takes to reach a plateau.

My (BB) comments:

My intention was to suggest that the concept plateau or steady state should be (ought to be) different depending on (i) climate and (ii) plant community giving different litter species. Still we have this phenomenon that the concept 'steady state' is one that often occurs and often is used but in a not very clear way. We could treat it as a theoretical concept (more below).

Maybe I can start with a bit of background – using the limit-value terminology we may say that a humus build-up can be described as dependent on amount of litter fall and the size of the stable fraction, which possibly could be 100-limit value.

Litter fall. If we use data for foliar litter fall we may see that for both Scots pine and Norway spruce there is a higher litter inflow with increasing temperature, and highly significant positive relationships to MAT and to AET. Such relationships were found for a region from the Arctic Circle to Normandy. In addition – foliar litter fall for Norway spruce was higher than that for Scots pine.

About **far-decomposed litter** in a climate gradient. Figure 2.13 gives data for Scots pine litter. Initially the litter is decomposing at very different rates – related positively to MAT – a very traditional image. As litter becomes gradually richer in gravimetric lignin the difference in decomposition rates between sites with different MAT/AET becomes smaller. Finally, in the red circle (figure 2.13) they converge and in the original figure they even cross each other. This means that far-decomposed litter – all Scots pine needle litter collected at the same site - is decomposed at the same rate - once it has reached the far-decomposed state. A consequence and conclusion is that - at that stage - temperature is not important and that at a certain decomposition level it does not influence decomposition rate. Rather, some other factor(s) is more important and more limiting. A similar conclusion was reached by Marie-Madeleine Couteaux and her group in Montpellier, using standard wheat straw in a climate gradient (Dalias et al. 2001). We also tried to evaluate the effect of MAT vs that of substrate quality once again using another approach (Berg et al. 2015) by comparing four main properties of litter and site, namely site MAT, and litter concentrations of Mn, N, and AUR (gravimetric lignin). That study was made in a climate gradient. There was a clearly significant, negative effect of MAT ($p=0.017$) but the more pronounced effects were those of litter chemistry. That the effect of MAT was negative is in accordance with the studies by Johansson et al. (1995) and Dalias et al. (2001).

Limit values and stable residues for pine species, mainly Scots pine were investigated for regulating factors. Ten factors including climatic and substrate quality were related to limit values and the only significant relationship was that to Mn concentration. No effect of MAT on limit values (Berg et al. 2010). Further, average limit values are also different among litter species and as far as we know Norway spruce has a somewhat larger stable residue than litter of Scots pine. The stability of this stable residue is uncertain but should vary among litter species – depending on their chemistry.

Humus in large-scale field measurements. I will jump to an investigation we made on humus growth along Sweden (Berg et al. 2009). We used about half a million humus-depth values collected over a 41-year period. They were distributed all over Sweden and we subdivided them into grid plots of 25x25 km. The annual measurements started in the 1960-ies when wild-fire protection had been well built up.. After a first investigation of data we divided the grid plots into three climate zones (Berg et al. 2009) based on temperature sum. In addition – each of the grid plots had a determination of temperature sum, which we used for relating C sequestration rate to temperature sum. The humus layer measured was F plus H or the FH layer. This layer would be made up of stable litter residues and judging from data (cf

figure 2.13 and results from a limit value study – Berg et al. 2010) its decomposition would not be sensitive to temperature.

First – in all the three climate zones there was an increase in humus depth (and C sequestration) with time. There was a difference initially between them, with the thickest layers in the south (region High) and the thinnest ones in the north (region Low). As you will see (Berg et al. 2009) the long-term increase was highest in the south (region High) and lowest in the north (region Low). We also found that there was a positive correlation between temperature sum and the increase rate in humus layers ($R^2=0.29$; $n=548$; $p<0.0001$)).

We also found a significant difference in increase rate between pine- and spruce-dominated plots with a higher sequestration rate for pine ($p < 0.0001$) – in spite of a higher foliar litter fall for spruce.

My conclusion from this data is that the inflow of litter is determining for C sequestration rates in the organic layers and that the increase is positively related to temperature effect on amount of litter fall. Of course, such a conclusion is based on the existence of a relatively stable residue.

Further – with a higher inflow of litter to spruce stands and a lower sequestration in organic layers we may conclude that there are different humus build-up rates among species and that litter chemistry may be a dominant factor as there are really high differences in chemistry between pine and spruce litter.

Plateau. Then we come to the question of a steady state or a plateau, at which there should be equilibrium between inflow and outflow of carbon. I agree – we do not have to show that there is one. Still – as far as I have been able to follow the literature no one has shown that a steady state exists. Some scientists have openly questioned the idea (e.g. Botkin 1990). To write that such a state has not been proven may be provocative, although it may mean the same thing as to write that we do not have to prove it. Anyway, we may simply write that a steady state is a theoretical concept and discuss it from that viewpoint.

My point was that the concept 'steady state' may take a long time to reach (#1), alternatively we may have one that is reached 'immediately' (#2). In other words we should expect a variability within the concept.

#1. If we use the example from an article by Wardle et al. (1998), a humus-layer thickness of 150 cm was reached in close to 3000 years (2984 years) which gives an annual increase of 0.5mm. We may use the data of Berg et al. (2001) and plot the increase in mass or in C vs time. That relationship is linear and does not indicate any plateau. Although the growth is slow, we deal with a system that has been protected from fire for a period of 2984 years. That may be a point too, namely that the natural way to break the humus growth could be through e.g. fire. An investigation of a number of forests in Sweden using dendrology has shown that there had been a fire (pine forests) about every 50-60 years for as long as it was possible to follow, in some case for close to 900 years. That was before wild-fire protection was built out properly.

2. I was a co-author on a paper on litter mass loss over a long gradient across Eurasia (Kang et al. 2009). In that data set I found measured litter mass-loss values that were 100% in one year or even a shorter time, which means a litter component that is so much degraded that an organic layer should not be formed. Using these litter mass-loss values we identified a niche with deciduous litter of N concentrations in the range 0.94 to 3.1%, lignin 10.8 to 22.4%, MAT between 14.1 and 28.1°C, and MAP between 1400 and 2820 mm, which potentially should not give a humus layer assuming an annual litter fall.

My point with this is simply that a steady state (even a theoretical one) may be very different among different species and systems

Augusto Zanella

Dear Björn, Finally, your measurements and analysis (even in many other articles) sustain that **temperature does not influence "humus" decomposition**. From my point of view, this should mean

that “at a given stage of decomposition”, humus might be without available energy for living organisms. It sounds not natural as life processes rarely (never?) end in a “no- way-out” situation. Even death deserves infinite undergoing processes of life. Thus, our discussion can turn around the concept of “humus at a given stage of decomposition”, corresponding to a **Not Influenced by Temperature humus (NIT-humus)**. What is “humus at this given stage of decomposition”, what is a NIT-humus?

We may search an issue by observing a standard humus genesis in the field and following this genesis in three standard climatic situations.

Standard genesis (in chapter 4, figures and detailed description of each horizon):

1. OL (fallen litter) becomes OF horizon (fragmented litter), then
2. OF becomes OH horizon (humified litter) and finally
3. OH becomes A horizon (organic-mineral aggregates).

The process is cyclic: the soil Carbon is transferred to the air by respiration/mineralisation of the litter (dead organisms), the air Carbon is newly integrated in living organisms (plants, and animals eating plants in a pyramidal theoretical structure), Carbon in living organisms returns to the soil after the organism's death and goes through another mineralisation (short overview at the beginning of this Chapter, or in Part 7th : titles reported at the beginning of the chapter, or more detailed information in Hopkins et al. 2005, O'Donnell et al. 2005, Standing et al. 2005, Wardle 2005, Antunes et al. 2012, Berg 2012). We do not consider CaCO₃ formation/alteration and the related water cycle, a longer and very important process that has been let aside (nevertheless crucial: Baudin et al. 2007), accepting as an approximation for the present discussion, namely that it does not have an influence.

However, simplifying "not too much" and considering three types of climatic conditions, few common plant and animal groups, which are easy to recognize (in Chapter 8, if necessary), we can write that:

In very cold zones (high latitudes areas, taiga latitudes, high altitude mountains, zones characterized by very harsh conditions for soil organisms...) we generally observe the presence of organic horizons and absence of A organo-mineral horizons (Chapter 5 for detailed description). We call these humipedon Mor systems, i.e. a relatively thick horizon (OL+OF) directly laying on mineral substrates. In these cases, NIT-humus corresponds to still not decomposed organic residues (needle and leaf litter and other organic bodies). In this type of systems we do not find any anecic or endogeic earthworms mixing organic and mineral matter in large casts. In extreme conditions, no soil animal can survive. Litter stays as litter, slowly becoming OF horizon and eventually breaking down like inert substrate. Accumulation is stopped by fungi, which entertain a balance between organic matter inflow (litter fall) and outcome (litter biodegradation), the “plateau” of figures 2.10, 2.11 and 2.12. Fungi mostly act at the level of OL and OF horizons (OH horizon made of animal droppings may be present but generated in warmer conditions) and are able to attack even coniferous litter, very rich in lignin. The process depends of the succession of wet/dry periods, some years being favourable to the formation of a high numbers of fungal carpophores, other years/periods being less favourable, in a cyclic casual frequency. In the long run fungi are able to stop the increase in thickness of organic horizons. Fire may also play a great role, freeing in a short time a considerable amount of carbon, mineralizing the soil organic layers of a forest in a few days

(http://www.nytimes.com/2016/05/11/science/global-warming-cited-as-wildfires-increase-in-fragile-boreal-forest.html?_r=0). The canopy may also be opened during processes of natural/artificial regeneration of these forests, when old trees fall onto the soil or are harvested and sunlight, warming the soil, activates the process of biological decomposition involving cyclic fauna migrations and sylvogenesis (examples in Bernier & Ponge, 1994).

In temperate zones (ex. European plains, areas with relatively high air temperature and no water or mineral elements constraints) OL horizons directly become A horizons, setting a Mull system. This system consists essentially in a machinery of earthworms consuming the leaf litter (broadleaf plants dominate in this climatic zone, in Chapter 5 for details). Leaf litter is transformed and transferred into

the soil as organic-mineral casts. In this case, NIT-humus corresponds to "earthworm casts". In them, organic matter is linked with mineral clay and bound to not very accessible places (in Chapter 8 for details). Roots cannot directly consume this organic matter, but bacteria and fungi must release it first. It seems that plants need to activate (simply by feeding) these microorganisms, which can then develop and consume this humus. In a second step these microorganisms would die and free the consumed organic matter in the soil in the form of dead microorganisms, when their protective constitutive membranes break and free their cytoplasm. Mostly at this secondary stage, plants and other macro-organisms can use this organic matter, previously stored by large earthworms in casts (examples in Janzen 1980, Bastow 2012, Berg M.P. 2012, Antunes et al. 2012, Blouin et al. 2005, 2013). At this stage, a "plateau" (= equilibrium between input and output of Carbon/organic matter) is dependent on : 1) input: living earthworms feeding on leaf litter and restoring the soil with their casts; 2) output: roots, activated by plants microorganisms pinching organic matter from earthworm casts, soil biodegradation and respiration.

Between temperate and very cold climate zones, in forests dominated by conifers or mixed broadleaves, we may find high numbers of small animals feeding on litter, animals of a size that allows them to go even inside the pine or spruce needles, feeding on the tissues around the xylem of these organs (details in chapter 8). In the litter, outside needles, we may find other animals like collembolan, enchytraeids, and insect larvae in thousands per square meter. In this case, the minute excrements of these animals accumulate under the fresh litter horizon (= OL) and form OF and OH horizons, which may rise to even more than 10 cm in thickness. Biologically formed, OF and OH horizons disappear under biological control, the whole system finding an equilibrium as a results of different processes:

1. Biodegradation by fungi and bacteria as well as by specific groups of arthropods and enchytraeids which intervene and biodegrade OL into OF and OH horizons. As a result a Moder system substitutes the Mor humus system described in temperate to very cold conditions;
2. in a Moder system, the NIT-humus corresponds to a (OF+OH) layer, i.e. organic residues and excrements of small arthropods and potworms.
3. Formation of (OF+OH) horizons: activity of animals and deposition of droppings.
4. Disappearance of (OF+OH): biodegradation and respiration; soil animals mortality and mineralization; nutrients evacuation by water; roots up taking of nutrients and organic molecules;
5. when climatic and underground conditions allow earthworms to enter the system from the bottom (they arrive when canopy is opened, when old trees die and fall, for instance), earthworms feed on and integrate the organic horizons in underlying organic-mineral A horizons. In this case, Amphi system substitutes potential Mor or Moder systems;
6. in the process of formation of this dynamic Amphi system, the former NIT-humus (OF+OH) becomes another bipartite NIT-humus (OH + A). The equilibrium is now due to droppings of arthropods and enchytraeids (forming organic OH) and casts of large earthworms (generating organic-mineral A) depending from animals evolving in two different related but independent niches and habitats;
7. in Amphi, NIT-humus shows a more dynamic and plastic reaction to climatic conditions. Amphi is a system able to glide from temperate zones to very cold zones in response to climatic variations.

The Amphi humus system is potentially a more adaptable humipedon and may become more common on a planet under the influence of a forecasted warmer and more variable and contrasted climate (Ponge et al. 2014).

Björn Berg

Dear Augusto. Thank you for your arguments. My response becomes a bit limited as I have focused on boreal and temperate coniferous forests, with mainly pine systems. I will comment on two phenomena,

(i) temperature vs decomposition rate and (ii) that we may consider 'steady state' for humus growth – also called 'plateau' as a theoretical concept.

(i) far-decomposed pine needle litter, being close to Mor humus decomposed at the same rate over a climate gradient (Fig 2.13). We have even seen a negative effect of MAT on decomposition rate, let be that the significance was just at $p=0.017$ (Berg et al. 2015). We may limit this observation to pine systems with Mor/Moder humus. So far we have observations. That humus, not sensitive to temperature should not support living organisms (not giving energy to living organisms) is not entirely correct. In fact, there is a study (Hintikka and NÄyki, 1967) which has shown that 'stable' Mor humus layers in Scots pine forests may disappear at a high rate. A mycorrhiza fungus *Hydnellum ferrugineum* could be active as decomposer. Similar phenomena have been reported for other systems.

(ii) we may consider a 'steady state' for humus growth – also called 'plateau' as a theoretical concept. I followed a few studies which mentioned 'steady state' and tried to find the original study, in which the steady state of the humus layer should have been analyzed for or determined. In all three cases I ended with a paper in which I found a statement that 'the forest was in a steady state'. So the humus layer was not investigated, but in later papers there was a citation about a steady state for the humus. The original concept may thus have been a bit diffuse and thus easy to convert from the whole system to encompass different parts.

Some examples on growth rates; Berg et al. (2009) used measured data to determine humus-layer growth rates and found a set of rates ranging from <0.5 to >1.1 mm per year. Those rates covered a period of 41 years – as long as there were measurements. Wardle et al. (1998) who found an average growth rate of c 0.5 mm per year for a humus layer that had grown without interruption for close to 3000 years. We may use the same data (Wardle et al. 1998) for accumulated humus and plot the amount as dependent on time. Doing that we obtain a quadratic function, which thus should have a maximum. We set the first derivative to zero (indicating the maximum) and obtain a rough figure of 5200 years. I will underline that this is a rough estimate made just for the sake of an argument. The maximum was not before before 2900 years had passed and may appear earlier than or after 5200 years depending on what happens to the environment. Still, when we deal with millennia we should be aware of that although a given system/stand has a humus-layer development in the direction of a steady state, that development may be interrupted (never reached) and we can probably find such examples as a consequence of a change in climate and wild fire.

This argument makes me consider a steady state as a theoretical concept – at least we could treat it like that. Why? Simply because we do not have any possibility to determine when a system has reached a plateau/steady state.

Most of my arguments are based on pine systems. Still deep humus layers are found not only on the study of Wardle et al.. Tanglehumus is one concept and I have seen meter-deep humus layers in Spanish Galicia and on Monte Taburno in Campania (Italy), the latter with a Mull humus.

Augusto Zanella

Dear Björn, You are right, accumulation has to overlap biodegradation, be larger than biodegradation, because biodegradation is a secondary process and it may stop before ending the substrate, or starting on new litter before ending all old litter. Genetic variations in natural populations may also generate species progressively more adapted to each other and able to increase the recycling capacity of the system. In fact, the historical natural evolution that characterizes our planet might be intended as a non-stop process of increasing complexification. This recorded continuous insertion of "functional-organized-biomass" needed energy. The solar input being more or less constant in a short time (< 1000 years) and in a given surface of our planet, a potential difference in the structural biological complexity of the ecosystems developing in correspondence of this given surface has probably its source in the soil. In theory, the soil of a given surface should receive more organic matter than necessary for entertaining

the system, getting richer with time (Fig. 2.4). This hypothesis may explain why we observe the succession from pioneer ecosystems with thin soil to forest ecosystem with deep soils. More precisely, soil has to be understood as NIT-humus (not influenced by temperature humus). And NIT-humus, naturally, always increases, fast in temperate regions, slowly in harsher climatic conditions. If humans try to stop this process and unfortunately we are trying to: agricultural soils lost 50 to 75% of their historical pool (in Lal R., 2007, Chan Y., 2008, Li et al. 2013, Schwartz J.D. 2014.), we run the risk to be substituted by a more grateful species. With the content of Humusica we would like to convince people to take reason and inverse the course, putting organic matter in the soil and re-establishing everywhere an equilibrium that respect what you Björn described as dynamic process for natural soils, i.e. a never stopping accumulation of organic matter in the soil, as source for a never ending diversification of a living...Gaia.

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