Ann Sci For (1995) 52, 535-546

Original article

Classification of forest humus forms: a French proposal

A Brethes [1], JJ Brun [2], B Jabiol [3], J Ponge [4*], F Toutain [5, 3]

[1] ONF, département des recherches techniques, cité administrative Coligny, 131, rue du Faubourg-Bannier, 45042 Orléans cedex;
[2] CEMAGREF, domaine universitaire, 2, rue de la Papeterie, BP 76, 38402 Saint-Martin-d'Hères cedex;
[3] ENGREF, 14, rue Girardet, 54042 Nancy cedex;
[4] Muséum national d'histoire naturelle, laboratoire d'écologie générale, 4, avenue du Petit-Château, 91800 Brunoy;
[5] CNRS, centre de pédologie biologique, BP 5, 17, rue Notre-Dame-des-Pauvres, 54501 Vandœuvre cedex, France

(Received 2 January 1994; accepted 18 March 1995)

Summary — A 2-way classification grid and a nomenclature are proposed for French forest humus forms but which could include mountain, Mediterranean and tropical forms as well. This proposal takes into account our present knowledge of biological mechanisms that take place in plant litter decomposition, transformation of soil organic matter, linkage of the latter to mineral particles and building of the structure in the A horizon. Basically, by adjoining free qualifiers, humus forms may be defined by accounting also for their chemical and physical particularities.

humus form / forest / classification / nomenclature / soil biology

Résumé — La classification des formes d'humus forestières : proposition française. *Une grille de classification à 2 entrées et une nomenclature sont proposées pour les humus forestiers de France, mais pouvant s'appliquer aussi aux formes d'altitude, tropicales et méditerranéennes. Cette proposition prend en compte les connaissances actuelles concernant les phénomènes biologiques intervenant dans la décomposition de la litière, la transformation de la matière organique, ses liens avec les particules minérales et la structuration de l'horizon A. Par son principe même, grâce à l'adjonction de qualificatifs dont le choix est libre, les formes d'humus peuvent être précisées quant à leurs caractères chimiques ou physiques particuliers.*

forme d'humus / forêt / classification / nomenclature / biologie du sol

* Corresponding author

INTRODUCTION

The humus profile is comprised of different scales which may be integrated: regional climate, parent rock, vegetation, soil organisms (Toutain, 1987a, b; Bernier and Ponge, 1993). Humus forms are unevenly distributed over the world, for climatic and historical reasons. As a consequence, various classifications have been in use until now, each focused on regional aspects.

In Europe, Kubiëna (1953) described numerous humus forms, covering a wide range of climates, parent rocks and vegetation types. His criteria were derived mainly from his own morphological observations. Duchaufour (1956) and Babel (1971) later investigated different chemical and microstructural aspects, giving a scientific basis for more refined classifications. Delecour (1980) then proposed an identification key for most humus forms present in western Europe.

In North America, the need for another type of classification was emphasized by Wilde (1954, 1971). More recently, a detailed taxonomy of humus forms was achieved by Klinka *et al* (1981) and Green *et al* (1993).

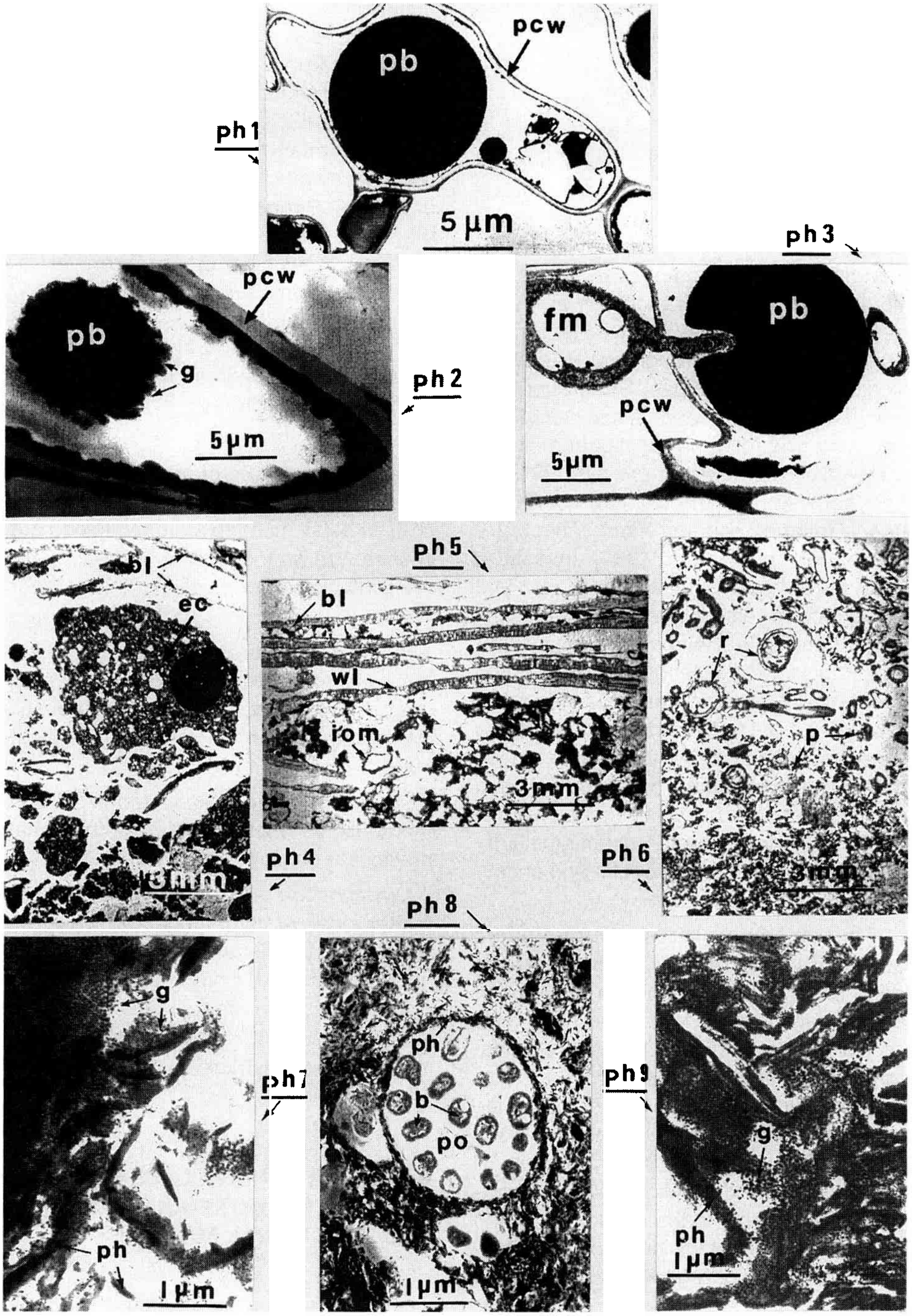
In other regions of the world, others endeavoured to describe tropical and Mediterranean soils on the same basis (Marin *et al,* 1985; Ferry, 1992; Leroy *et al,* 1993).

Progress in the scientific knowledge of the soil, both in its chemical and biological aspects, now allows us to propose a functional classification of forest humus forms. A worldwide tool is needed to enable soil scientists and foresters to describe every kind of existing humus profile. For that purpose, we propose a classification which is not taxonomical. Rather, it aims to answer the question of how to see processes when observing the soil with the naked eye and use this knowledge to identify humus forms with more certainty.

The proposed classification is based on the same principles as the French Pedological Reference Base for soil types (AFES, 1992). This is a reference system and not a hierarchical and exhaustive classification. Humus forms are described by linking them to some well-defined reference forms and freely adjoining as many qualifiers as needed. An effort was made to make this classification scientific and pragmatic, precise, but, nevertheless, flexible.

Waterlogged soils (gley and pseudo-gley) and their humus forms (AFES, 1992) will not be discussed here, as a better knowledge of biological mechanisms in poorly aerated horizons is needed.

Fig 1. Biological processes taking place in decomposition of plant litter and incorporation of organic matter to mineral matter. *ph1:* brown pigments (pb) in a cell of the spongy parenchyma of beech leaves; pcw = primary cell wall; *ph2:* a cell of the spongy parenchyma of beech leaves in the intestine of the earthworm *Nicodrilus velox*; g = granules of organic matter; *ph3:* transformation of the brown pigments (pb) of the spongy parenchyma of beech leaves by a white-rot fungus; fm = filamentous mycelium; pcw = primary cell wall; *ph4:* thin section in a mull profile under beech with an intense earthworm activity; bl = brown beech leaves; ec = earthworm cast; *ph5*: thin section in a mull profile under beech with an intense activity of white-rot fungi; bl = brown beech leaf; wl = white beech leaf, iom = insolubilized organic matter; *ph6:* thin section in a dysmoder profile; r = root, p = faecal pellets of enchytraeids and microarthropods; *ph7* = granules (g) of organic matter adsorbed on phyllites (ph) in an earthworm cast (clay-humus complexes = organoargillic humin); *ph8:* microaggregate (bacterial colony) in an earthworm cast; b = living bacteria; po = polysaccharides; ph = phyllites: *ph9*: granules (g) of organic matter insolubilized on phyllites (ph).


ph1
pb
pcw
5 µm
ph2
pb
pcw
g
5µm
ph3
fm
pb
pcw
5µm
ph4
bl
ec
3mm
ph5
bl
wl
iom
3mm
ph6
r
p
3mm
ph7
g
ph
1µm
ph8
ph
b
po
1µm
ph9
g
ph
1µm

STUDIES ON FUNCTIONAL ASPECTS

Transformation of leaf litter

Recent studies emphasized the importance of the chemical nature of plant macromolecules in the fate of humus layers. In particular, following earlier observations by Handley (1954), Reisinger *et al* (1978), Toutain (1981) and François *et al* (1986) described the pathway followed by tannin-protein complexes through soil food webs in different humus types. Several critical phases were recognized, at first the senescence of tree foliage, with appearance of stable dark pigments where nitrogen was sequestered (*eg* 70% of total nitrogen in beech foliage), rending it unavailable for plant nutrition (Toutain, 1981). Investigations on different scales (soil slides, leaf ultrastructure, *etc*) showed that only a few biota, such as earthworms and white-rot fungi (fig 1), were able to disintegrate such recalcitrant molecular assemblages (Toutain, 1981). When these organisms were present and active, the disappearance of leaf litter was rapid (mull humus). When they were absent, however, litter slowly disappeared through the activity of small animals, such as microarthropods and enchytraeid worms (moder humus).

Thus, there is a threshold for nutrient cycles that may or may not be a lockup, depending on the presence or absence of efficient organisms. Their presence depends on environmental (Toutain, 1987a) and historical conditions that lead to a variety of functional types (fig 2). Here is the borderline between mull and moder. In moder humus forms, biological activity is effective but soil food chains are discontinuous. The principal activity, visible to the naked eye, is the transformation of plant litter into animal faeces where a lot of organic matter remains untouched, at least temporarily (Webb, 1977; Toutain *et al*, 1982; Ponge, 1991a, b).

The borderline between moder and mor humus forms is more difficult to determine, and more knowledge on biological processes is needed before clear trends can be perceived. Our own observations indicated that enchytraeid worms were particularly abundant in mor humus forms (Bernier *et al*, 1993; Ponge, unpublished data); thus, their dominance could be more than an exclusion of the other groups; however, the true mechanisms are unknown.

Assemblage of organic matter with mineral particles

The chemical nature of organic matter and its assemblage with mineral matter in the A horizon depend on the aforementioned processes. We may distinguish 3 main pathways (Berthelin *et al*, 1994; Duchaufour, 1995):

– *Biomacrostructured A horizon:* Clay-mineral complexes may be cementing macroaggregates, due to the mixing activity of soil-dwelling earthworms (Bernier and Ponge, 1994);

– *"Insolubilisation" A horizon*: Soluble metabolic products of white-rot fungi may precipitate on clay-iron particles;

– *"Juxtaposition" A horizon*: Inherited organic matter made of plant-fungal cell walls recognizable in transmission (Toutain, 1981) or even light microscopy (Ponge, 1991a, b) may be present in faecal pellets of many small animals (litter-dwelling earthworms, arthropods, enchytraeids), side by side with mineral grains.

BASES FOR A NEW CLASSIFICATION INTEGRATING MORPHOLOGICAL AND FUNCTIONAL FEATURES

The existence of a close relationship between morphology and biochemistry

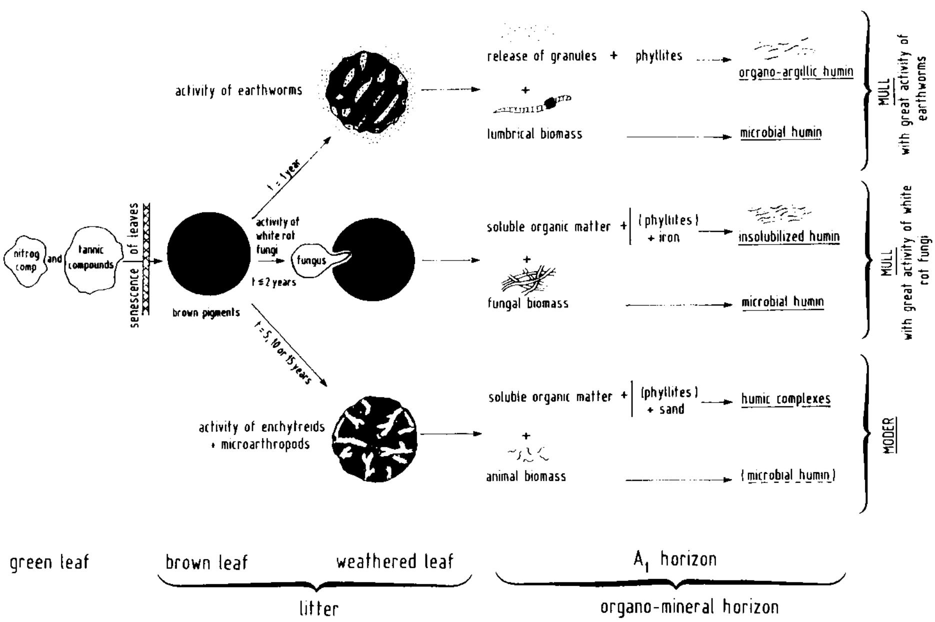


Fig 2. Biological processes used to separate mull and moder humus forms.

(Duchaufour, 1995) has been often questioned. The same humus type with a high biological activity (mull humus from a morphological point of view) may well correspond to a wide range of pH values and indicator plant species (Duchaufour, 1995). Conversely, different morphological types may have the same pH or C/N.

Given these discrepancies with the current view that morphology of the humus profile is the reflection of its chemical properties, we decided to use the latter as qualifiers for groups primarily based on morphology, thus traducing the importance given to the building of the profile by living organisms.

Table I presents the main features of the different horizons used in our classification. These horizons have been used previously by various authors in order to classify humus forms (fig 3). For delineating morphological types, we took into account not only morphological but also functional thresholds, a borderline based on the principle that morphology is senseless if without any biological support.

The results of our observations are presented in figure 4, which concerns mainly lowland sites. O and A horizons were considered as distinct entries, allowing apparent conflicting features to occur in the same humus profile. Thus, names can be given to most humus forms we observed in French sites under Atlantic influence (fig 5). Our classification may also be used as a key for the identification of the principal humus forms (fig 6).

The addition of qualifiers (table II) may help to define any humus form that needs to be characterized by particular features. For instance, table III indicates the principal features of a humus form that could be coined “Acid desaturated clay-loamy oak mesomull” according to our nomenclature.

Table I. Nomenclature and principal features of the different horizons used in the classification of humus forms.

OL horizon	
	OLn: plant remains, whole, poorly transformed OLv: plant remains, poorly fragmented, discoloured, permeated by fungal mycelia, appressed against each other OLt: plant remains, more or less fragmented, recognizable to the naked eye, with earthworm casts but without aggregates of humidifed organic matter
OF horizon	
	Plant remains, more or less fragmented, recognizable to the naked eye, mixed with aggregates of dark humified organic matter (= "fine organic matter") which are rare at the top and abundant at the bottom but comprise less than 70% of the total organic matter OFr: between 10 and 30% «fine organic matter» OFm: between 30 and 70% «fine organic matter» OFc: mycogenous structure
OH horizon	
	More than 70% "fine organic matter", made of animal faecal pellets and plant and fungal microdebris, a few plant remains recognizable to the naked eye, a few mineral grains, colour dark red to black (may be subdivided into OHr, OHf, OHc)
A horizon	
	Organomineral or hemiorganic horizon Biomacrostructured A horizon: clay-mineral complexes, organic matter unrecognizable to the naked eye, in the form of dark-coloured earthworm faecal pellets Insolubilization A horizon: microaggregates resulting from the insolubilization of percolating organic molecules by clay-iron particles, in the absence of definite earthworm activity but with an intense white-rot activity Juxtaposition microcoprogenic A horizon: organic faecal pellets juxtaposed to sand grains, which are clean and sparkling, bad structure Diffusion horizon: mineral horizon with percolating organic matter never complexing mineral particles

DISCUSSION

The arguments that helped us to separate moder and mull by the nature of the A horizon have been already noted by Duchaufour (1965) but were mainly derived from our own studies on the origin of soil organic matter (Brun, 1978; Toutain, 1981; Bernier and Ponge, 1994). Contrary to previous classifications based both on O and A horizons (Duchaufour, 1965), we decided to promote the morphology of the A horizon.

Our method allowed us to classify some puzzling humus forms without any clear relationship between what could be observed in the litter layers (O horizon) and the structure of the A horizon. This is the case for the amphimull humus form (fig 5) which has been overlooked time and again, being described either morphologically as a moder or chemically as a mull. The existence of 2 superposed horizons, with the one (O horizon) of the moder type overlying the other (A horizon) of the mull type, has been reported

Table II. Qualifiers used to describe humus forms.

Qualifiers related to the presence of organic matter in the A horizon	
Humus bearing	Richer in organic matter than normally described in AFES (1992)
Humic	With a high content in organic matter, giving it a black colour up to a depth of at least 20 cm
Clino-humic	With an accumulation of strongly coloured organic matter, decreasing progressively with depth
Light-coloured	With a low content in organic matter
Qualifiers related to chemical features of the A horizon	
Extremely acid	pH < 3.5
Very acid	pH between 3.5 and 4.2
Acid	pH between 4.2 and 5.0
Slightly acid	pH between 5.0 and 6.5
Neutral	pH between 6.5 and 7.5
Alkaline	pH between 7.5 and 8.7
Very alkaline	pH > 8.7
Saturated	S/T = 100% ± 5%
Sub-saturated	S/T between 80 and 95%
Meso-saturated	S/T between 50 and 80%
Oligo-saturated	S/T between 20 and 50%
Desaturated	S/T < 20%
Carbonated	Fine earth with calcium or magnesium carbonates, widespread effervescent
Calcic	Without calcium or magnesium carbonates, but saturated with Ca^{2+} dominant ($Ca^{2+}/Mg^{2+} > 5$)
Calci-magnesic	Without calcium or magnesium carbonates, but saturated with Ca^{2+} and Mg^{2+} (Ca^{2+}/Mg^{2+} between 2 and 5)
Magnesic	Without calcium or magnesium carbonates, but saturated with Ca^{2+} and Mg^{2+} (Ca^{2+}/Mg^{2+} between 0.3 and 2)
Hyper-magnesic	Without calcium or magnesium carbonates, but saturated with Ca^{2+} and Mg^{2+} ($Ca^{2+}/Mg^{2+} < 0.3$)
Sodic	Na^{+} is more than 6% of total exchange capacity (T)
Qualifiers related to soil-forming processes (nomenclature according to AFES, 1992)	
Chernic	With an A horizon showing features of a Chernosol
Andic	With an A horizon showing features of an Andosol
Pelosolic	With an A horizon showing features of a Pelosol
Colluvial	With a large proportion of a A horizon issuing from lateral inputs
Qualifiers related to texture	
	As for soils, humus forms may be specified sand, clay-loamy, *etc*
Qualifiers related to features of the O horizon	
Mycogenous	Dominated by fungal activity (mycelium abundant)
Rhizogenous	Dominated by root activity (fine root system abundant)
	Other structural patterns may be specified such as laminated, fibrous, granular, squamose, continuous, *etc*
Qualifiers related to the nature of leaf or needle litter	
	The tree species under which the humus form has been formed may be indicated as a qualifier: beech , spruce, *etc*

Most qualifiers were defined and used for soils in AFES (1992).

Table III. Principal features of a humus profile named "acid desaturated clay-loamy oak mesomull".

Area	Gazinet (France, Landes)
Topography	Lower slope
Soil type	Clay loam colluvium with silicate boulders
Vegetation	Oak forest with a field layer made of *Luzula sylvatica, Vinca minor, Blechnum spicant, Hyperichum androsaceum, Hedera helix, Ruscus aculeatus*
Description	OLn continuous, regular OLv thin, 1-year-old, locally absent OLt present, made of twigs, leaf nerves, acorns, more or less incorporated into the underlying horizon OFr only locally A horizon clay-loamy, pale grey-yellow, fairly crumby, with a high earthworm activity
Classification	MESOMULL. Transitional features towards EUMULL, given a discontinuous OLv, confirmed by the structure of the A horizon and the earthworm activity. Spots of OFr not developed enough to change the diagnosis.

Analyses of the A horizon

Clay	Fine silt	Coarse silt	Fine sand	Coarse sand (%)
20.3	34.9	19.7	12.0	11.2

pH water	C per thousand	C/N	S/T (%)
4.75	11.2	9.6	12.5

K^+ (meq/100 g)	Mg^{2+} (meq/100 g)	Ca^{2+} (meq/100 g)
0.14	0.59	0.61

previously, particularly in mountain sites, as well on alkaline (Bottner, 1971) as on acid substrate (Bernier *et al*, 1993).

In agricultural soils, the assemblage between organic and mineral materials in the A horizon were similarly used by Barratt (1964) and Jacquin (1985) to help distinguish between different types.

Our functional approach to humus morphology makes it possible to better understand dynamic processes into which climate, vegetation and humus profiles are involved. For instance, in artificial or natural changes, the evolution of the humus profile may be followed up and described with a better certainty, accepting that different horizons may evolve at different rates. This was observed experimentally after liming and fertilization (Toutain *et al*, 1988). In mountain sites, Bernier and Ponge (1993, 1994) described changes in humus form during the development of bilberry-spruce forests along an altitudinal gradient. Similarly, Leroy *et al* (1993) observed microscale changes in humus form under different tree species growing in tropical rain forests.

Comparisons with studies or observations made in other bioclimatic zones (mountain, tropical, Mediterranean) gave evidence that our nomenclature can be successfully used in other countries (Toutain, 1984; Bernier and Ponge, 1993). Nevertheless, for northern and boreal climates, there is a need for more investigations on the mor group if

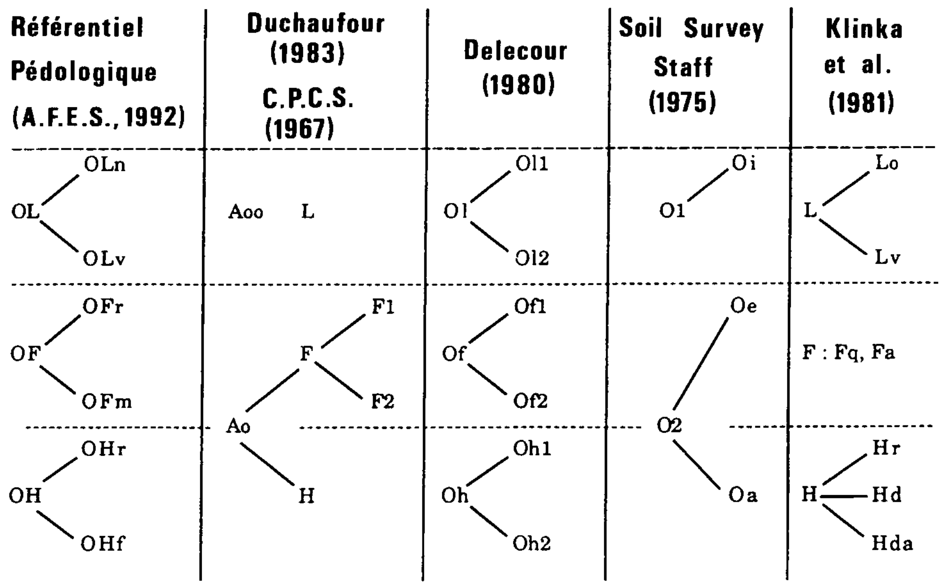


Fig 3. Correspondences between horizons described by different authors.

O HORIZONS		A HORIZONS AND O-A TRANSITIONS			
		abundant clay-humus complexes		clay-humus complexes rare or absent	
		discontinuity between O // A		O-A progressive transition	discontinuity O // min. horiz
		biomacrostructured A	"insolubilisation" A	"juxtaposition" A	no O.M. or diffused O.M.
		MULL		MODER	MOR
OL or OL + (OF)	(OLn)	EUMULL			
	OLn (OLv)	MESOMULL			
	OLn OLv (OF)	OLIGOMULL	"Oligomull mycogène"		
OL + OF		DYSMULL		HEMIMODER	
OL + OF + OH or (OH)		AMPHIMULL (to be examined)		EUMODER (OH < 1 cm) DYSMODER (OH ≥ 1 cm)	MOR (to be examined)

Fig 4. Classification of humus forms present in lowland well-drained sites, by observing features of O and A horizons. Horizons in parentheses may be locally absent; * = may be an OLt horizon above the A horizon.

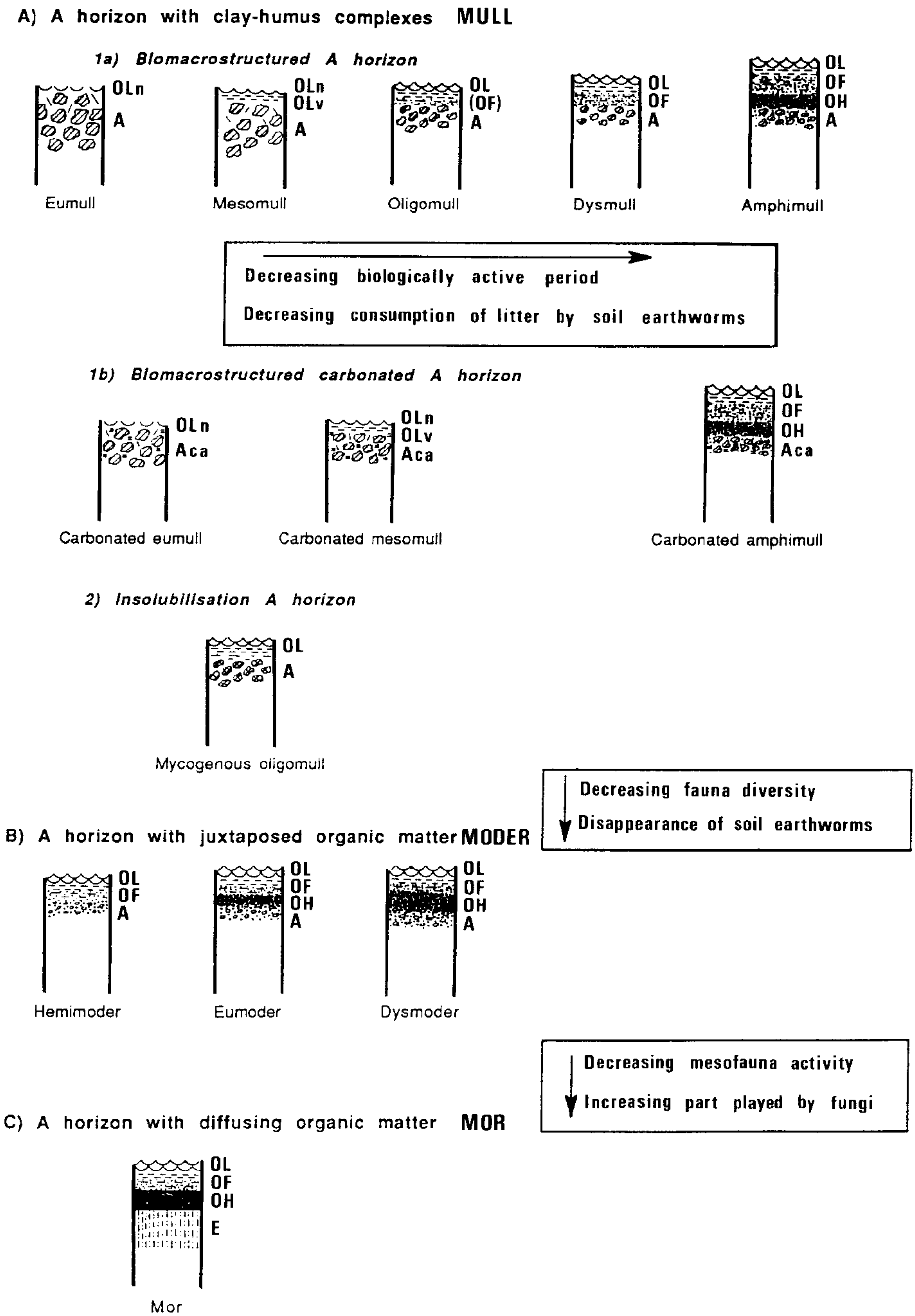


Fig 5. Morphological features of the principal humus forms present in lowland well-drained sites.

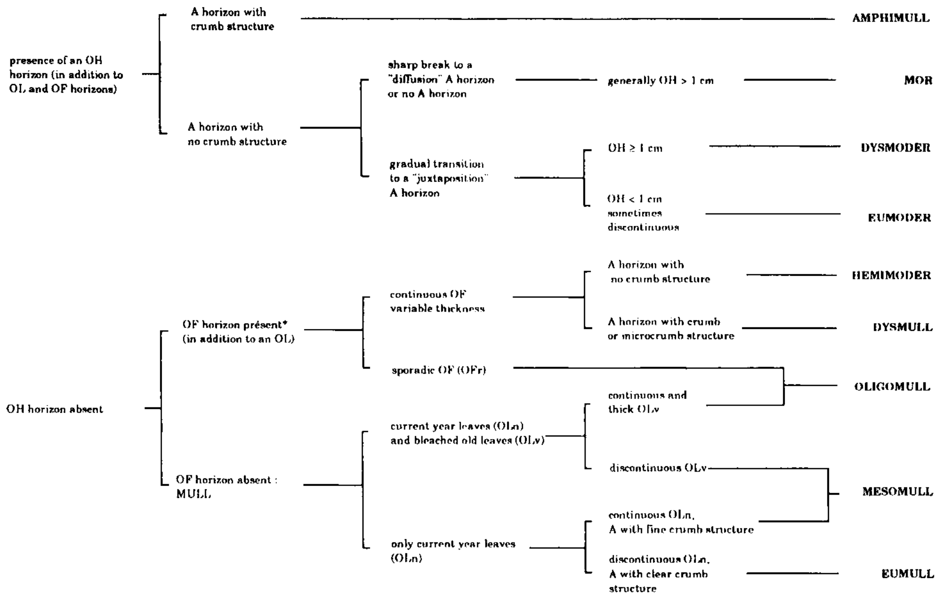


Fig 6. Key for the identification of principal lowland well-drained humus forms.

we need to describe the great variability of raw humus forms on the same basis. The work of Green *et al* (1993) is exemplary inasmuch as they included functional aspects (biology, water movement, *etc*) in a refined description and classification of mor (and other) humus forms. In contrasting their work with the present proposal, the main difference lies in the fact that we considered the structure of the A horizon as a key point, distinguishing between the 3 main groups (mull, moder, mor) on this basis. In their classification, Green and co-workers used the total thickness of the O horizon (and the presence of some diagnostic OF subhorizons) as a primary criterium. Secondly, they did not authorize contradictory processes (or traits) to occur within the same humus profile, thus giving no allowance for integrating rapidly changing humus forms. These 2 proposals should not be considered as opposed to each other and in the near future an effort will be made to work together to develop a functional classification of forest humus forms which would include all aspects of soil biology and chemistry.

REFERENCES

AFES (1992) *Référentiel pédologique. Principaux sols d'Europe.* INRA, Paris, France

Babel U (1971) Gliederung und Beschreibung des Humusprofils in mitteleuropäischen Wäldern. *Geoderma* 5, 297-324

Barratt B (1964) A classification of humus forms and micro-fabrics of temperate grasslands. *J Soil Sci* 15, 351-356

Bernier N, Ponge JF (1993) Dynamique et stabilité des humus au cours du cycle sylvogénétique d'une pessière d'altitude. *CR Ac Sci Paris, Sciences de la Vie,* 316, 647-651

Bernier N, Ponge JF (1994) Humus form dynamics during the sylvogenetic cycle. *Soil Biol Biochem* 26, 183-220

Bernier N, Ponge JF, André J (1993) Comparative study of soil organic layers in 2 bilberry-spruce forest stands *(Vaccinio-Piceetea).* Relation to forest dynamics. *Geoderma* 59, 89-108

Berthelin J, Leyval C, Toutain F (1994) Biologie des sols. Rôle des organismes dans l'altération et l'humification. *In: Pédologie. 2. Constituants et propriétés du sol* (M Bonneau, B Souchier, eds), Masson, Paris, France, 143-237

Bottner P (1971) La pédogenèse sur roches-mères calcaires dans une séquence bioclimatique méditerranéo-alpine du sud de la France. Thèse de doctorat d'Etat, univ Montpellier, France

Brun J (1978) Étude de quelques humus forestiers aérés acides de l'est de la France. Critères analytiques. Classification morphogénétique. Thèse de doctorat de spécialité, univ Nancy, France

CPCS (1967) *Classification des sols.* ENSA, Grignon, France

Delecour F (1980) Essai de classification pratique des humus. *Pédologie* 30, 225-241

Duchaufour P (1956) *Pédologie. Applications forestières et agricoles.* École nationale des eaux et forêts, Nancy, France

Duchaufour P (1965) *Précis de pédologie.* Masson, Paris, France

Duchaufour P (1983) *Pédologie. I. Pédogenèse et classification.* Masson, Paris, France

Duchaufour P (1995) *Pédologie. Sol, végétation, environnement.* 4^{e} ed, Masson, Paris, France

Ferry B (1992) Étude des humus forestiers de la région des Ghâts occidentaux (Inde du Sud). Facteurs climatiques, édaphiques et biologiques intervenant dans le stockage de la matière organique du sol. Thèse de doctorat d'État, univ Nancy, France

François C, Rafidison Z, Villemin G, Toutain F, Andreux F (1986) The accumulation and fate of brown pigments in leaves of *Fagus sylvatica* L: a morphological and chemical study. *In: Current perspectives in environmental biogeochemistry* (G Giovannozzi-Sermanni, P Nannipieri, eds), CNR-IPRA, Rome, Italy, 317-327

Green RN, Trowbridge RL, Klinka K (1993) Towards a taxonomic classification of humus forms. *Forest Sci Monogr* no 29

Handley WRC (1954) Mull and mor formation in relation to forest soils. Forestry Commission of London, Bulletin no 23

Jacquin F (1985) Dynamique de la matière organique en sols cultivés sous climats tempérés. *CR Ac Agric France* 71, 635-642

Klinka K, Green RN, Trowbridge RL, Lowe LE (1981) Taxonomic classification of humus forms in ecosystems of British Columbia. First approximation. Province of British Columbia, Min For, Land Manage Rep no 8, Victoria, BC, Canada

Kubiëna WL (1953) *The soils of Europe. Illustrated diagnosis and systematics.* Thomas Murby and Company, London, UK

Leroy C, Toutain F, Lavelle P (1993) Variations des caractéristiques de l'humus forestier d'un sol ferrallitique (Guyane) selon l'essence arborée considérée. *Cahiers de l'ORSTOM, Série Pédologie* 27, 37-48

Marin MS, Corral L, Paneque G (1985) Morfologia y propriedades quimicas de suelos forestales de Argelia. Suelos bajo *Abies numidica* y *Cedrus atlantica. Anales de Edafologia y Agrobiologia* 4, 369-381

Ponge JF (1991a) Food resources and diets of soil animals in a small area of Scots pine litter. *Geoderma* 49, 33-62

Ponge JF (1991b) Succession of fungi and fauna during decomposition of needles in a small area of Scots pine litter. *Plant Soil* 138, 99-113

Reisinger O, Toutain F, Mangenot F, Arnould MF (1978) Étude ultrastructurale des processus de biodégradation. I. Pourriture blanche des feuilles de hêtre (*Fagus sylvatica* L). *Can J Microbiol* 24, 725-733

Soil Survey Staff (1975) *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys.* USDA Soil Conservation Service, Washington, DC, USA

Toutain F (1981) Les humus forestiers, structures et modes de fonctionnement. *Rev For Fr* 33, 449-477

Toutain F (1984) Les phénomènes de biodégradation et d'humification dans les écosystèmes forestiers tropicaux. *Biol International* (special issue) 6, 19-29

Toutain F (1987a) Activité biologique des sols, modalités et lithodépendance. *Biol Fertil Soils* 3, 31-39

Toutain F (1987b) Les litières : siège de systèmes interactifs et moteur de ces interactions. *Rev Ecol Biol Sol* 24, 231-242

Toutain F, Villemin G, Albrecht A, Reisinger O (1982) Étude ultrastructurale des processus de biodégradation. II. Modèle enchytréides-litière de feuillus. *Pedobiologia* 23, 145-156

Toutain F, Diagne A, Le Tacon F (1988) Possibilités de modifications du type d'humus et d'amélioration de la fertilité des sols à moyen terme. *Rev For Fr* 40, 99-107

Webb DP (1977) Regulation of deciduous forest litter decomposition by soil arthropod feces. *In: The role of arthropods in forest ecosystems* (WJ Mattson, ed), Springer Verlag, New York, NY, USA, 57-69

Wilde SA (1954) Forest humus: its genetic classification. *Trans Wisconsin Acad Sci Arts Lett* 43, 137-163

Wilde SA (1971) Forest humus: its classification on a genetic basis. *Soil Sci* 111, 1-12