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PLANOSOLS IN THE "CHAMPAGNE HUMIDE" REGION, FRANCE
A MULTI-APPROACH STUDY

D. BAIZE

Abstract

This article is devoted to acid soils with strong differentiation that have developed in sedimentary clay material of the early Cretaceous period (Champagne Humide, France).

Macro and micromorphological, granulometric, physico-chemical and mineralogical studies were conducted on seven profiles selected from an initial 60 pits. Also, the soil water regime was investigated in situ over a 5-year period by simple procedures using piezometers, tensiometers and neutron measuring devices; 200 to 420 mm of rainfall are removed annually by lateral flow as a temporary shallow water-table.

Four isoquartz balances were established, indicating that these soils became differentiated as a result of the lateral translocation of clay minerals from the upper horizons without significant accumulation in the deeper layers. Initial homogeneity of the parent material was determined by various methods, so that these soils can be defined as "pedomorphic planosols" whose formation is not related to a particular climate, but to two combined site factors : a slowly permeable clay parent material and a subhorizontal topography. Unlike sandy or silty materials, the clay materials studied here showed an essentially lateral natural drainage.

Key-words

Planosols, pedogenesis, clay materials, France.

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1. INTRODUCTION

1.1. Purpose and approach

This paper presents the main approaches and major results of an extensive overall study of the highly acid planosols of Champagne Humide (southern Paris Basin) which have developed from cretaceous clay deposits (Baize, 1983). Details on the methods employed and on general results are given in the three following articles : study of particle size distribution (Baize, 1980a), isoquartz balances (Baize, 1980b) or soil water regime (Baize, 1984).

The research was conducted by following a "multi-approach" procedure. First, the greatest possible number of independant methods have been used. In preference, the more comprehensive methods (such as soil survey) and those for investigating the soil mantle in situ have been employed. Each independant approach yielded basic data. After critical examination, the latter served to elaborate partial syntheses. The relevant combination of these syntheses (i.e. taking into account any apparent contradiction between existing phenomena and results of earlier processes) led to reliable final conclusions.

Table 1 shows in part the approaches followed and the methods and material used. The various study methods have been applied to a relatively large number of selected representative profiles. A sizeable amount of data has therefore been collected. It is also evident to which point these methods differ in terms of site (field or laboratory) and scale of observations (from micrometre to kilometre). For such an article, it was also necessary to condense the obtained results to a great extent. This is why each chapter contains only an indication of these methods used and an outline of the major results and partial conclusions.

1.2. Planosols - Previous works

The name planosol was introduced in the 1938 USDA Soil Classification. This designation is now widespread, especially after its use at the highest taxonomic level in the legend of the FAO-UNESCO Soil Map of the World (1974).

Dudal (1973) summarized all the studies carried out in the world until 1971 concerning planosols or related soils. Since that time, several surveys can be mentioned. Most of them have taken place in Africa or in South America, a few in Europe (Carvalho Cardoso and Teixeira Bessa, 1973; Conea et al., 1973; Trashliev et al., 1975; Feijtel et al., 1988).

Morras (1979), after a book-review, states that the only consistent feature of all planosols appears to be their seasonal waterlogging; this may be related to climatic conditions, topographic posi-

Table 1.
The "multi-approach" proceeding applied to planosols of Champagne Humide : questions, methods and material.

QUESTION TO BE SOLVED	METHODS USED	STUDY MATERIAL
1. What is the morphology of these soils, their constituents, their wawater regime?	. medium-scale mapping . soil descriptions; particle-size and chemical analysis . X-ray diffraction	. about 40,000 ha . 60 pits both described and sampled . 7 profiles
2. Are there pedomorphic or lithomorphic planosols?	. arguments relating to mapping . particle-size distribution study . test area study . heavy minerals study	. > 1500 auger borings . 282 sampled horizons . 12 ha, 8 profiles . 2 profiles
3. Are there evidences of illuviation?	. microscopic examination of thin sections	. 21 horizons from 5 profiles
4. What are the factors and conditions of the soil water regime?	IN SITU : . piezometer and tensiometer readings; neutron scattering . bulk density and weight soil moisture measurings LABORATORY MEASUREMENTS : . solid density . relationship moisture/ pF	. 2 sites for five years . samples from the two sites
5. Do material losses from the E horizons accumulate within the S horizons, in invisible form?	. isoquartz balances	. 4 profiles
6. What is the composition of waters in the subsurface runoff?	. chemical analysis of waters and suspended particles	. 11 water samplings from one site (brook)

tion or slow permeability of the parent material. Thus, the morphology of planosols appears to result from convergence, different soil-forming processes and mechanisms occurring according the case.

In France, the term planosol was first applied by Favrot and Legros in 1972. In this particular case, these were "lithomorphic" planosols in which a heterogeneous double layer material existed, previous to soil formation. At the same time, Begon and Jamagne (1973) described planosols and planosolic soils corresponding to the ultimate stage of "sols lessivés dégradés", in which the slowly permeable horizons result from considerable clay illuviation. Planosols formed directly from homogeneous clay material have been reported, for the first time, in the Paris Basin (Baize, 1976; Begon et al., 1976; Isambert, 1984).

2. THE ENVIRONMENT : THE "CHAMPAGNE HUMIDE" REGION

The "Champagne Humide" is located in the southeastern Paris Basin, France. It is clearly differentiated from the wine growing Champagne because it is strictly confined to the outcropping of sedimentary strata of the early Cretaceous period. The present study is only concerned with a part of this region (areas near Chaource, St. Florentin and Auxerre).

The stratigraphic sequence (Barremian to Cenomanian) displays abrupt vertical and lateral lithological variations, but clay deposits remain dominant. Many parent materials result directly from clay sedimentation. In addition, several materials that did not initially consist of clays were converted into clay materials due to moderate weathering processes; for instance, the "green sands" of the Albian period were transformed by disintegration of glauconitic pseudo-sands and the Cenomanian marls by simple decarbonatation.

Several lithological facies can be distinguished among parent materials : marls, glauconitic or non-glauconitic calcareous clays, non calcareous glauconitic clays and continental variegated clays. From a granulometric point of view, four categories can be recognized in the field : heavy clays, clays with a silty skeleton, clays with a fine sand-sized skeleton and sandy clays. Thus, there is a great diversity of materials exposed to pedogenetic processes, and this diversity is increased by the variety in mineralogical compositions (see below).

The "Champagne Humide" is a gently plain at low altitudes (120-130 m). Most soils are temporarily waterlogged and show strong acidity. For this reason, the vegetation consists chiefly of forest stands and permanent pastures.

Local climate is characterized by moderate annual rainfall (630-770 mm), well distributed throughout the year. Mean annual temperature is close to 10.5° C. This predominantly oceanic climate, affected by western and southwestern winds, has rather mild winters and temperate summers. Temperature in Auxerre averages 2.5° C in January (coldest month) and 18.6° C in July (warmest month).

3. SOILS

The initial basic knowledge was derived from medium-scale mapping (Baize, 1976). Material is described in table 1.

3.1. Morphology of the profiles

The studied soils always show horizons poor in clay (silty of sandy) that overlie clay or sandy-clay horizons. In addition, they exhibit a strong textural differentiation and an abrupt nearly-horizontal transition between the two types of horizons.

During field mapping, the upper clayey horizons had been presumed to be structural horizons rather than the result of illuviation. This hypothesis was to be tested. Thus, the sequence of horizons can be designated as : A, E, Eg, S, SC, C (new French nomenclature, Référentiel Pédologique, 1988; E = previously A_2 and S = previously (B)).

Some variations exist nevertheless, depending on type of humus, podzolic evolution in the A horizon, thickness of coarse-textured E horizons (widest range of 20 to 90 cm; usual range of 35 to 45 cm), waterlogging intensity and hydromorphic properties of the Eg horizons, aspect and importance of "morphological degradation" phenomena (Jamagne, 1978; Pedro et al. 1978) at the textural contact, and presence or absence of a clay "bulge" (highest clay content in the S horizon);

Hydromorphic features of the Eg horizons vary with each profile. In dry periods (June through November), the following features can be observed : streaks combining light colours and rust-brown colours, bleached spots or mottling and ferro-manganic nodules of variable size. In humid periods (January through April), waterlogging occurs due to temporary subsurface watertables, giving the coarse-textured upper horizons a nearly sludge state and ephemeral greyish or greenish colours (gleying is weakly expressed due to the lack of iron).

"Morphological degradation" at the top of the S horizons is evidenced by both discoloration and local alteration of the texture. Volumes of soil material of varying size become differentiated at the top of the clay horizons. These volumes contain much less clay (hence their greater porosity and looser structure) and much less iron (hence their whitish colours) than the remainder of the S horizons. Morphological degradation only occurs in one solum out of two : it is not a general phenomenon. When clearly visible, such degradation fluctuates between two extremes. At last, there are thin skeletans coating the ped surfaces over the upper 5 to 8 cm of the S horizon (designated as Sd sub-horizon). As a maximum, degradation affects 20 to 60 % of the volume of the Sd horizon, which may be from 10 to 30 cm thick. These degraded volumes are, however, preferentially oriented : they extend more deeply along the vertical faces of the prismatic peds. This type of glossic-like degradation is encountered mainly in the soils richest in silt-sized skeletal grains. This last facies is very similar to that observed in the "sols lessivés dégradés" (CPCS, 1967) on medium-textured materials.

The S horizons are characterized by : heavy clay or sandy-clay textures; cubic and/or prismatic structures, which are finer in the upper part of the horizon; presence of many ochre or rust-coloured spots that are clearly visible on the beige, grey of green matrix; moderate and constant humidity contrasting with the winter waterlogging of the E horizons. Other features can also be observed in some exceptional profiles : slanted slickensides, few thin reddish or brownish clay coatings, and grey coatings.

The C horizons consist of slightly weathered cretaceous sediments that have been little affected by soil-forming processes. There are four criteria of field identification. If the parent-rock contains $CaCO_3$, the C horizons are not fully decarbonated and show fequently a calcic Cca sub-horizon in their upper part. The passage from S to C horizons is sometimes gradual and is characterized by loss of structure. The C horizons have only a coarse and weakly developed prismatic structure. Whatever the season, these deep horizons appear to be dry. Lastly, the clayey geological sediments become clearly recognizable on the base of their colour (blackish, brownish or slate-coloured) and of their "soapy" of "rubbery" touch. It is only at this depth that the glauconitic green sands maintain their sandy texture, the glauconite grains being intact and well individualized.

3.2. Mineralogical data of the clay fraction

The parent rock shows a diverse mineralogical composition. Within each profile, few qualitative differences are noted between E, S and C horizons. A more thorough study (separating clay fraction into granulometric sub-fractions) points to three main statements :

- the E horizons exhibit a relative accumulation of the coarsest clays (0,2 - 2 µm) and of quartz, kaolinite and titaniferous minerals;

- from the bottom to the top of the glauconiferous profiles, the finest glauconites show a geochemical evolution : progressive opening of the layers with acquisition of swelling properties ("transformation smectites", Robert and Barshad, 1973) and along with a loss of potassium, magnesium and iron;
- concerning the Flogny profile, vermiculitization of the illites has been established, a significant loss of potassium affecting the finest particles. The genesis of "transformation smectites" seems to have been inhibited in the Eg horizon by the fixation of probably aluminous ions.

The clay minerals currently found in planosols of the Champagne Humide are mainly inherited from cretaceous sedimentation. Only those clay minerals that result from the transformation or neoformation are of pedogenetic significance, but it is difficult to point them out as they remain a minority "drowned" in the original heritage.

Planosolization is not related to one type of phyllite mineral in particular, although it affects 2:1 minerals much more than kaolinite. The 2:1 minerals seem nevertheless to be more weatherable and/or smaller and/or more mobile.

3.3. Major analytical data

The forested planosols of the Champagne Humide show an acid or strongly acid pH in water. All A and E horizons as well as most deeper horizons are below pH 5.5. The highest acidity level is found in the "podzol-like" humus-rich A horizons (pH in water < 4.0). Base saturation values remain lower than 65 % in the A and E horizons (usually < 30 %), and range from 8 to 100 % in the S horizons, depending on the parent material (table 2).

CEC values obtained for the clay fractions show a systematic decrease in the E horizons. This might be due to the interlayer position of aluminous compounds blocking a number of exchange sites.

Ratios of total iron to clay content suggest a relative accumulation of iron in the Eg horizons. Furthermore, the highest total iron levels are usually encountered in Sd or S horizons. Consequently, there is some absolute accumulation of iron in the uppermost S_1 horizon.

Ratios of free to total iron clearly indicate that weathering increases from the bottom to the top of the profiles. The same applies to ratios of Al extracted with Tamm's reagent to total Al levels. The horizons closest to the abrupt textural change (Eg, Sd or S_1) contain the highest amount of exchangeable aluminium. Finally, Al^{3+} plays a dominant part in the E horizons where its level exceeds that of basic cations.

A major gradient therefore exists between (i) slightly acid (sometimes calcareous), saturated or weakly desaturated, slightly weathered C horizons devoid of free aluminium; (ii) clayey, acid, more or less desaturated, increasingly weathered S horizons containing considerable amounts of exchangeable and "free" aluminium; (iii) coarse-textured, highly acid (organic protons and Al^{3+}), strongly desaturated and highly weathered A and E horizons.

Table 2.
Some physico-chemical data of planosols in the Champagne Humide. (Note : nothing is mentioned concerning the C horizons because of their large variability).

Horizons	Clay content (%)	CEC of the horizon* (me/100g)	Base saturation (%) (forest)	CEC of the clay fraction (me/100g)
A, E & Eg	5 to 26 mostly 10 to 18	1 to 8	10 to 65 mostly 10 to 30	5 to 39 mean = 14
Sd, S & SC	32 to 60	8 to 24	8 to 100	16 to 56 mean = 36
* at pH 7, saturation with NH_4Ac				

3.4. Additional field data

During soil survey and profile pit examination, several major facts have been registered. First, an everyday field observation from December to May showed temporary shallow watertables circulating above slowly permeable clay layers. Not only is waterlogging visible in any pit or hole, but also water circulation does (rather fast in spite of the slight slopes). For instance, the deeply rutted forest tracks become small active brooks.

Secondly, during summertime, the clayey S horizons, although located at small depth, are never dry and show no obvious shrinkage. In fact, these horizons are sheltered from evaporation because they are under tree cover, thick litter and silty or sandy surface layers.

3.5. Conclusions

It is obvious that the above-described soils correspond exactly to the concept of planosol (Dudal, 1973; FAO-UNESCO, 1974) because of their morphology and of their peculiar type of temporary subsurface waterlogging.

4. LITHOMORPHIC OR PEDOMORPHIC PLANOSOLS?

A prerequisite to a pedogenetic interpretation was to find out whether the strong textural differentiation was due to some initial abrupt lithological discontinuity (cretaceous sedimentation or recent deposit), or to a particular soil-forming process in situ. In the first case, it would be possible to speak of "lithomorphic" planosols (Favrot and Legros, 1972); in the second case, these soils could be referred to as "pedomorphic" planosols. To elucidate this point, arguments relating to mapping or particle size distribution have been used.

4.1. Arguments relating to mapping

A first qualitative argument was provided by medium-scale mapping. During the survey, the textural variations of the E horizons were shown to be well correlated with the lithological facies of the geological layers appearing in successive outcrops (fig. 1).

In fact, field surveys on E horizons show rapid textural variations, on a decametric scale. The observed textures range continuously from pure medium sand to sandy silt loam. This excludes the hy-

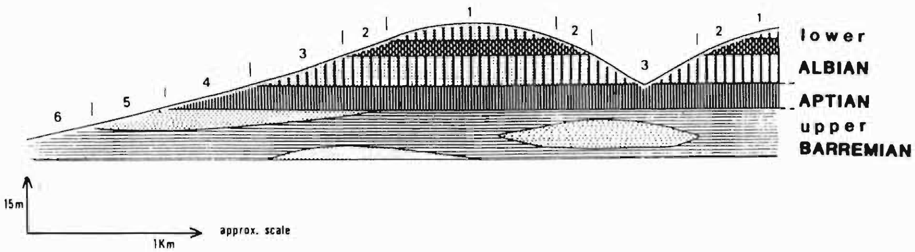


Fig. 1.
Textural variations of the Eg horizons are well correlated with the lithological facies appearing in successive outcrops (schematic presentation) :
- 1 and 3 = medium sand over glauconitic "green sands"
- 2 = silty sand over grey clays with a fine-silty skeleton;
- 4 = sandy silt loam over slightly calcareous yellow clays;
- 5 = fine sand over variegated sandy clays;
- 6 = sandy silt over variegated clays with a fine-silty skeleton.

pothesis of a shallow deposit of remote origin. Furthermore, the details of these variations can only be understood in relation to the detailed facies variations of the geological sequence. For example, sandy-textured surface horizons (n° 1 and 3, fig. 1) always overlay deep green sandy-clay horizons, whereas silty loamy textures overlay the aptian yellow clays (n° 4).

Rapid variations within the cretaceous sedimentation are the only cause of granulometric variability in surface horizons. This is a major argument in favour of the rather strict autochtony of the A and E horizons. Consequently, the latter seem to have had the same parent material as the deeper clay horizons.

4.2. Study of "granulometric skeletons"

This study (Baize, 1980a) was conducted on a large number of samples (282 horizons), with the interest exclusively been oriented towards the sand and silt fractions. The clay fraction was excluded by calculation because the < 2 µm fractions are more mobile (vertical or lateral translocation), more sensitive to geochemical degradation, and because they may occur within the horizons as a result of the in situ weathering of coarser particles (disintegration of glauconitic pseudo-sands or micro-division of the fine silt-sized illites). Six granulometric fractions could be used (table 3). These values, expressed as a percentage of their sum, served as a basis for comparing horizons of the same profile ("vertical" comparisons, fig. 2) or horizons of different sites ("horizontal" comparisons).

Table 3.
Calculation of the "écart brut" (Eb) between two horizons, i.e. the sum of differences of the six granulometric fractions (absolute values in per cent). Example : Héry profile.

Horizon	LF (2-20 µm)	LG (20-50 µm)	SF1 (50-100 µm)	SF2 (100-200 µm)	SG1 (200-500 µm)	SG2 (500-2000 µm)	
Eg	14.1	13.0	37.1	28.1	6.8	0.9	
Sd	17.5	12.3	42.0	24.1	3.4	0.8	
=/=	3.4	0.7	4.9	4.0	3.4	0.1	Eb=16.5

As a first qualitative approach, diagrams were constructed. For the purpose of simplification, they only compared the Eg and Sd or S_1 horizons of each profile (two samples vertically close, but

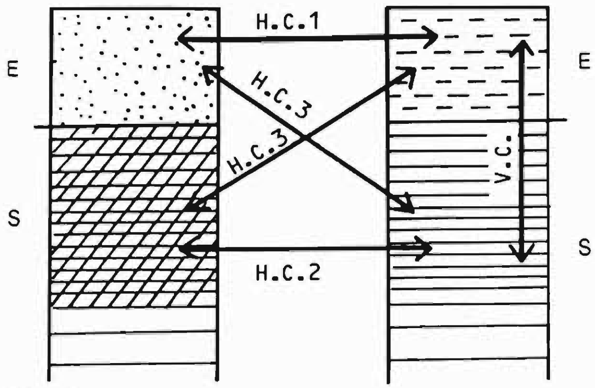


Fig. 2.
Comparisons between "granulometric skeletons" (V.C. = vertical comparisons; H.C. 1, 2, 3 = horizontal comparisons).

placed on either side of the abrupt textural change). Among the 55 studied pairs, similar material was found in 53 cases besides 1 doubtful case, and 1 certain case of heterogeneity.

Afterwards, a quantitative index termed "écart brut" (Eb) was calculated (table 3). Many treatments were applied to this index, but only one result will be mentioned, namely the distribution of the "écart brut" obtained by vertical comparison within the 55 profiles. Some forty sites showed Eb indices lower than 20. It was felt that this result indicated a good homogeneity in particle size distribution. For the other profiles, however, there are no clear answers due to the lack of references for this kind of index.

4.3. Study of a small test area

This study was made in three steps : mapping over 95 ha, sampling of 17 E horizons, and then sampling of 8 profiles located within a 12-ha polygon. In order to examine the 8 E and S pairs, the 120 "écarts bruts" that distinguish the "granulometric skeletons" of the 16 horizons have been calculated. The E and S horizons of a same profile generally showed rather low Eb indices, lower than those calculated between two horizons of two distinct profiles. This, however, is not an absolute rule : the two horizons most similar in terms of particle size distribution are derived from eluviated horizons of two remote sites. Then, the profiles were geographically relocated in relation to each other in order to compare spatial proximity with mathematical proximity. Of the 15 relations examined in this way, 14 show that the E and S horizons of the same profile are more similar than the E and S horizons in closely spaced profiles.

In conclusion, there is a variability from one site to another over very small distances but a relatively strong genetic link within each profile.

4.4. Heavy minerals

A study of the heavy minerals in four profiles pointed to the cretaceous nature of all E and S horizons. This fact, once again, excludes the hypothesis of an allochtonous deposit of remote origin.

4.5. Conclusion - New question

The cretaceous sedimentation appears to be quite heterogeneous with abrupt field variations, especially in particle size distribution. All qualitative and quantitative arguments converge to one and the same conclusion : the rapid and substantial changes from one site to the next contrast with the close similarities between horizons of a same profile located on either side of the abrupt textural change ("planic contact"). A number of technical and pedologic difficulties were encountered. A good initial uniformity in particle size distribution could however be demonstrated in over fifty profiles, hence in the majority of the soils considered. Differentiation of the surface horizons poor in clay is therefore not related to some original sedimentary discontinuity or recent deposit, but results from soil formation in situ. This had to be elucidated before pursuing any research on the evolution of this type of planosol. We are dealing with pedomorphic planosols.

The above considerations lead to a further question : does the strong textural differentiation result from relative clay accumulation in a S horizon, or does it result from absolute clay accumulation in a BT horizon due to argilluviation?

5. MICROMORPHOLOGY

Regarding the distribution of clay, observations of thin sections in five profiles revealed a nearly total lack of argillans and ferri-argillans (usually indicating clay illuviation) in the clayey S horizons. The few cutan-like features seem rather to be diffusion or stress cutans, but they are of little importance considering the textural differentiation of the soils. The very few typical illuviation cutans were found in the Eg and Sd horizons rather in the clay-rich S horizons.

In addition, thin section examination allowed recognition, at the microscopic level, of some features already observed in the field, e.g. conversion of glauconite grains into yellow-greenish poorly limpid plasma, stress cutans and vo-sepic plasmic fabric along fissures corresponding to slickensides, iron impregnation and nodulation representing the rust-coloured spots typical of waterlogging or weathering, and "morphological degradation" at the top of the S horizons associated with the disappearance of the clayey plasma.

Consequently, the planosols of Champagne Humide do not appear to have undergone significant clay illuviation. Additional evidences must, however, be provided in support of this statement (see chapter 7).

6. WATER REGIME

Two forested sites have been selected in order to understand the water dynamics under the best possible natural conditions. Several independant in situ methods were used from May 1977 to January 1982, as well as laboratory tests (table 1). The results obtained on both the HERY and PONTIGNY sites were in good agreement, except for a few slight differences. For lack of room, only the main results will be presented here. Any reader interested by more detailed results can refer to Baize (1983; 1984).

Climatic water balances were calculated. They indicate a considerable soil water deficit in 1978 (July to November), a smaller one in 1979 (July to September), a slight shortage in September 1980 and 1981, and no deficit in 1977. Winter water surplusses were determined as being 178 mm, 306 mm, 217 mm, 282 mm and > 162 mm respectively for each winter period. In summer, natural drainage may have occurred in August 1977. In June 1981, a considerable water surplus is pointed out by calculation : 45 mm during the first 10-day period, 11 mm during the third.

The presence of water in short piezometers pointed to the existence of a subsurface watertable, hence to waterlogging of the coarse-textured E horizons. This shallow watertable appears every year in January, February and March. It was observed once in late December 1980, in May 1979, on 10 June and 10 August 1981, but was not detected in April nor during the other months. It could not be determined whether the watertable is continuously present in winter. Three long periods of watertable existence have nevertheless been identified : 20 days from 24 January to 14 February 1979; 63 days from 9 January to 14 March 1980 and 22 days in January 1981. The shallow watertable was present for less than 8 days in May 1979, March 1980 and December 1980.

The absence of a subsurface watertable may be as ephemeral as its presence, e.g. it could be observed on 27 December 1980 and 1 January 1981 but not on 30 December 1980.

81 neutron moisture measurements have been carried out between May 1977 and January 1982, i.e. an average of one every 21 days for nearly 5 years. To study variations in the course of time, the raw readings have been expressed in a standard form as a percentage of the total variation throughout the 81 measurements for each horizon (0 % = min. reading; 100 % = max. reading). In such a way, the horizons can exhibit four different states :

- dry (raw readings < 30 %);
- wet (raw readings > 65 %): : very close to field capacity;
- transitional : rewetting or drying;
- waterlogged (raw readings exceeding 80 %) : excess of water saturating all the voids, especially packing voids, channels and macropores.

There was a good correlation between these raw values and the presence of a subsurface watertable detected with the short piezometers.

Temporary waterlogging was only encountered at depths of 15, 25 and 35 cm in the two sites (A and E horizons). At these depths, the wet state corresponds to raw data ranging from 65 to 80 %, whereas the waterlogged state would be evidenced by higher percentages. None of the horizons occurring under the "planic contact" exhibits a waterlogged state which differs from the wet state.

After calibrating the raw data and converting them into volumetric moisture amounts, the soil moisture contents could be calculated for each measuring date (expressed in mm). Table 4 shows which is possibly a favourable period. Between 10 November 1978 and 24 January 1979, 142 mm of rainfall were recorded. It may be assumed that 103 mm of water rewetted the soil and that 39 mm were removed laterally (or evapotranspired) because they did not reach the C horizons. From 24 January 1979 till May 1979, 335 mm of rainfall were recorded. Of these 335 mm, 15 mm are assumed to have contributed to the soil rewetting, whereas 320 mm were laterally drained, evapotranspiration being probably negligible at this period, under deciduous trees.

Various field and laboratory measurements were used in establishing some kind of volumetric balance at extreme moisture contents (assuming that the total porosity remained constant). Such balances demonstrate :

- the large water capacity available in the E horizons (> 24 %);
- the small water capacity available in the S horizons (7 to 8 %) and their high content of strongly retained water;
- the very small volumes occupied by air during periods of maximum moisture content (1.5 and 4 % in the S horizons; 3 to 7 % in the E horizons). At these times, aeration is there-

Table 4.
Water balance during a rewetting period. Example : Héry profile (under deciduous forest).

Horizon	10.11.1978 (date of max. drying) water amount in mm.	24.01.1979 increasing of the water amount since 10.11.78	21.05.1979 increasing of the water amount since 24.01.79
0			
A + E	70 mm	+ 68 mm	+ 3 mm
40 cm			
S + SC	313 mm	+ 33 mm	+ 12 mm
130 cm			
C_1	107 mm	+ 2 mm	- 4 mm
170 cm			
$C_2 + C_3$	140 mm	- 2 mm	- 5 mm
230 cm			
RAINFALL :		142 mm	335 mm

142 mm → 103 mm in the soil profile to a depth of about 170 cm
142 mm → 39 mm are laterally removed or evapotranspired

SOIL WATER STORAGE RECONSTITUTION

335 mm → 15 mm in the soil profile to a depth of about 130 cm
335 mm → 320 mm are laterally removed or evapotranspired

LATERAL RUNOFF

fore very weak and the medium becomes reducing. In the driest periods, maximum air volume in the S horizons remains low (9 and 11 %).

The relationship between matric potential (pF) and moisture weight has been studied. Measurements were made on undisturbed and undried soil samples (collected in the field, using 1000 cm^3 cylinders), and peds of about 5 cm^3. Between pF 2.0 and 3.5, for the E horizons, moisture values obtained on cylinders disagree with those found on peds. It may be inferred that there is a rather coarse porosity (between 0.5 and 15 μm) corresponding probably to inter-aggregate and/or biological voids.

This discrepancy does not occur in the S horizons, because such voids do not exist at this pF range of common occurrence in the field. In the clayey horizons, only slight moisture variations are noted between pF 1.0 and 2.5. These horizons have few voids > 5µm; in other words, they are slowly permeable in all seasons.

In conclusion, all the horizons exhibit their lowest moisture level in autumn, as a result of evapotranspiration and prolonged water deficit. Early in winter, the rain rewets and saturates the E horizons, and rewets the upper part of the S horizons. If small cracks exist in autumn within these layers, they rapidly close due to rewetting and swelling. By late winter and early spring, the rain still saturates the E horizons, but penetrates no longer or very slowly, into the S horizons. Most of the water excesses are quickly carried away laterally by temporary subsurface watertables. The C horizons do not seem to be reached by precipitation water. The constant moisture content of these weakly structured horizons indicates a slow water transit.

Those detailed studies have only confirmed and quantified the facts which have been observed during mapping. The abrupt textural change is the main cause of the essentially lateral water movements. Conversely, this lateral soil water dynamics is involved in the existence of the planosolic morphology (see chapter 9.4.).

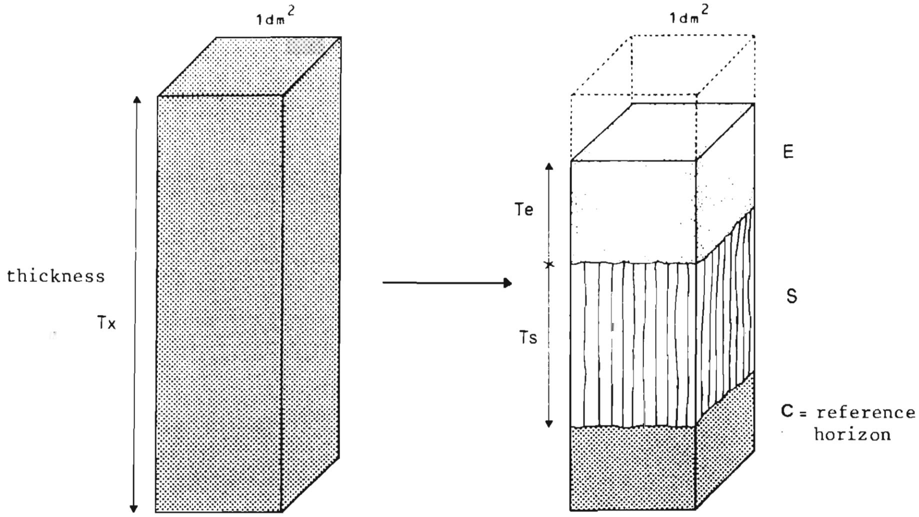
7. ISOQUARTZ BALANCES

7.1. The method : its choice and aims

The purpose of introducing these balances was to elucidate clearly whether the materials that had left the upper horizons had moved laterally of vertically, and whether the clay horizons result from absolute or from relative accumulation of clay (Baize; 1980b).

In an "open" system such as the soil mantle, the different compositions of the current horizons do not provide enough information on material gain of loss in each horizon. Such gains or losses can be determined either by hydrochemical and hydrological procedures for the investigation of current movements, or by chemical-mineralogical methods demonstrating absolute variations, in the course of time, of such or such constituent within a profile relative to an invariable constituent. One advantage of the isoquartz balance is that it relies on a constituent which is stable in temperate climates and abundant in the studied soils, hence subject to only slight estimation errors.

The material balances, which are established in relation to the presumably invariable quartz content, enabled us to evaluate absolute gains or losses of the major horizons relative to their original



IN THE BEGINNING	IN THE MEANTIME	TODAY
Hypothesis : Parent material was homogeneous and strictly identical with the current reference horizon in all respects.	*Hypothesis :* - Quartz has remained insoluble. - Neither erosion nor new deposit has occurred.	*Analytical knowledge of :* - thickness, - bulk density, - quartz content, - mineralogical and chemical amounts per cent. - particle size distribution. FOR EACH HORIZON ↓ CURRENT WEIGHTS CALCULATION

ORIGINAL WEIGHTS CALCULATION

↓

LOSSES OR GAINS DETERMINATION

(Weights for a 1 dm^2 column, in absolute values)

Fig. 3.
Principles in establishing the isoquartz balances.

state. They also express the entire pedologic evolution throughout the period of time required for the profile's differentiation. Several processes distinct from those currently involved, may have occurred successively or conflictually. The global values obtained may represent the algebraic sum of different types of gains and losses. Thus, the chemical-mineralogical and hydro-chemical methods yield complementary rather then similar informations.

7.2. Principles and execution

The method used is derived directly from Marshall and Haseman (1942), who had chosen zircon as a basic invariable constituent. It allows the calculation of absolute weights of the various horizons of a pedon. Unlike the usual isoquartz expressions, this method takes into account the relative thicknesses of the horizons, so that one can compare the gains and losses possibly occurring at various depths of a profile. This type of balance relies on four hypotheses or conditions which cannot be readily verified in nature (figure 3).

First, it was necessary to determine the quartz contents of the main horizons. This preliminary work was not easy because the quartz could not be directly determined. It required complex and often "acrobatic" mineralogical reconstructions which were made as follows : (i) evaluation of the type of minerals present in significant amount (X-ray diffraction, microscopic examination, DTA); (ii) quantitative determination of the minerals other than quartz (thermogravimetric analysis, magnetic separation of the grain glauconite, chemical analysis, etc); (iii) percentage determination of the quartz either by selective dissolution of the phyllite minerals (Kiely and Jackson, 1965), or by simple calculation (% quartz = 100 - all other minerals). Various methods of calculation independant of each other have been used in order to be virtually certain of the good agreement between converging results.

Knowing the current weight and the original weight (before differentiation) of each horizon, it was possible to calculate their global weight change. It was then easy to compare the current weight of an element, a mineral or a granulometric fraction (= Z), with the original weight of Z and to infer the gains or losses of Z.

7.3. Results

A first isoquartz balance was made on a mineralogically simple soil (quartz + glauconite only) : the HERY profile. Another three balances were then established on soils showing different particle size distributions and mineralogical compositions. In these three cases, it has been proceeded under less favourable conditions (complex mixtures of many minerals, less analytical data), but according

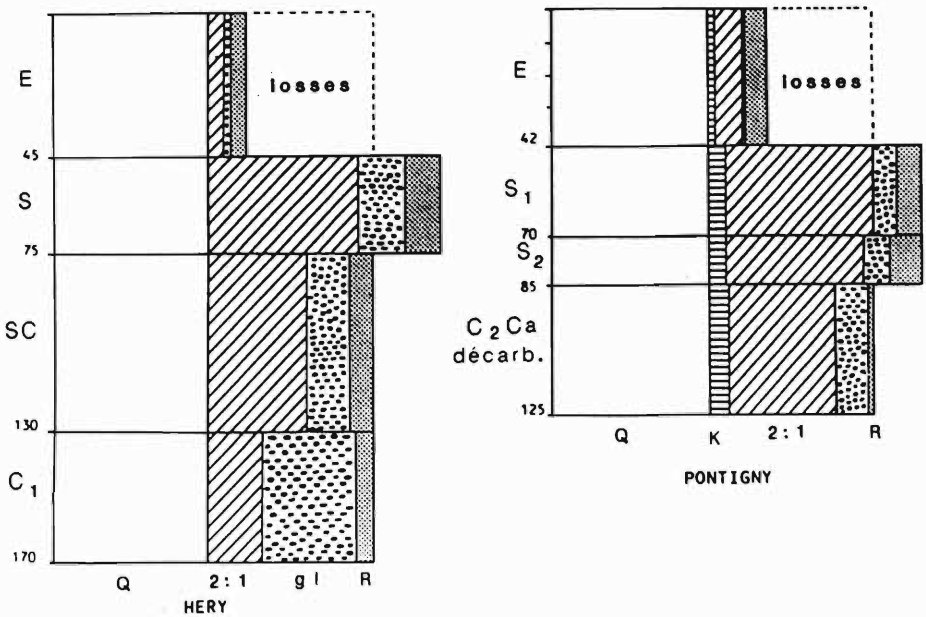


Fig. 4.
Diagrammatic presentation of the isoquartz balances calculated for HERY and PONTIGNY profiles (Q = quartz; 2.1 = glauconite + illites; gl = grain glauconite; k = kaolinite; R = another minerals and materials).

to the same principles as those adopted for the HERY profile.

7.3.1. Héry profile

Quartz contents have been evaluated in six different ways. The following values (weighted averages) have been retained : 80.0 % in Eg, 39.2 % in S, 47.6 % in SC and 47.8 % in C horizons. The Eg horizon was considered to be representative of all the clay-poor upper horizons (down to a depth of 45 cm), and the S and SC horizons of the 45-75 and 75-130 cm soil layers respectively.

The global weight balance (table 5) already provides interesting information : the E horizons appear to be strongly impoverished (40 % weight loss), whereas the S horizon is markedly enriched (22 % gain). The 0.4 % gain noted in the SC horizon is not significant. The results concerning the six major chemical constituents (table 6) fully confirm the global balance : strongly impoverished E horizons, and markedly enriched S horizon. But irrespective of whether are considered total weights or oxides, material losses in the E horizons are never compensated by the gains in the S horizon (figure 4).

Table 5.
Global weight and thickness balances (Weights expressed in hg/dm^2, bulk density measured with membrane densitometer) in the Héry profile.

Horizon	1 Present thickness (cm)	2 Present bulk density (g/cm^3)	3 Present weight (hg/dm^2)	4 Original weight (hg/dm^2)	Difference 4 - 3 (hg/dm^2)	Difference 4 - 3/4 (%)	5 Original thickness (cm)	6 Thickness difference 5 - 1 (cm)
Eg	45	1.51	67.95	113.61	-45.66	-40%	70.6	-25.6
S	30	1.28	38.40	31.48	+ 6.92	+22%	19.6	+10.4
SC	54	1.48	81.40	81.07	+ 0.33	+0.4%	50.4	+ 4.6
C_1	40	1.61	64.40	64.40	0	0	40	0

Table 6.
Balance of the 6 major chemical constituents (expressed in oxides) in the Héry profile. Weight gains or losses (hg/dm^2, upper line) and as a percentage of the original weight (in brackets). The gains in S are not at all equivalent to the losses in E.

	SiO_2*	Al_2O_3	Fe_2O_3	K_2O	MgO	CaO
E	-23.56 (-28%)	-5.62 (-73%)	-8.41 (-76%)	-2.34 (-78%)	-1.23 (-88%)	-0.27 (-85%)
S	+ 2.56 (+11%)	+1.44 (+67%)	+1.02 (+33%)	+0.10 (+12%)	+0.08 (+21%)	-0.04 (-43%)
SC	- 1.09 (- 2%)	+0.03 (+0.5%)	-0.39 (- 5%)	+0.02 (+ 1%)	-0.08 (- 8%)	-0.04 (-18%)

* As quartz is supposed invariant, it is solely combined SiO_2.

Table 7 shows the chemical composition of materials lost in the E horizon to be very similar to both that of the grain glauconite and that of the < 2 µm fraction of the reference C horizon. This similarity reveals an impoverishment in 2:1 clay minerals. This impoverishment may result from lateral movement of particles out of the profile, or from total geochemical degradation of the clay minerals associated with the removal of all residues.

Table 7.
Chemical composition of the materials lost in the E horizons and comparison with that of the < 2 µm fraction of the reference horizon in the Héry profile.

Oxide	Losses in E horizons		Reference C horizon	
	Weight hg/dm^2	Chemical composition	Grain glauconite 100-200 µm	< 2 µm fraction
SiO_2	- 23.56	56.87	56.48	55.27
Al_2O_3	- 5.62	13.57	11.71	16.59
Fe_2O_3	- 8.41	20.30	21.90	18.39
K_2O	- 2.34	5.65	6.50	5.71
MgO	- 1.23	2.96	3.05	3.38
CaO	- 0.27	0.65	0.90	0.12
Na_2O	-	-	0.16	0.11
TiO_2	-	-	0.15	0.44
sum :	- 41.43	100.00	100.85	100.01

Gains in the S horizons consist of 49. % SiO_2, 27.7 % Al_2O_3, 19.6 % Fe_2O_3, 1.9 % K_2O and 1.6 % MgO. This composition is difficult to interpret because it has been obtained from figures of low absolute value, likely to be affected by strong relative errors.

The glauconite consisting of unweathered grains was isolated with a magnetic separator and its chemical composition determined. So, it was possible to estimate the glauconite contents of the silts and sands in the four major horizons. The isoquartz balances of this grain glauconite and of all the 2:1 phyllite minerals (particles of all sizes) are shown in table 8. They indicate that the glauconitic pseudo-sands disappear from the bottom to the top of the profile, and that the 2:1 phyllite minerals represent almost the entire losses of the upper horizons, and most of the gains of the S horizon. This causes no surprise, since we mentioned earlier that the mineralogical composition of the soil is confined to the quartz + glauconite association.

Therefore the "clay-content bulge" observed in the HERY profile does not result from absolute clay accumulation due to argilluviation, but from the combination of three phenomena of unequal importance : (i) marked conversion of the glauconite grains into clay, an upward moving process that increases with decreasing depth; (ii) considerable clay impoverishment of the upper horizons, a process

Table 8.
Isoquartz balance of grain glauconite and of the sum of 2:1 clay minerals (including grain glauconite) in the Héry profile. Weight gains and losses as a percentage of the original weight.

Horizon	Grain glauconite (silts + sands)		Sum of the 2:1 clay minerals		Global weight gains or losses of the horizon (cf. table 5)
	hg/dm^2	%	hg/dm^2	%	
E	- 29.7	- 92	- 43.9	- 84	- 45.7 hg/dm^2
S	- 4.4	- 49	+ 5.5.	+ 38	+ 6.9 hg/dm^2
SC	- 11.3	- 49	- 0.3	- 1	+ 0.3 hg/dm^2

laterally directed but leading to the progressive lowering of the claypan; and (iii) slight accumulation of illuviated clay, confined to the top of the S horizon. Thus, the clay horizons of the HERY profile are essentially weathered S horizons.

7.3.2. Other profiles

The detailed results concerning three other profiles will not be presented here : PONTIGNY (developed from a sandy and glauconi-

Table 9.
Estimated total weight gains or losses of the four studied profiles (hg/dm^2).

Profile	HERY	PONTIGNY	REBOURSEAUX	FLOGNY
Horizons	E : - 45.7	E : - 30.2	Eg_1 : - 30.2 Eg_2 : - 8.5 E & S : - 6.8	Eg : - 38.1
	S : + 6.9 SC : + 0.3	S_1 : + 5.4 S_2 : + 3.1	S_1 : - 1.8 S_2 : - 2.9 SC_1 : - 3.1	S_1 : + 4.2 S_2 : + 7.1
reference horizon	C_1 (glauconitic loamy sand)	C_2Ca (decarbonated) (silty clay)	SC_2 (clay)	C_2 (clay with 3,6 % $CaCO_3$)

tic marl of the upper Albian); REBOURSEAUX (cenomanian clay); FLOGNY (aptian calcareous clay). The estimated weight gains and losses of these soils are listed in table 9.

7.4. Conclusions

The four studied profiles show the following features : (i) major loss of material in the E horizons (30 to 45 % of the original weight); (ii) material gains in the upper part of the S horizons (except at REBOURSEAUX); (iii) these gains remain limited and do not compensate for losses in the E horizons. Thus, the materials lost in the surface horizons seem to have left the profiles. This lost material seems to consist only of particles < 2 µm (60 to 82 % of the original fraction).

8. ANALYSIS OF THE SUBSURFACE RUNOFF

At HERY, water samples were collected in a small pond which is the natural drainage way of the surface watertables. 11 samplings were made at 6 winter dates and 1 summer date. pH range was 4.8-6.8, resistivity 9,300-12,600 Ohm/cm, and the amount of material in suspension 2.7 to 32.2 mg/l. The presence of Ca, Mg, K and Na in solution is related to the bio-geochemical cycle, whereas the relatively abundant dissolved silica (10.5 to 20.0 mg/l SiO_2) might result from current weathering of the crystal lattices of some silicates.

A 60-1 sample was collected in February 1982 and the material in suspension separated by centrifugation at 50,000 g. The centrifugate only consisted of particles < 2 µm very similar in composition to the fine-clay fraction (< 5 µm) of the E horizons of the HERY profile. Furthermore, the XRD curves obtained with these residues showed similar features (presence of glauconite, smectites, interstratified minerals, and kaolinite) to those of the E horizons.

Water samplings were taken from little brooks. Thus, it is possible to answer the following question : what has happened with the clays lost by E horizons? These suspended materials have been drained through the hydrographic network. It must be noticed that, within the region, all the latest alluvial deposits are clays or heavy clays, in small as in large valleys.

9. GENERAL SYNTHESIS - SOIL GENESIS

In order to understand both formation and dynamics of these planosols, numerous approaches were used : macro-morphological observations, microscopic examinations of thin sections, arguments related to mapping or to particle size distribution, determination of heavy minerals, samplings of the subsurface runoff, analysis of the weathering complex, isoquartz balances, study of the soil water regime (based on various procedures). Each of them yielded data which were critically examined, enabling a partial synthesis to be drawn. The latter can be summarized as follows :

1. Originally, the parent materials were homogeneous;
2. today, the soils are developing in a medium marked by strong mineral acidity;
3. "morphological degradation" (of variable importance) occurs at the interface between Eg and S horizons;
4. only the finest clay minerals seem to be affected by weathering;
5. the profiles show strong textural differentiation (clay indices S/E range from 2.4 to 5.2, mean = 3.3);
6. the upper horizons have been strongly impoverished in clay;
7. there has been little vertical clay illuviation within the S horizons, only in their upper part;
8. the soil water dynamics is essentially lateral;
9. each year, 200 to 400 mm rain are removed by subsurface watertables;
10. the lateral runoff carries away (in brooks) some amount of clay in suspension.

To draw final conclusions about soil genesis, it was necessary to overcome some apparent contradictions between current phenomena (items above 2, 8, 9 et 10) and the integrated effects of earlier successive or simultaneous processes (items 4, 5, 6 and 7).

9.1. Hypothetical reconstruction of soil evolution

The textural evolution will be artificially presented separately from the physico-chemical evolution. The former can be subdivided in three stages :

STAGE 1. From a clay material, creating of a physical and biological macro-porosity down to an "abrupt structural change". Beginning of the lateral water circulation = beginning of clay impoverishing (cf. "pélosols brunifiés").

STAGE 2. Gradually the impoverishment increases, the "structural change" deepens and turns into an "abrupt textural change".

STAGE 3. The E horizons show an increasing porosity, while S horizons remain slowly permeable. The lateral water flow increases and impoverishing becomes self-accelerating. The planosolic morphology becomes more and more pronounced.

The physico-chemical evolution can be described as follows :

STAGE 1. Beginning of pedologic structuration and of weathering (iron release). Decarbonatation (if calcareous parent material). Clay formation from grain glauconite (case of the albian "green sands").

STAGE 2. Deepening of the three above-mentioned processes. Beginning of the base desaturation. Clay minerals remain stable. Tendancy to waterlogging of the surface horizons by rainfall.

STAGE 3. Occurrence of first real hydromorphic features at a shallow depth. Reduction/reoxidization cycles. Increase of the base desaturation and beginning of aluminization. Progressive opening of the micaceous clay layers.

STAGE 4. Increase of waterlogging. Rather strong mineral acidity. Secondary illuviation resulting in the degradation at the top of S horizons (in such a desaturated and temporarily reducing medium, clay is dissociated from iron and is able to be removed separately).

STAGE 5. Acidity and waterlogging continue to increase. Beginning of total acido-ferrolysis of some clay minerals. Podzolization is possible at the surface (due to alteration of the vegetation), but is not at all inevitable.

A number of factors can inhibit these evolutions or limit the downward movement of the abrupt textural change. These factors are as follows : (i) presence of $CaCO_3$ in the parent material (upward movement of Ca^{++} as a result of the bio-geochemical cycle); (ii) clay contents > 50 % (in such a case, there is a large amount of clay to be desaturated, removed or dissolved); (iii) slowly permeable parent material (bimodal particle size distribution, stratified and dense sedimentation), as a result of which all processes "hit" against a true claypan, water dynamics is only lateral, and the deepening of the abrupt textural change is much slower.

On the other hand, some factors accelerate the soil differentiation : (i) occurrence of sulfides in the parent material, the oxidation of which will cause the early release of a strong mineral acidity (occurrence of jarosite in the C horizons of some soils on "green sands"); (ii) presence of materials that are less rich in clay or more permeable; (iii) areas showing more intense water flow, hence faster clay impoverishment.

9.2. Comparison with other types of soils under humid temperate climates

No comparisons were made with other types of planosols that developed under other climates, in a totally different environment from that of the Champagne Humide. Instead, the present planosols were compared with two types of soils of common occurrence in northern France, which developed under the same humid temperate climate, in similar topographical positions, but on rather different materials (table 10) : "sols lessivés dégradés", differentiated from

Table 10.
Comparison between evolutions of "sols lessivés dégradés" of the Paris Basin, planosols of the Champagne Humide region and "pélosols brunifiés" of Lorraine. The different stages of evolution are numbered in roman figures.

	LOESSIC MATERIALS (PARIS BASIN)		CRETACEOUS CLAY MATERIALS (CHAMPAGNE HUMIDE)	TRIASIC CLAYS (LORRAINE)	
I	• Decarbonatation • Pedologic structuration.	I	• Decarbonatation (facultative). • Pedologic structuration. • Beginning of brunification (iron releasing...) • Clay formation from grain glauconite.	• Decarbonatation. • Pedologic structuration. (beginning).	I
II	• Brunification : iron releasing and moderate clay formation.				
III	• Beginning of desaturation and vertical primary illuviation. ↓	II	• Increasing of weathering. • Beginning of base desaturation. ← Beginning of lateral illuviation. Tendancy to waterlogging. Clay minerals remain unweathered.	• Beginning of brunification, • Base desaturation and ← lateral illuviation. Pedological structuration (continuation). Clay minerals remain unweathered.	II
IV	• Increasing of base desaturation and beginning of aluminization. First hydromorphic features. • Progressive opening of the micaceous clay layers. ↓ Continuation of the primary illuviation.	III	• Increasing of base desaturation and beginning of aluminization. First hydromorphic features. • Progressive opening of the micaceous clay layers. ← Increasing of the lateral illuviation.		
V	↓ Increasing of waterlogging.		← Increasing of waterlogging.		

Table 10. (continued).

	↓ "Secondary" vertical illuviation and glossic-like degradation of the Bt horizon.		● Rather strong mineral acidity.
			← Lateral illuviation (continuation)
		IV	← Secondary illuviation with a planic degradation at the top of S horizons.
	Interlayer hydroxy-Al ion fixation within the Eg horizons.		Interlayer hydroxy-Al ion fixation within the Eg horizons.
VI	← Idem but with a planosolic tendancy.		← Increasing of mineral acidity and of waterlogging.
		V	Beginning of acidoferrolysis of a part of clay minerals.
			● Surface podzolization is possible.
			← Lateral illuviation (continuation).

loessic materials in the northeastern Paris Basin (Jamagne, 1973, 1978; Pedro et al., 1978), and "pélosols brunifiés", formed from the Lorraine triasic clays (Nguyen Kha, 1973, 1975, 1976).

Circles in table 10 indicate the processes that tend to develop along a vertical line, hence to "go deeper" into the solum in the course of time (all forms of weathering). Vertical arrows indicate all essentially vertical translocations of material (vertical illuviations), while small horizontal arrows refer to transfers laterally directed as a result of the presence of a claypan. The two chronosequences on the left hand side share a number of common features. Their essential difference lies in the early occurrence of lateral movements in the case of soils overlying clays. The "pélosols brunifiés" can be considered as poorly developed soils that have only reached a primitive stage, but probably take place in the phylum leading to planosols.

9.3. Dominant factor of soil genesis

Parent material rather than local climate plays a predominant role in the formation of the planosols in the Champagne Humide. The early and definitive trend of soil genesis towards planosolic morphology and behaviour is specifically due to the occurrence of slowly permeable, sedimentary clay parent materials. Unlike the sandy or silty materials, where soil genesis develops initially (and for a long time) along a vertical axis, the clay materials examined in this study showed an essentially lateral dynamics.

9.4. Relationships between morphology and behaviour

As mentioned previously, the planosolic morphology now generates almost exclusively lateral water movements. Conversely, this lateral water flow has something to do with the existence of a planosolic morphology. Today, under highly acid, hence unfavourable physico-chemical conditions, fine clays are carried away in suspension by water at the rate of 3 to 32 mg/l. These clay minerals show the same chemical composition and the same XRD curves as the finest clays extracted from the Eg horizons. Besides, the water balances reveal that 200 to 420 mm of rainfall are drained laterally each year as temporary subsurface watertables. Thus, clay impoverishing still affects the upper horizons in current times. This process has probably existed for several thousands of years, and is the primary agent in the formation of the planosols studied here.

9.5. Classification

The clay-impoverished horizons of the FAO legend (1974) perfectly correspond to the definition of the E horizons, but not all of them deserve to be qualified as "albic" due to their ochre colour. This is a minor aspect. The planosols studied in this paper actually belong to the Planosols soil unit. The base saturation rate, determined by ammonium acetate (threshold at 50 %), is used in identifying eutric or dystric property of these soils. According to this criterion, some profiles such as the FLOGNY one, cannot be classified as dystric, even though its acidity is evidenced by KCl pH lower than 4 (including the clay S horizons)! This raises questions once again as to the determination of CEC by ammonium acetate at pH 7 for acid soils.

With reference to Soil Taxonomy (1975) the author does not agree to designate as argillic B horizons those clay horizons whose formation was little affected, or unaffected by clay illuviation, and which are chiefly inherited from sediments. These soils, or at least most of them, would be listed among Albaqualfs.

The French classification and in particular the C.P.C.S. system (1967) could not satisfactorily take into account these soils. The new typology (Référentiel Pédologique, 2nd approximation, 1988) recognizes the concept of PLANOSOLS and defines three units of them (= REFERENCES). So, the studied soils can be referred to as "PLANOSOLS PEDOMORPHES, d'appauvrissement, dystriques".

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Les Planosols de Champagne Humide, France : Etude multi-approches

Résumé

Des sols acides, fortement différenciés se sont développés à partir de sédiments argileux crétacés en Champagne Humide.

Des études granulométriques, physico-chimiques, minéralogiques et micromorphologiques ont été menées sur 7 solums sélectionnés à partir de 60 fosses. Le régime hydrique des sols a été suivi pendant 5 ans. 200 à 420 mm de pluies sont évacuées latéralement chaque année par des nappes perchées temporaires.

4 bilans isoquartz ont confirmé que la forte différenciation texturale résulte de l'entrainement latéral de particules argileuses hors des horizons de surface, sans accumulation notable dans les horizons profonds.

La formation de ces planosols "pédomorphes" est liée à deux facteurs stationnels : roches-mères argileuses peu perméables et position sub-horizontale. A la différence des matériaux sableux et limoneux, ces matériaux argileux connaissent dès l'origine une dynamique hydrique essentiellement latérale.

Planosols uit de vochtige Champagne streek, Frankrijk : een brede benadering

Samenvatting

Op de kleiige sedimenten van het Krijt in de vochtige Champagne streek hebben zich zure, sterk gediffentieerde bodems ontwikkeld.

Granulometrische, fysico-chemische, mineralogische en micromorfologische studies werden uitgevoerd op 7 geselekteerde profielen. Het bodemvochtregime ervan werd gevolgd gedurende 5 jaar. Hierbij werd aangetoond dat 200 tot 420 mm neerslagwater per jaar via laterale weg wordt geëvacueerd langs tijdelijke stuwwaterlagen.

De 4 uitgevoerde iso-kwarts balansen hebben aangetoond dat de

sterke textuur-differentiatie het gevolg is van een laterale afvoer van kleideeltjes uit de oppervlaktelagen, zonder dat hierbij een noemenswaardige accumulatie optreedt in de diepere horizonten.

De vorming van deze "pedomorfe" planosols wordt geassocieerd met 2 specifieke lokatie-gebonden faktoren : een weinig doorlatend klei-substraat en een subhorizontale ligging. In vergelijking met de zandige en lemige materialen, vertonen deze klei-afzettingen vanaf het begin een overwegend laterale vochtdynamiek.

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EFFECTS OF LABORATORY INCUBATION WITH ORGANIC SUBSTRATES ON THE STABILITY OF SOIL AGGREGATES TO WATER

J.S.C. MBAGWU

Abstract

Changes in the water-stability of natural soil aggregates to which organic substances were added and incubated under non-sterile conditions, were studied. The aggregates were collected from the Ap horizon of three contrasting agricultural soils from north central Italy. On the Lamporecchio (sandy loam) and Vicarello (clay loam) soils high rates, i.e. above 2.5 % of either peptone (P) or glucose (G), enhanced aggregate stability on the anaerobically-incubated samples, whereas on the Cremona soil (sandy clay loam) increased stability was observed more on the aerobically-incubated treatments.

On all soils, the higher G/P ratio, the more the stability was of the aggregates irrespective of the aeration condition. At the 10/1 ratio, aerobic incubation favoured better stability than the anaerobic condition. On the P- or P+G amended samples, aggregate stability was enhanced early but was maintained for a short period. Conversely, on the G-amended soils stabilization was slow initially but increased with time and was maintained for a longer period. The aggregate-stabilizing mechanisms involved are discussed.

Key-words

Aggregation, microbial activity, soil structure.

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1. INTRODUCTION

Recently there has been a renewed interest in the study of biological controls of soil aggregate stability. This is so because the nature of soil aggregates influences many physico-chemical processes going on in the soil, especially those related to the proneness of the aggregates to detachment and transportation by either wind or water forces, gaseous exchange within the root zone, crusting potential, water storage and availability to crops and the overall productivity of soils (Harris et al., 1966a; Lynch and Bragg, 1985; Skinner, 1979).

One of the most important factors that determine the degree of aggregation in soils is their organic matter contents. Organic matter is generally made up of two groups : the non-humic substances and the humic substances. The non-humic substances which comprise between 20-30 % of organic matter, are made up of mainly carbohydrates, proteins, peptides, and amino-acids. Their metabolic products act as transient binding agents which are rapidly decomposed by micro-organisms and are largely associated with the > 0.25 mm transient stable aggregates (Tisdall and Oades, 1982). The humic substances which make up between 70-80 % of organic matter consist of humic acid, fulvic acid and humin. In terms of their roles in forming and stabilizing soil aggregates the most studied group are the humic substances (Chaney and Swift, 1986; Piccolo and Mbagwu, 1988; Mbagwu and Piccolo, 1989). It is now recognized that the persistent binding agents of microaggregates (< 0.25 mm) in soils are the humic materials associated with amorphous iron, aluminium and alumino silicates (Edwards and Bremner, 1967; Tisdall and Oades, 1982).

In view of the fact that humic substances are formed in soils after prolonged decomposition of organic residues, their action in stabilizing soil aggregates takes very long periods to be noticed. The rapid improvement in aggregate stability observed after short periods of incubating soil/organic residue mixtures either in the field or laboratory (Chandra and De, 1982; Mbagwu and Bazzoffi, 1988) is due to the action of the microbial decomposition products of the carbohydrates (especially polysaccharides) and proteins such as gums and mucilages. Even though their stabilizing effects are transient they have important agronomic significance in that they do confer on soil aggregates some measure of stability against water forces especially during the start of rains (Allison, 1968; Molope et al., 1987). Their roles in stabilizing aggregates studied in some British soils (Skinner, 1979; Chaney and Swift, 1986) using glucose and peptone as substrates produced conflicting results. This may be due to the types of soils used, the variety of microbes decomposing the substrates and the technique used to determine aggregate stability. Most of the studies carried out in this area of research have, unfortunately, been with soils that do not vary much in their physico-chemical properties. This limits the extent of generalizations that may be made from such studies. It is, therefore, necessary to carry out such investigations with soils that offer a wide range of properties. Moreover, no such studies have been reported for Italian soils. Yet to the extent that some of the results obtained elsewhere are soil-dependent, extrapolations of results from one soil type to another could be very misleading. These considerations necessitated carrying out this study.

The effects of incubating three types of agricultural soils from north central Italy with either glucose or peptone or a mixture of both (in the laboratory) on the stability of aggregates to water are reported here. Since under field conditions aerobic and anaerobic conditions exist simultaneously within the soil, the effects of these conditions on the action of the substrates were also investigated. It is still not clear which of these two aeration conditions is more important in influencing aggregate stability (Harris et al., 1963).

2. MATERIALS AND METHODS

2.1. Soils

The 1-2 mm (diameter) air-dried aggregates from the Ap (0-20 cm) horizons of three contrasting soils from north central Italy were used for this study. These aggregates were obtained by dry-sieving and some of their physico-chemical characteristics are shown in table 1. Their metallic oxides and mineralogical composition are also given in table 2.

The soils were chosen to provide a wide range of characteristics especially in texture, mineralogy and stability of their natural aggregates to water. In each of the three experiments described below, 10 g of soil was used. To increase the range of micro-organisms present in each medium, finely ground, air-dried soil from the top layer of a forest was sprinkled on each sample (Chaney and Swift, 1986).

2.2. Experiment 1 : effects of different application rates of glucose and peptone

In this experiment the design used for each of the three soils was a split-plot in a randomized complete block. The mainplot treatments were the following amendments and aeration conditions : glucose-aerobic incubation, glucose-anaerobic incubation, peptone-

Table 1.
Some properties of the Ap-horizons of the three soils.

Soil property	Lamporecchio (Sandy loam, Typic Psammaquent)	Cremona (Sandy clay loam Aquic Xerofluvent)	Vicarello (Clay loam Vertic Xerochrept)
pH (1:2.5 H_2O)	6.3	6.2	7.6
O.M. %	0.93	2.57	2.33
C:N ratio	8.8	12.2	12.4
CEC (meq/100g)	21.2	21.7	22.3
$CaCO_3$ %	Nil	Nil	12.3
Exch. bases (meq/100g)			
Ca	8.50	11.25	14.50
Mg	2.97	1.23	4.25
K	0.28	0.46	0.62
Na	0.26	0.20	0.35
Aval.P ($\mu g g^{-1}$)	30.0	23.3	13.2
Sand %	52.0	49.2	26.0
Silt %	28.3	29.9	36.6
Clay %	19.7	20.9	37.4
Mean weight diameter of water stable aggregates	0.18	0.39	1.18

aerobic-incubation, and peptone-anaerobic incubation. The subplot treatments consisted of five application rates of each substrate viz : 0, 0.25, 0.50, 2.5 and 5.0 %. The 10 g 1-2 mm aggregates of each soil was placed in a petri-dish and thoroughly mixed with the appropriate amount of the substrate equivalent to the desired application rate. Thereafter, each petri-dish and its contents were moistened to field capacity (w/w) and incubated at 20° C for 15 days either aerobically or anaerobically (under a nitrogen atmosphere in a dessicator). The aerobically-incubated samples were weighed periodically to replenish evaporative moisture losses. Each treatment was replicated three times.

Table 2.
Chemical (above) and mineralogical composition (below) of the three soil samples studied.

Soil	Metallic oxides (%)							
	MgO	FeO	CaO	K_2O	Al_2O_3	SiO_2	TiO_2	MnO
Lamporecchio	1.9	3.7	0.7	2.5	14.2	69.3	0.43	0.08
Cremona	1.5	4.5	1.4	2.4	14.1	68.6	0.65	0.11
Vicarello	3.6	5.3	7.4	2.5	14.2	55.1	0.51	0.12

Soil	Mineralogical composition (%)					
	Quartz	Calcite	Muscovite	Chlorite	Feldspar	Kaolinite
Lamporecchio	27.7	Nil	22.5	6.0	25.0	20.5
Cremona	35.4	Nil	32.5	3.0	11.0	9.0
Vicarello	21.5	7.5	17.5	16.5	11.0	26.5

2.3. Experiment 2 : effects of varying ratios of glucose and peptone and aeration condition

A 2 x 5 factorial design was used for each of the three soils in this experiment. The first factor was two aeration conditions : aerobic and anaerobic, whereas the second factor was five glucose/ peptone ratios viz, 0:0 (control), 0.5:1, 1:1, 5:1 and 10:1. The following procedure was used to obtain the respective ratios. Each 10 g soil was mixed with 0.50 % peptone. Thereafter 0.25 %, 0.50 %, 2.5 % and 5.0 % glucose was added to the soils (depending on treatments) to obtain the following glucose/peptone ratios : 0.5 :1, 1:1, 5:1 and 10:1. The controls and treated samples were then moistened to field capacity and incubated either aerobically or anaerobically under conditions detailed above. Three replicates per treatment were used.

2.4. Experiment 3 : effects of types of substrate and incubation period

In this study, a 4 x 6 factorial design with three replications was used on each soil. The first factor was four types of amendments viz, distilled water, glucose (G), peptone (P) and glucose + peptone (G + P). Six incubation periods (in days) listed below constituted the second factor. Each 10 g soil was mixed separately with 0.5 % glucose, 0.5 % peptone or 0.5 % glucose + 0.5 % peptone. Both the controls and these amended soils were then maintained at field capacity and incubated aerobically (at 20° C) for 28 days. Periodic weighings of the samples were done to enable them maintained at field capacity moisture level. Sampling for determination of aggregate stability were done at the following days after incubation : 1, 3, 7, 14, 21 and 28.

2.5. Determination of aggregate stability

After each incubation period the soil samples were dried at 40° C for 4 days before aggregate stability determination. The procedure used for this determination was the single-sieve technique (DeBoodt, 1967) in which 10 g sample was placed on a 0.2 mm sieve and pre-soaked for 30 minutes. Thereafter the sieve and its contents were oscillated helicoidally for 20 times along a 4 cm stroke at the rate of one oscillation per second using a mechanical device. The fraction remaining on the sieve was oven-dried at 105° C for 24 hours, weighed and corrected for the sand fraction to obtain the proportion of true aggregates (Kemper, 1965). The percent water-stable aggregates was then computed as follows,

$$S = (Ma + s - Ms) / (Mt - Ma)\ 100$$

where : S = percent water-stable aggregates; Ma + s = mass of the resistant aggregates plus the sand fraction (g); Ms = mass of the sand fraction alone (g); and Mt = total mass of the soil sieved (g).

All data were subjected to an analysis of variance (ANOVA) test and the statistical significance of the F-values estimated for each soil.

3. RESULTS

In the Lamporecchio and Cremona soils, aerobically-incubated soil samples amended with either peptone alone or peptone plus glucose started developing a large network of mycelia which enveloped the soil aggregates 3 days after incubation. These wooly very hydrophobic mycelia were still visible until the end of the incubation period. In the Vicarello soil no such mycelia were noticed indicating that in this highly calcareous soil, different aggregating mechanisms were involved.

3.1. Effects of application rates and aeration conditions

As shown in table 3, on each soil there were highly significant differences in percent water-stable aggregates due to the type of substrates and aeration condition (the main treatment) and the rate of application (the sub-treatment). There were also highly sig-

Table 3.
The F-values of the analysis of variance tests of treatment effects on water-stability of soil aggregates.

Treatments	Source of variation	D.F.	F-values[1]		
			Lamporecchio	Cremona	Vicarello
Expt. 1 : Effects of application rates	Substrates/aeration condition (A)	3	54.90	61.08	36.82
	Application rate (R)	4	462.42	594.06	85.90
	A X R	12	65.82	72.16	54.11
Expt. 2 : Effects of amendment ratio and aeration condition	Aeration condition (A)	1	46.50	55.92	25.02
	Substrate ratio (R)	4	692.80	801.06	101.07
	A X R	4	NS	NS	33.11
Expt. 3 : Effects of amendment types and incubation period	Substrate type (A)	3	2096.80	2187.19	496.51
	Incubation period (P)	5	865.22	901.13	86.03
	A X P	15	106.15	135.50	92.11

1. Except where indicated otherwise, all F-values were significant at the 1 % probability level.
NS = Not significant at the 5 % probability level.

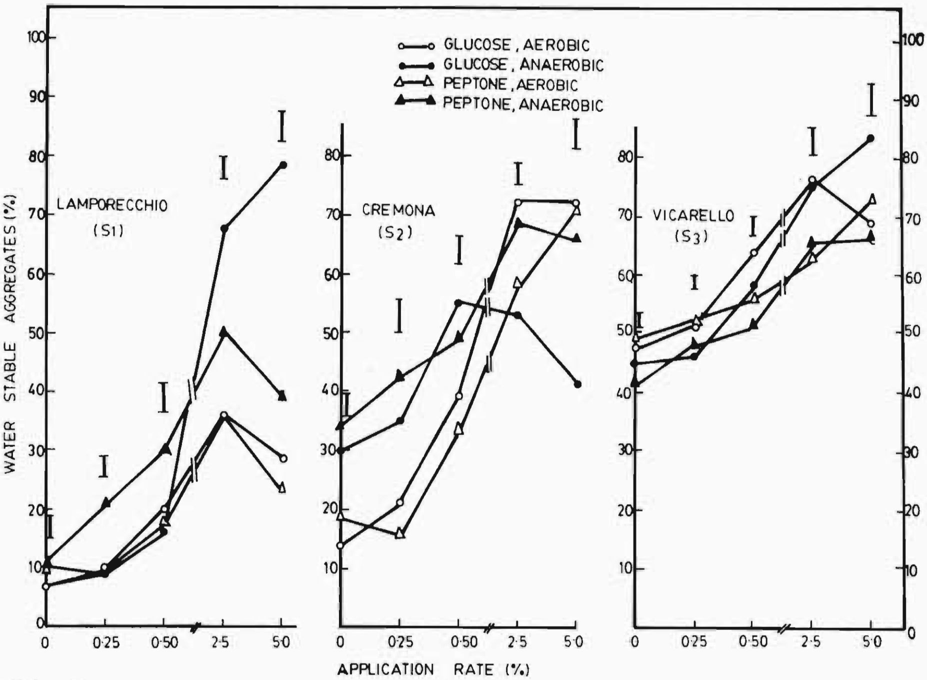

Fig. 1.
Influence of different rates of glucose and peptone on the aggregate stability of three soils to water under aerobic and anaerobic conditions.

nificant interactions between the main and subtreatments on each soil, indicating that the level of stability induced by the type of substrate and aeration condition was dependent on the rate of application of the substrate. This is shown in figure 1. With the exception of the control (0 % rate) of the Lamporecchio soil, on all soils at each application rate significant differences in percent water-stable aggregates were observed.

On the fragile Lamporecchio soil, aggregate stability increased gradually up to the 0.50 % rate, then rapidly up to the 2.5 % rate, on all treatments. On the aerobically-incubated, glucose-amended soil samples of Lamporecchio, aggregate stability decreased beyond the 2.5 % rate. The same was true for the peptone-amended Lamporecchio soil irrespective of aeration condition. On the glucose-amended, anaerobically-incubated samples aggregate stability increased progressively and significantly with application rate.

On the mildly stable Cremona soil with the exception of the glucose-amended, anaerobically-incubated samples where aggregate stability progressively decreased beyond the 0.50 % rate, stability was enhanced by increasing substrate rates. With glucose under aerobic incubation and peptone under anaerobic condition, application rates beyond 2.5 % did not significantly change aggregate stability on this soil.

On the highly stable Vicarello soil, aggregate stability increased with application rates on all treatments but the glucose-amended, aerobically-incubated samples, where stability decreases beyond the 2.5 % rate. It is therefore, evident that the stabilizing effects of these treatments was soil-dependent. For example in the glucose-amended, anaerobically-incubated samples, at the highest level of stability obtained in this experiment, there was a relative increase in stability over control of 70 % in Lamporecchio, 25 % in Cremona and 40 % in Vicarello. Also, whereas in this treatment stability progressively improved with application rate on the Lamporecchio and Vicarello soils, it decreased beyond the 0.50 % rate on the Cremona soil.

3.2. Effect of glucose : peptone ratio and aeration condition

Since glucose (G) is a carbon source and peptone (P) a nitrogen source, changes in the proportions of these substrates will indicate variations in C:N ratios. On each soil both the G:P ratio and the aeration condition significantly ($P \leqslant 0.01$) influenced aggregate stability to water (table 3). The interaction between aeration condition and G:P ratio was however significant on the Vicarello soil only. This is shown in figure 2.

On all soils, under aerobic conditions aggregate stability increased significantly with wider G:P ratios. With this aeration condition at the 10:1 ratio there was a relative increase in stability over the control of 70 % in Lamporecchio, 96 % in Cremona and 64 % in Vicarello soil samples. Under anaerobic conditions, stability increased with wider G:P ratios (on the Lamporecchio and Cremona samples) up to the ratio of 5:1, after which a sharp decrease occurred at a wider ratio. On the Vicarello samples, however, aggregate stability increased all through the different G:P ratios under anaerobic conditions but the highest relative increase in stability as indicated by the slope of the curve occurred between the control and the 0.5:1 ratio.

Between the control and the 5:1 ratio, anaerobically-incubated Lamporecchio and Cremona samples had a significantly ($P \leqslant 0.01$) higher stability than the aerobically incubated ones, whereas on the Vicarello soil no such statistically significant differences were observed. On all three soils at the 10:1 G:P ratio, aerobically-incubated samples had a significantly ($P \leqslant 0.01$) higher aggregate stability than their anaerobically-incubated counterparts. The possible aggregate stabilizing mechanisms involved under these conditions will be discussed later.

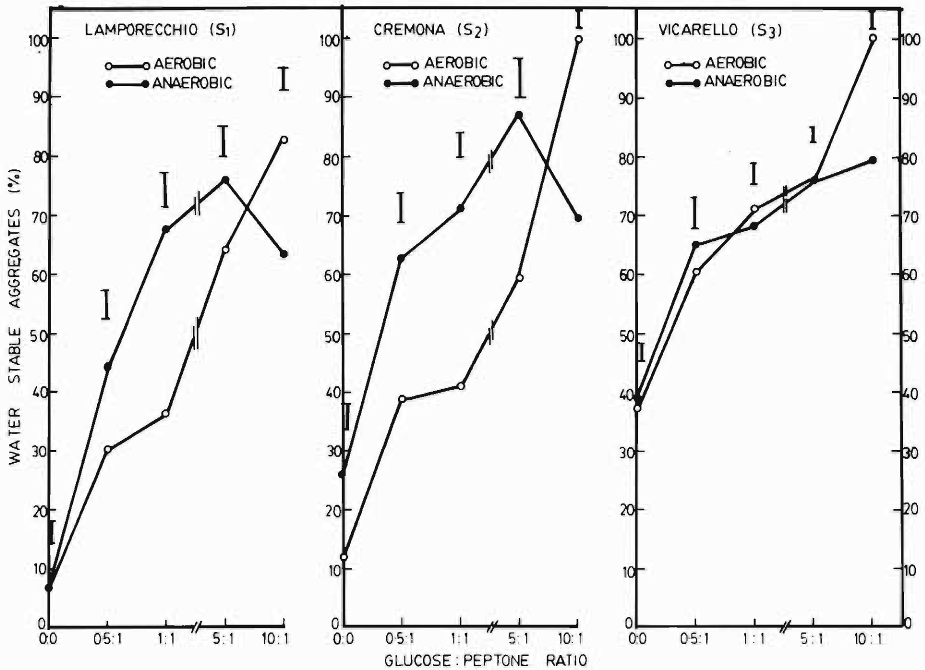

Fig. 2.
Effects of varying ratios of glucose and peptone on the water-stability of aggregates of three soils under aerobic and anaerobic conditions.

3.3. Effects of type of substrate and incubation period

Again in table 3 it is shown that on all soils, the aggregate stability was significantly influenced by the type of substrate and the incubation period. The significant interaction indicates, however, that the level of stability obtained from each substrate was dependent on the period of incubation under the conditions of this experiment. This is shown in figure 3.

As evident from this figure, on the dry controls, aggregate stability (which did not change with incubation period) was 7 % on Lamporecchio, 36 % on Cremona and 50 % on Vicarello which is a reflection of increasing clay contents (see table 1). With water alone as substrate, the stability of Lamporecchio soil did not vary significantly ($P \leqslant 0.01$) from the control throughout the 28-day incubation period. On the Cremona soil a significant decrease in stability with increasing incubation period occurred after the third day. On the Vicarello soil, water significantly reduced the aggregate stability all through the 28-day incubation period. Hence, the effect of water on the stability of the aggregates was soil-dependent.

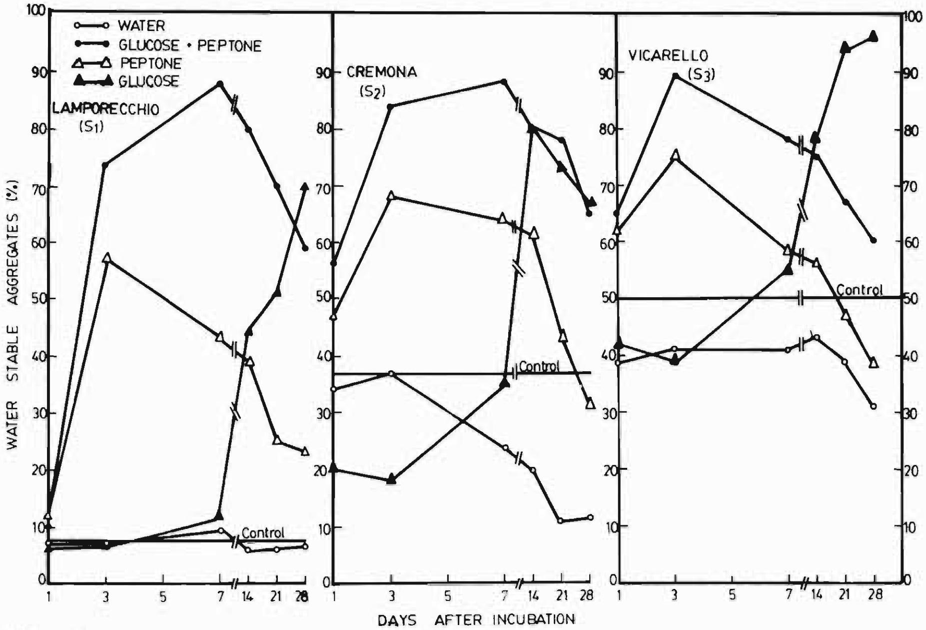

Fig. 3.
Effects of type of substrate and incubation period on the stability of aggregates of three aerobically-incubated soils to water.

On all soils with glucose solution as substrate, aggregate stability increased slowly up to the 7th day of incubation after which there was a rapid increase in stability. This increase continued up to the end of the incubation period on the Lamporecchio and Vicarello samples, but on the Cremona soil the stability decreased progressively after the 14th day of incubation. It is important to note that with this glucose solution substrate, stability decreased below control in the first 3 days of incubation on Lamporecchio, the first 7 days on Cremona and the first 5 days on Vicarello. This implies that any aggregating agents being produced during this period were being utilized by the microorganisms leaving little or nothing to bind and/or stabilize the soil particles.

With either the peptone solution alone or the glucose + peptone mixture the trend in aggregate stability was essentially the same on all soils. Here maximum aggregation was attained rapidly (within the first 3 to 7 days), after which a progressive decline in stability occurred as incubation period increased. In comparison to either the glucose or peptone solution alone, the combination of both substrates was positively synergistic in enhancing the stability at least within the first 14 days of incubation. Contrary to the glucose substrate alone, it appears that in the presence of peptone the metabolites responsible for stabilizing the soil aggregates were formed rapidly at first, after which they were either degraded or utilized by the microorganisms producing them with a consequent decline in stability as the incubation period progressed.

4. DISCUSSION

It was suggested by Swaby (1949) that, since microbial aggregating substances are very susceptible to decomposition, their role in influencing long-term aggregation under field conditions may be limiting. Bond and Harris (1964) however, observed that the hyphae of basidiomycetes which play important roles in soil aggregation persist in field soils, implying that they are slow to decompose. More recently, Molope et al. (1987) noted an increased temporary stability on soil aggregates from fungal hyphae.

In this study all aggregates were incubated under non-sterile conditions. This was done to make sure that all the soil samples contained indigenous microbial populations (Harris et al., 1963; Chaney and Swift, 1986). Even though a complete evaluation of the influence of indigenous microbial populations on soil aggregate stability would entail the use of sterile controls, this was not considered necessary in this study in view of earlier findings that little or no change in aggregate stability occurred when soil-organic mixtures were incubated under sterile conditions (McCalla et al., 1957; Martin et al., 1959). Moreover, a sterile condition will not mirror what occurs in the field.

As already pointed out, under aerobic conditions peptone- or peptone + glucose-amended samples developed fine networks of macroscopic mycelia around the aggregates of the Lamporecchio and Cremona soils only. Harris et al. (1966b) made similar observations and, in fact, concluded that the stabilization of soil particles (> 0.5 mm) was a function of the onset and rate of development of these fungal mycelia. Such mycelia did not develop on the Vicarello soil samples and on all samples amended with glucose alone. This suggests that glucose as an energy source and also some properties of the Vicarello soil did not favour the development of these fungal mycelia. The only soil properties possessed by Vicarello alone are the presence of MgO, CaO, $CaCO_3$ and chlorite in relatively large amounts (table 1), and it is possible that these compounds inhibited the formation and growth of mycelia.

Results of the role of aeration conditions on aggregate stability were conflicting. Skinner (1979) reported higher stability under aerobic than anaerobic conditions, an observation made also in this study at high substrate rates (> 2.5 %) on the Cremona soil. But

Harris et al. (1963) noted that in sucrose-amended artificial soil aggregates anaerobic incubation gave more stable and long-lasting aggregates than aerobic incubation, an observation made also on the Lamporecchio and Vicarello soils at high substrate application rates. It is possible that on these soils different binding substances were produced under aerobic and anaerobic conditions. Clapp et al. (1962) indicated that the type of clay mineral in soils may have an important effect on the action of rhizobial polysaccharides on the stability of aggregates. Of particular interest in this study is that the Cremona soil, in which aerobic incubation produced higher stability than anaerobic conditions, contains relatively less kaolinite and more muscovite than the other two soils (table 2). The role of these clay minerals in microbial mediated aggregate stability will need further study. What can be inferred from this study, however, is that both aerobic and anaerobic conditions favour the formation of aggregate stabilizing-substances. This depends on the type of soil, and the amount of the energy-supplying substrate available.

In figure 2, it was observed that the smaller the content of peptone (a nitrogen source) relative to glucose (a carbon source) the higher the stability in spite of the aeration condition. It is possible that lower C:N ratios (e.g. 0.5:1 G/P ratio) favoured rapid decomposition of microbially-synthesized aggregate-stabilizing materials. Harris et al. (1963) also noted that when nitrogen was added to amendments of high carbon contents, the aggregate-stabilizing effect of these amendments was reduced.

It was also noted that on Lamporecchio and Cremona samples anaerobically-incubated soils developed more stable aggregates than the aerobically-incubated ones up to the G:P ratio of 5:1. It is possible that anaerobic microflora metabolized the predominantly glucose substrates to form large amounts of organic aggregate-binding substances. At the 10:1 G:P ratio, however, aerobic incubation favoured better aggregate stability than anaerobic conditions on all the three soils. At this ratio there were disporportionately more carbonaceous than nitrogenous substrates and the aerobic microflora may have produced large quantities of gums and other more effective binding agents under this condition.

As indicated in figure 3, on the peptone- or peptone + glucose-amended soils aggregate stability was enhanced early but was maintained for a short period. Conversely on the glucose-amended samples stabilization was slow to develop but increased almost exponentially with time. This is in conformity with the results of Harris et al. (1964). It appears that the microorganisms that utilized peptone as energy source metabolized this substrate very rapidly to form aggregating materials but utilized these metabolites as energy sources with consequent reduction in stability. On the other hand the microorganisms that utilized glucose as energy source metabolized this material very slowly and accumulated the aggregating substances which they were unable to utilize subsequently.

5. CONCLUSION

Organic materials differ in their potential to stabilize soil aggregates depending on the ratio of the carbonaceous to nitrogeneous substances they contain. From this study it is obvious that incubation with glucose has a more lasting effect on aggregate stability than incubation with peptone. Also both aerobic and anaerobic conditions could lead to the production of aggregate-stabilizing materials. It is recognized that extrapolation of laboratory studies such as this to field situation is difficult, but changes in aggregate stability under different aeration conditions and with different energy-supplying substrates can give an idea of the mechanisms favouring the rapid formation of stable soil aggregates when organic residues are incorporated into field soils. The results of this study point to the need to characterise the organic materials that are incorporated into soils with a view towards understanding their possible effects on the stability of aggregates to water.

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Invloed van de incubatie van organische substraten op de waterstabiliteit van bodemaggregaten onder laboratorium omstandigheden

Samenvatting

De verandering in de water-stabiliteit van natuurlijke bodemaggregaten werd onderzocht na toevoeging en incubatie met organische bestanddelen onder niet-steriele omstandigheden. Deze aggregaten waren afkomstig van de Ap-horizonten van drie verschillende bodems uit Centraal-Noord Italië. Op de Lamporecchio en Vicarello bodems

verhoogde bij toevoeging van meer dan 2,5 % peptone (P) of glucose (G) de aggregaatstabiliteit in anaeroob-geïncubeerde grondstalen, terwijl voor de Cremona-bodems een verhoogde stabiliteit werd waargenomen bij de aeroob-geïncubeerde behandelingen.

In alle bodems beïnvloedde, een grotere G/P verhouding de aggregaatstabiliteit ten goede, onafgezien van de verluchtingscondities. Bij een 10/1 verhouding verbeterden de aerobe behandelingen meer de stabiliteit dan de anaerobe. Bij de P en P+G behandelde grondstalen verbeterde de stabiliteit wel eerder, maar duurde ze minder lang. Omgekeerd was voor de G-behandelde stalen de stabiliteit in het begin zwak, maar nam ze wel toe met de tijd en over een langere duur. De mekanismen die met dit stabiliseringsproces gepaard gaan werden ter diskussie gevoerd.

Effet de l'incubation avec des substances organiques sur la stabilité structurale du sol sous conditions de laboratoire

Résumé

Les changements de la stabilité à l'eau des agrégats de sol sont étudiés suite à une incubation, sous conditions non-stériles, avec des substances organiques. Les agrégats proviennent de l'horizon Ap de trois sols différents du Centre-Nord de l'Italie. De fortes teneurs (plus de 2,5 %) en peptons (P) et glucoses (G) améliorent la stabilité dans les sols du type Lamporecchio et Vicarello sous traitement anaérobie, tandisque sur les sols du type Cremona ce processus s'observe plutôt sous traitement aérobie.

Pour tous les sols étudiés la relation G/P affecte la stabilité dans le sens positif, indépendamment des conditions d'aération. A une valeur G/P = 10 l'incubation sous conditions aérobies était plus favorable que le traitement anaérobie. La stabilisation était plus rapide mais de plus courte durée sous traitement P et P+G. Par contre, sur les sols traités au glucose (G) la stabilisation était plus lente au départ mais s'améliorait avec le temps. Les méchanismes qui sont à l'origine de ces processus de stabilisation des agrégats de sols ont été discutés.

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A PEDOLOGICAL CHARACTERIZATION OF SOILS OF THE HADEJIA ALLUVIAL COMPLEX IN THE SEMI-ARID REGION OF NIGERIA

I.E. ESU

Abstract

Soils within the levees, backswamps and terraces of the Hadejia River in the semi-arid region of Nigeria were studied.

The soils are micaceous, mottled and contain $CaCO_3$ nodules and Fe-Mn concretions. The levee and terrace soils both have a loamy particle-size class, while the backswamp soils are clayey. Organic carbon and clay contents are irregularly distributed with soil depth indicating the fluvial and stratified nature of the parent material. The levee and backswamp soils are immature but the terrace soils have attained maturity through the combined processes of clay migration, ferrolysis, gleization and increased sodification. Argillipedoturbation is also a major process in the backswamp soils.

Kaolinite, smectite, mica, palygorskite, quartz and K-feldspars are the dominant minerals in the clay fraction. According to the criteria of Soil Taxonomy and the FAO-UNESCO legend, the levee soils are classified as Typic Ustifluvents or Eutric Fluvisols; the backswamp soils are Entic Pellusterts or Pellic Vertisols and the terrace soils are Typic Natraqualfs or Solodic Planosols.

Key words

Alluvium, semi-arid, Fluvisols, Vertisols, Planosols.

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1. INTRODUCTION

The Hadejia river rises from the Jos Plateau and flows north-eastwards through the semi-arid to arid regions of Nigeria before it empties into the Lake Chad. The adjoining uplands usually consist of very sandy or desertic soils which are very droughty in most years. Soils of the Hadejia alluvial complex, therefore, offer the rather Sahelian region of Nigeria the best hope for profitable and sustained irrigation farming.

In a land systems study of North-East Nigeria, Bawden et al. (1972) described the soils of the Hadejia alluvial complex as consisting of deep, imperfectly drained to poorly drained hydromorphic soils, which are abundantly mottled with iron concretions at depth. They also recognized the presence of cracking clay soils with some halomorphic tendencies. Schultz International Ltd. (1976), in a semi-detailed soil survey carried out as part of a "Hadejia River Basin Study", classified the soils mainly as Cambisols, Solonetz, Fluvisols and Vertisols. Apart from these generalized information provided by the two studies, no detailed characterization of these rather important agricultural soils of the area has been carried out.

The objectives of this study were, therefore, (i) to carry out a detailed characterization of the morphological and physico-chemical properties, as well as of the clay mineralogical compositions of the soils of the Hadejia alluvial complex in relation to their various geomorphic positions and (ii) to classify the soils according to the criteria of the USDA Soil Taxonomy (Soil Survey Staff, 1975) and the FAO/UNESCO soil map of the world legend (FAO/UNESCO, 1974). Such investigations will provide basic data for soil correlation, for land use management applications and aid in the assessment of the agricultural potential of the soils.

2. MATERIALS AND METHODS

2.1. Description of study area

The study area lies within Lat. 11°49'N and Long. 8°51'E in the Wudil area of Kano State (fig. 1). The area falls within the Sudan savanna ecological zone (Keay, 1959), and the geology consists mainly of old and recent alluvium, overlying igneous and metamorphic Basement Complex rocks at great depth. Climatological data show that the total annual potential evapotranspiration of 1770 mm is double the total annual rainfall of 884 mm. Long-term monthly records of air temperatures show a range of 21.2 to 30.5° C with an annual mean of 26.0° C (Kowal and Knabe, 1972).

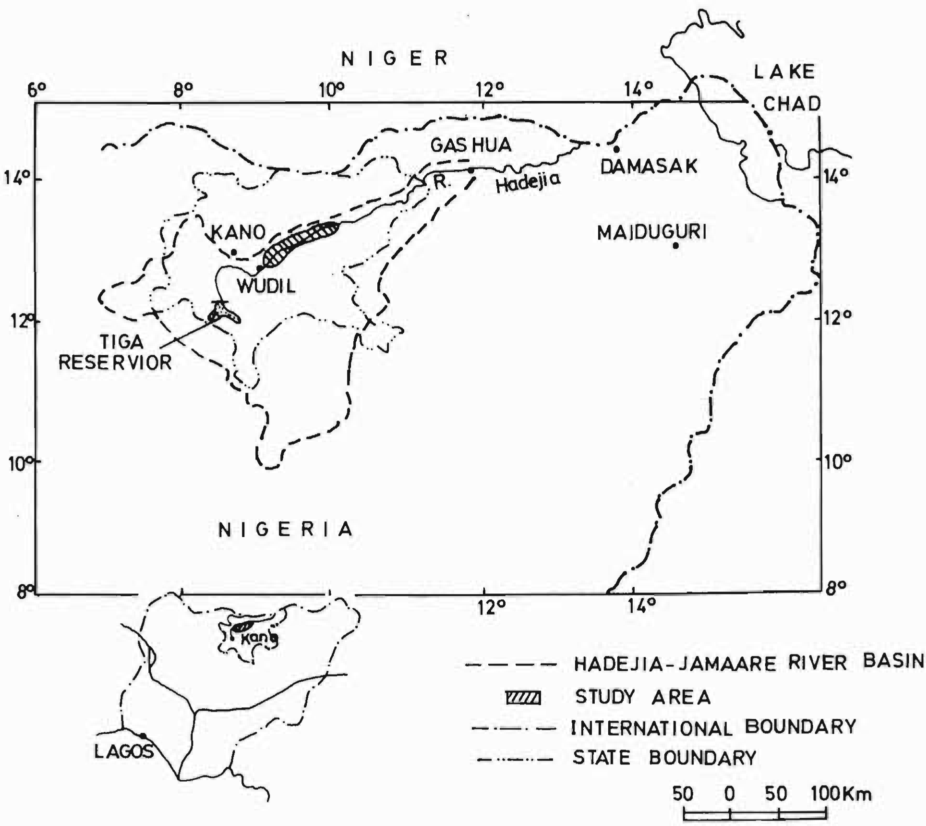

Fig. 1.
Location map of the study area.

2.2. Field studies

Soils occurring on the levees, backswamps and terraces within the Hadejia river valley were studied.

At least two soil profile pits were dug in each of the three main geomorphic units. The morphological characteristics of each of the profile pits were then described, after which bulk soil samples were collected for laboratory analyses.

Soil profile descriptions followed the pattern outlined in the Soil Survey Manual (Soil Survey Staff, 1951, 1981). Soil descriptions are for the moist state of the soil unless otherwise stated.

2.3. Laboratory studies

Soil samples were air-dried and passed through a 2-mm sieve. Particle size distribution was determined by the hydrometer method (Bouyoucos, 1951). Soil pH was determined potentiometrically after equilibration with water in a 1:2.5 soil/liquid ratio, and organic carbon was determined by the Walkley-Black method (Allison, 1965). Total nitrogen was determined by the micro-Kjeldhal method (Bremner, 1965) and the Bray No. 1 method was used for extraction of phosphate while the ammonium molybdate-blue method was used for determining the extractable phosphate (Bray and Kurtz, 1945). Exchangeable Ca, Mg, K and Na were extracted by leaching with 1N NH_4OAc (pH 7.0). Calcium and Mg were determined by atomic absorption spectrophotometry, while Na and K were determined by flame emission spectrophotometry. Electrical conductivity (EC) was measured in a 1:2.5 saturation extract (Richards, 1954). Cation exchange capacity was determined by 1N NH_4OAc (pH 7.0) saturation followed by the displacement of the adsorbed NH_4^+ (Chapman, 1965).

For clay mineralogical analyses, soluble salts and carbonates were removed from the soil by NaOAc (pH 5) and organic matter was removed by H_2O_2. The sand, silt and clay fractions were separated by wet-sieving, sedimentation and centrifugation (Jackson, 1969). Mineralogy of the clay fraction (< 2µm) was determined by X-ray diffraction with a Philips diffractometer and Fe-filtered cobalt Kα radiation. Samples were oriented on porous ceramic plates according to the method of Van Reeuwijk (1979). To obtain the necessary measurements, the goniometer was set at a scanning speed of 1°(2θ)/min from 3° to 34°(2θ) to detect both phyllosilicates and non-phyllosilicates and from 3° to 16°(2θ) when only the identification of phyllosilicates was desired. The (001) reflections were obtained following Mg-saturation, Mg-saturation and glycerol solvation, and K-saturation or Mg-saturation heated to 550° C.

3. RESULTS AND DISCUSSION

3.1. Morphological properties

The morphological descriptions and the classification of the pedons studied are presented in table 1.

The levee soils (pedons 1 and 2) are moderately well-drained and have Ap horizons with a range in thickness of 30 to 45 cm. The soils possess sandy loam to sandy clay loam textures, matrix colours with chorma ≫ 2; and moderate, medium subangular blocky peds of friable to very friable consistence. Many to common manganiferrous concretions commonly occur between 30 to 150 cm depth, indicating perhaps the active zone of alternating wet and dry cycles. Gleization appears to increase with soil depth with the colour hues decreasing from 10YR to 2.5Y. Fine mica flakes often occur throughout the depth of the pedon. Apart from the ochric A horizon, no other diagnostic horizons are present in the levee soils indicating their extreme youthfulness.

Table 1.
Morphology and classification of pedons studied.

Horizon	Depth cm	Munsell colour (moist)	Mottling+	Texture+	Structure+	Consistence+ (moist)	Boundary+	Other features+
				Levee soils				
Pedon 1 - Typic Ustifluvent, fine - loamy, mixed, isohyperthermic								
Ap1	0-15	10YR 4/3	7.5YR 5/8, f2f	scl	2msbk	fr	gs	Common fine roots
Ap2	15-45	10YR 5/2	7.5YR 5/8, c2d	scl	2msbk	fr	cs	Common fine mica; few fine roots
2Ccg	45-110	10YR 7/1	7.5YR 5/8, m3d	gr-scl	2csbk	fr	cs	Common fine mica; many medium soft manganiferrous concretions; few fine roots
2Cg1	110-140	2.5Y 7/2	7.5YR 5/8, c3d	sl	1msbk	vfr	cs	Many fine mica; few fine roots
3Cg2	140-175	2.5Y 7/2	7.5YR 5/8, m3p	sl	2msbk	fr	-	Many fine mica
Pedon 2 - Typic Ustifluvent, coarse-loamy, mixed, isohyperthermic								
Ap	0-30	10YR 4/4	10YR 4/6, c1d	sl	2msbk	vfr	cs	Common fine roots
2Cc1	30-90	10YR 4/4	7.5YR 4/4, m3d	gr-sl	2msbk	vfr	cs	Many fine mica; many medium soft manganiferrous concretions; abundant sand lenses; common fine roots
2Cc2	90-120	10YR 5/6	7.5YR 7/8 & 5YR 4/6, m2d	gr-sl	2msbk	vfr	cs	Many fine mica; common medium soft manganiferrous concretions; few fine roots
3Cgc	120-150	2.5Y 5/2	5YR 5/6, m2p	gr-l	3msbk	fi	-	Common fine mica, many fine manganiferrous concretions.

Table 1. (continued).

			Backswamp soils				
Pedon 3 - Entic Pellustert, fine, mixed, isohyperthermic							
Apg	0-20	10YR 4/1	7.5YR 5/6, c m1d	3fgr	vfi	gw	Gilgai micro-relief; Deep wide verticals & oblique cracks; many fine roots
ACg	20-45	10YR 5/1	7.5YR 5/6, c c1f	3cpr & sbk	vfi	gs	Vertical & oblique cracks from soil surface; many slickensides on peds; common fine roots
Cg1	45-90	N5/0	7.5YR 5/6, cl m3d	3cpr & sbk	vfi	cs	Vertical & oblique cracks from soil surface; abundant silt & fine sand lenses between peds; few fine roots
Cg2	90-130	10YR 4/1	7.5YR 4/6, c m3d	Om	vfi	-	Constricted vertical & oblique cracks from soil surface; many silt & sand lenses; few fine roots.
Abg	150-250 (Auger sample)	2.5YR 2/0	7.5YR 4/6, cl f2d	Om	-	-	Abundant silt and sand content
Pedon 4 - Entic Pellustert, very-fine, mixed, isohyperthermic							
Apg	0-20	10YR 4/1	7.5YR 5/8, c m1d	3fgr	vfi	cw	Gilgai micro-relief; Deep wide cracks; many fine roots
ACg	20-70	10YR 5/1	7.5YR 5/6, c c1f	3msbk & 3cpr	vfi	cw	Deep wide vertical & oblique cracks from soil surface; many slickensides on peds; many fine & medium roots
Cg	70-130	5YR 4/1	10YR 5/6, c m3f	3cpr	vfi	-	Constricted vertical & oblique cracks from soil surface; common fine roots

Table 1. (continued).

				Terrace soils				
Pedon 5 - Typic Natraqualf, fine-loamy, mixed, isohyperthermic								
Apg	0-20	10YR 5/4	7.5YR 5/8, c2d	sil	2msbk	fr	as	Common fine roots.
2Btg	20-45	2.5Y 5/2	7.5YR 5/8, m2d	gr-sicl	3mpr	fi	cs	Many small irregular soft manganiferrous concretions; common slickensides on peds. Beginning of impermeable layer
2Btgk1	45-85	5Y 5/1	7.5YR 5/6, m2d	gr-sicl	3cpr	fi	gs	Abundant small & medium manganiferrous concretions and $CaCO_3$ nodules; many slickensides on ped surfaces.
2Btgk2	85-110	5Y 4/1	7.5YR 5/8, c1d	gr-sicl	3mpr	fi	cw	Abundant small very soft manganiferrous concretions and $CaCO_3$ nodules; many slickensides on peds. End of impermeable layer.
3Cg	110-155	10YR 6/1	7.5YR 5/8, m2d	l	1msbk	fr	-	Many fine mica flakes.
Pedon 6 - Typic Natraqualf, fine-loamy, mixed, isohyperthermic								
Apg	0-6	10YR 5/2	5YR 5/6, c1d	l	1msbk	vfr	gs	Common fine mica; common fine roots.
Eg	6-35	10YR 6/1	5YR 4/6, m1d	l	1msbk	fr	aw	Common fine mica; common fine roots.
2Btg1	35-80	10YR 5/2	7.5YR 5/8, m3d	gr-cl	3csbk & pr	fi	gs	Common medium soft manganiferrous concretions; many slickensides on peds; few very fine roots. Beginning of impermeable layer.
2Btg2	80-110	5Y 5/1	7.5YR 5/8 m2d	gr-sicl	3cpr & sbk	fi	cs	Many fine to medium soft manganiferrous concretions; common fine sand lenses and many slickensides on peds. End of impermeable layer.
3Cg	110-160	10YR 6/3	7.5YR 5/8, m3d	gr-l	1csbk	fr	-	Many medium & fine soft & hard manganiferrous concretions; many fine mica; abundant sand lenses between peds.

+ symbols used are the same as given in Soil Survey Manual, USDA Handbook No. 18, pp. 139-140, 1951 and the New Soil Survey Manual, Chapt. 4, 1981.

The backswamp soils (pedons 3 and 4) consist of heavy cracking clays with extensive gilgai micro-relief features. Slickensides were observed within 20 to 70 cm depth, while silt and sand lenses with slickensides were observed at greater depths. Auger samples at between 150-250 cm depth indicate that a buried A horizon (Abg) is present in the backswamp soils. The occurrence of the buried A horizon might be due to the process of argillipedoturbation, which is known to be common in Vertisols (El Abedine et al., 1971; Buol et al., 1973; Yaalon and Kalmar, 1978).

The terrace soils (pedons 5 and 6) contain very slowly or almost impervious natric B horizons. Except where extensive ploughing has been carried out, the soils possess loam to silty loam Ap horizons with an underlying bleached albic E layer, abruptly overlying the slowly permeable natric B horizon of gravelly silty clay loam texture. The soils are gleyed to the top of the profile and the B and C horizons often contain many manganiferrous concretions and $CaCO_3$ nodules. Fine mica flakes also occur throughout the profile depth. Slickensides rather than oriented clay skins were observed on the peds in the natric B horizon indicating that some churning or sliding between peds has taken place. Federoff (1968) observed a similar phenomenon in soils high in swelling clay minerals in France. Apart from the occurrences of illuvial clay and $CaCO_3$ nodules and the consequently well developed natric B horizon in the terrace soils, both the levee and terrace soils are very similar morphologically, suggesting that it are the levee soils that must have evolved into the terrace soils over a period of time.

3.2. Physico-chemical properties

Table 2 contains the physico-chemical data of the soils.

Particle size distribution data show that the levee and terrace soils both have a fine-loamy to coarse-loamy particle-size class while the backswamp soils have a fine to very fine clayey particle-size class (Soil Survey Staff, 1975). The irregular profile-depth distribution of the clay fraction especially in the levee and backswamp soils indicates the stratified nature of the fluvial parent material. In the terrace soils, it appears that clay eluviation-illuvation has resulted in a distinct clay bulge within the natric horizon. Silt content is particularly high in the terrace soils with a range of 37 to 63 % and a mean of 52 % for pedons 5 and 6. Sand is the dominant fraction in the levee soils, while the backswamp and terrace soils are rather low in sand content.

Organic carbon content in all the pedons decreases irregularly with soil depth. This reflects the fluvial nature of the soil parent material. The organic carbon content of the medium-textured levee and terrace soils is rather low, but the fine-textured backswamp soils contain very high amounts. These findings are in agreement with data reported for some arid soils in Washington State, USA (Gilkeson et al., 1957) and in Iran (Mahjoory, 1975). However, the rather high surface soil content of organic carbon (4.24-4.36 %) in the backswamp soils which has been classified as Vertisols (table 1), is not in agreement with the usually low levels of organic matter content reported for Nigerian Vertisols (Esu, 1983; 1988; Lombin and Esu, 1988).

Total nitrogen and exchangeable potassium has the same distribution pattern as organic carbon. Extractable phosphorus is low in all the soils, irrespective of their geomorphic position. Moderate to very high levels of exchangeable calcium, and magnesium are present in all the soils, with calcium being the dominant cation (table 2).

Soil pH for the surface soils varies from a slightly acid range of 6.1 to 6.7 in the levee and backswamp soils to a more strongly acid range of 4.9 to 5.2 in the slowly permeable terrace soils. Subsoil pH values for all the soils are nearly uniform with a narrow range of neutral to moderately alkaline soil reaction. The slightly acid conditions in the surface soils of the levee and backswamp soils even within a rather alkaline environment may be due to the dissociation of strongly acid functional groups in the organic matter which are rather high, especially in the Apg and Abg horizons of the backswamp soils. The acidic conditions in the Apg and Eg horizons of the terrace soils may be due to the redox products of ferrolysis, which is common in slowly permeable pseudogley and gley soils (Brinkman, 1970). The generally alkaline subsoil reaction is attributable to the calcareous and sodic nature of the soils.

Values of electrical conductivity (EC) range from 0.10 to 1.20 d Sm^{-1} in all the soils. This indicates that the soils are non-saline. However, calculated values of the exchangeable sodium percentage (ESP) show that the terrace soils and some portions of the levee soils (pedon 1) are sodic, while the backswamp and part of the levee soils are likely to develop into sodic soils, especially when irrigated.

Cation exchange capacities are high in the backswamp soils, moderate in the terrace soils and moderate to low in the levee soils. The values appear to reflect the organic matter content and the clay mineralogy. Both organic matter and smectite clay minerals are higher in the backswamps than in the other soils. The soils generally have a high base status, as the percentage base saturation ranges from 68 to 100 % in all the soils.

Table 2.
Physico-chemical properties of pedons studied in the area.

Horizon	Depth	Particle size			pH	Org. C	Total N	Extr. P	EC	Exchangeable Bases				CEC pH7.0	ESP	Base Sat.
		Sand 2000-50µm	Silt 50-2µm	Clay < 2µm						Ca	Mg	K	Na			
	cm	%				%	%	mg/kg	dSm^{-1}	meq/100g of soil					%	
							Levee soils									
Pedon 1																
Ap1	0-15	54	24	22	6.1	1.12	0.12	10.15	1.20	5.5	2.2	0.18	4.60	12.8	35.9	98
Ap2	15-45	54	22	24	8.5	0.24	0.06	4.20	0.84	5.5	2.0	0.24	5.70	12.0	47.5	100+
2Ccg	45-110	56	22	22	8.4	0.16	0.04	2.45	0.55	3.7	1.3	0.10	5.60	9.1	61.5	100+
2Cg1	100-140	74	20	6	8.3	0.08	0.02	3.30	0.19	2.5	0.5	0.05	1.30	6.4	20.3	68
3Cg2	140-175	80	8	12	7.7	0.12	0.02	1.40	0.20	3.2	1.0	0.08	1.50	8.1	18.5	71
Pedon 2																
Ap	0-30	64	28	8	6.7	0.32	0.04	2.80	0.10	1.8	0.6	0.06	0.40	4.0	10.0	72
2Cc1	30-90	68	22	10	6.8	0.20	0.04	3.50	0.10	3.2	1.1	0.09	0.40	7.0	5.7	68
2Cc2	90-120	54	38	8	7.5	0.10	0.01	2.10	0.10	3.6	0.8	0.07	0.30	7.0	4.3	68
3Cgc	120-150	34	46	20	7.5	0.18	0.02	2.45	0.40	6.9	1.3	0.13	0.30	10.0	3.0	86
							Backswamp soils									
Pedon 3																
Apg	0-20	22	20	58	6.0	4.36	0.43	2.45	0.20	17.3	6.7	1.28	1.40	30.1	4.7	87
ACg	20-45	18	18	64	7.1	1.22	0.11	4.90	0.21	16.2	6.8	1.28	1.30	27.5	4.7	93
Cg1	45-90	32	30	38	7.0	0.48	0.08	5.60	0.13	10.8	4.3	0.63	1.40	17.4	8.0	98
Cg2	90-130	26	22	52	7.3	0.40	0.08	2.45	0.10	10.0	5.8	0.63	1.40	17.5	8.0	100+
Abg	150-250	24	40	36	5.8	4.16	0.56	1.40	0.11	13.5	5.1	0.80	1.30	31.7	4.1	65

Table 2. (continued).

Pedon 4																
Apg	0-20	20	22	58	6.1	4.24	0.48	2.80	0.25	18.2	7.9	1.33	1.40	33.8	4.1	85
ACg	20-70	10	16	74	7.6	0.82	0.10	4.20	0.16	17.5	7.8	1.23	3.50	31.2	11.2	96
Cg	70-130	12	30	58	7.9	0.22	0.05	2.80	0.20	19.9	6.5	0.92	3.30	29.4	11.2	100+
Terrace soils																
Pedon 5																
Apg	0-20	18	61	21	5.2	0.42	0.03	1.40	0.40	4.9	1.8	0.20	1.24	10.8	11.5	75
2Btg	20-45	9	63	28	7.3	0.44	0.04	2.80	0.35	9.3	2.8	0.10	3.24	18.4	17.6	84
2Btg k1	45-85	9	60	31	8.3	0.20	0.01	2.45	0.36	10.6	2.3	0.10	3.26	18.4	17.7	88
2Btg k2	85-110	6	59	35	8.2	0.10	0.01	1.40	0.35	11.0	2.8	0.11	4.55	20.0	22.8	92
3Cg	110-155	32	49	19	8.0	-	-	0.70	0.28	5.4	1.1	0.06	2.13	9.6	22.2	91
Pedon 6																
Apg	0-6	34	47	19	4.9	0.66	0.05	3.85	0.10	3.1	1.4	0.22	1.09	8.4	13.0	69
Eg	6-35	34	47	19	5.3	0.36	0.02	1.40	0.20	5.4	1.5	0.05	2.39	9.8	27.2	95
2Btg1	35-80	32	37	31	6.3	0.04	0.01	2.80	0.28	9.4	2.2	0.11	3.70	15.9	24.3	97
2Btg2	80-110	16	51	33	7.1	0.14	0.01	2.63	0.28	9.9	2.3	0.11	4.02	16.8	23.9	97
3Cg	110-160	32	49	19	7.9	-	-	2.63	0.20	4.9	1.1	0.06	2.94	10.4	28.3	87

3.3. Clay mineralogy

X-ray diffraction analyses of the clay fraction (< 2 µm) of the soils indicate that the two main constituents are kaolinite and smectite (fig. 2, 3, 4).

Kaolinite platelets are indicated by the sharp 0.72 nm (001) and O.356 nm (002) reflections with high intensities, except in the buried Abg horizon of the backswamp soils (pedon 3). The dominance of smectite and absence of vermiculite and chlorite is indicated by the complete shift or lattice expansion of the 1.47-1.54 nm peaks to a higher d-value of 1.83-1.96 nm after the treatment of Mg-saturated samples with glycerol. The K-saturated (pedons 1 & 3) or Mg-saturated, heated to 550° C (pedon 6) samples show a complete collapse of the 1.47-1.54 nm diffraction peaks to a reinforced 1.01-1.02 nm peak, indicating the absence of chlorite, which will otherwise persist at about 1.4 nm. The clean collapse of the peaks also indicates a lack of hydroxy interlayers.

The broadening of the peaks in the 1.5 to 1.96 nm region especially in pedons 1 and 6 (fig. 2 and 4) under Mg-saturated and glycerated conditions indicates the presence of poorly ordered smectite with thin platelets in the levees and terrace soils. In the backswamp soils (fig. 3) and the 2Ccg horizon of the levee soils (fig. 2), the peaks are sharper and may suggest the presence of relatively higher amounts and/or better crystallinity of the smectite minerals. The higher quantity or crystallinity of smectite in the backswamp soils (pedon 3) might be due to the rather poor drainage environment of the soils. Silica, Al and Mg would tend to remain in the soil profile in a poorly drained alkaline environment and cause in situ formation of smectites (Buol, 1965; Millot, 1970; Gharaee and Mahjoory, 1984).

Mica which is indicated by the 1.01-1.02 nm (001) reflections is present in almost the same proportions in all the soils. However, the intensity of clay mica peaks decreased slightly from the surface to the C horizons in each pedon, suggesting that the mineral amounts decrease from the surface to the subsoil. A decrease in clay mica from the surface horizon to the C horizon of soils in arid regions has also been reported elsewhere (Nettleton et al., 1973; Mahjoory, 1975; Gharaee and Mahjoory, 1984).

The 1.06 nm peaks in the various horizons of pedons 1 and 3 (figs. 2 and 3) suggest the presence of palygorskite (attapulgite) in the levee and backswamp soils. These are not, however, clearly indicated in the terrace soils (fig. 4), but the high angle shoulder on the 1.02 nm peak in the lower horizons of pedon 6 may also be evident of some palygorskite (Gharaee and Mahjoory, 1984). The occurrence of palygorskite (attapulgite) in the calcareous alkaline environment of arid soils has been reported by several workers (Hen-

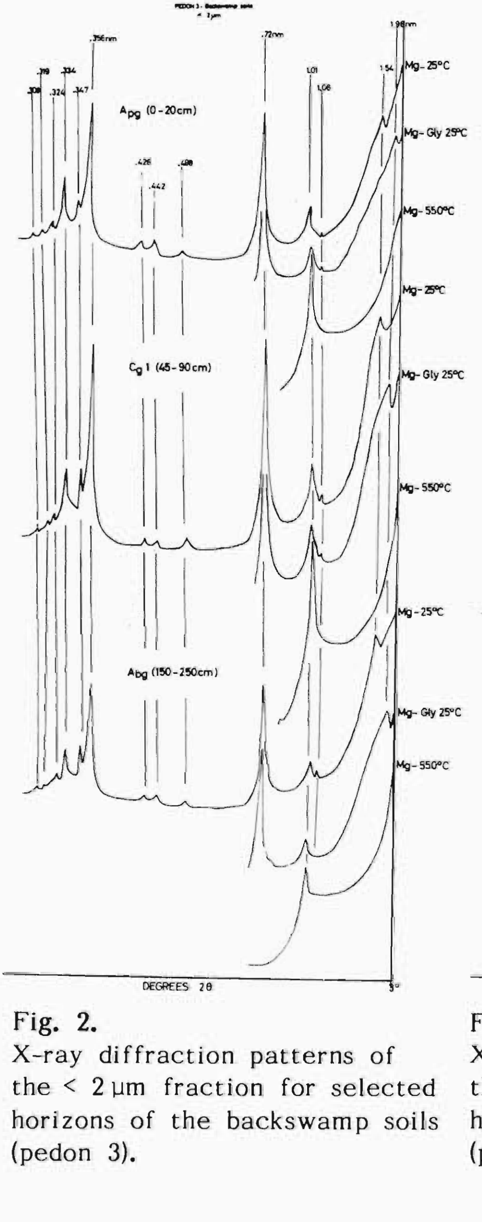

Fig. 2.
X-ray diffraction patterns of the < 2 µm fraction for selected horizons of the backswamp soils (pedon 3).

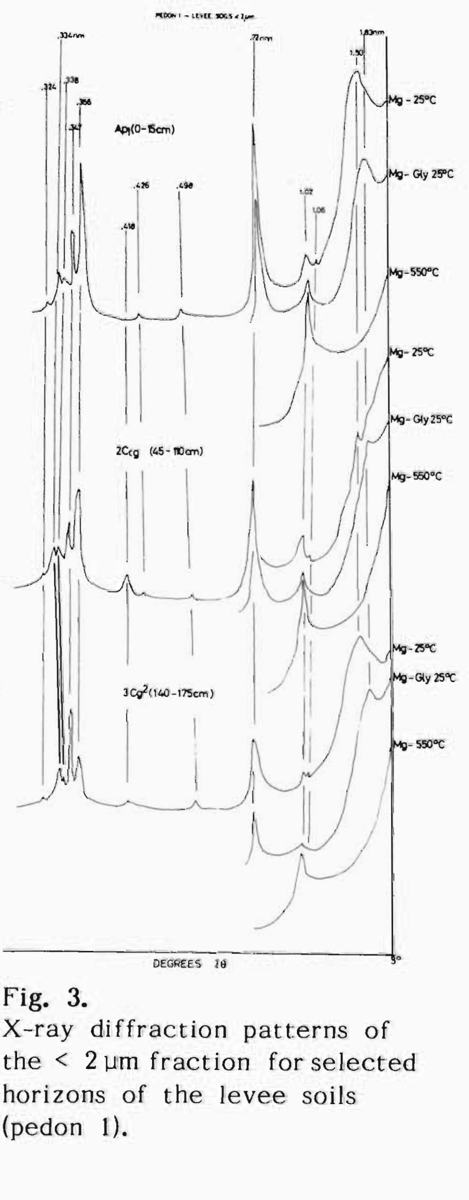

Fig. 3.
X-ray diffraction patterns of the < 2 µm fraction for selected horizons of the levee soils (pedon 1).

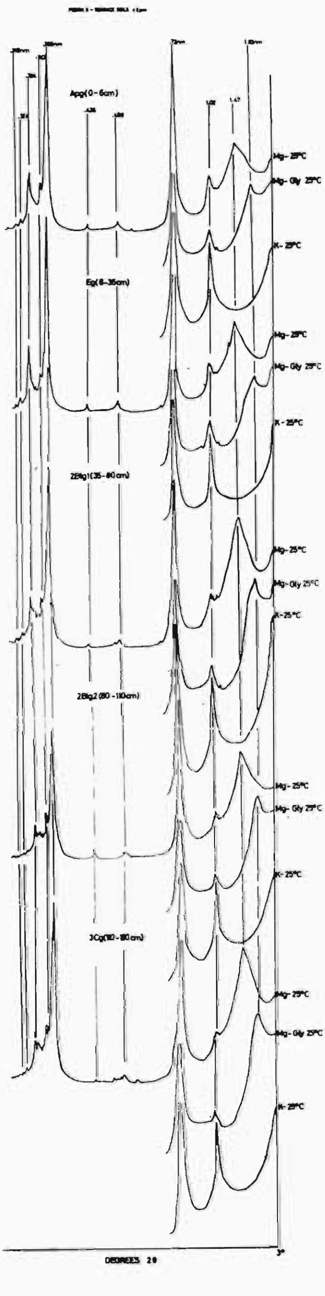

Fig. 4.
X-ray diffraction patterns of the < 2 µm fraction for horizons of the terrace soils (pedon 6).

derson and Robertson, 1958; Vanden Heuvel, 1966; Burnett et al., 1972; Gharaee and Mahjoory, 1984).

Quartz is present in all the soils, as indicated by the rather sharp but low intensity peaks at 0.426 and 0.334 nm. Potash feldspars with a characteristic peak at 0.324 nm, is also present in about equal amounts in all the soils, but plagioclase feldspars with very weak reflections at 0.319 nm occur in the levee and terrace soils, but are absent in the backswamp soils. Similarly, goethite with a 0.418 nm reflection was detected only in the iron-rich, stratified horizons of the levee and terrace soils, while calcite with a weak peak at 0.308 nm was only detected in the backswamp soils.

4. CLASSIFICATION

Based on the criteria of the USDA Soil Taxonomy (Soil Survey Staff, 1975), the levee soils (pedons 1 and 2) meet all the requirements for classification at the familiy level as Typic Ustifluvent, coarse-loamy, mixed, isohyperthermic. However, pedon 1 does not meet the coarse-loamy particle-size family placement but is rather marginally a fine-loamy taxadjunct. According to the criteria for the FAO/UNESCO soil map of the world legend, (FAO/UNESCO, 1974), the levee soils may be classified as Eutric Fluvisols.

The backswamp soils (pedons 3 and 4) meet all taxonomic requirements for a classification as Entic Pellustert, fine or very fine, mixed, isohyperthermic. In the FAO/UNESCO system, the soils are classified as Pellic Vertisols.

It appears largely that through the processes of clay migration and increased sodification, the levee soils must have developed into the present terrace soils. Those terrace soils (pedons 5 and 6) meet all the requirements for a classification as Typic Natraqualf, fine-loamy, mixed, isohyperthermic according to the criteria of Soil Taxonomy, while they are classified as Solodic Planosols in the FAO/UNESCO system.

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Bodemkundige karakteristieken van het Hadejia alluviaal complex in de semi-aride zone van Nigeria

Samenvatting

Een studie werd gemaakt van de oeverwallen, kommen en terrassen van de Hadejia rivier in het semi-aride gebied van Nigeria.

De bodems bevatten glimmers, zijn gevlekt en hebben kalk nodules en ijzer/mangaan concreties. De oeverwal- en terrasgronden hebben een lemige textuur terwijl de komgronden kleiig zijn. De gehalten aan organische stof en klei volgen een onregelmatig verloop met de diepte, hetgeen wijst op een gelaagde rivier afzetting. De overwal- en komgronden vertonen nog weinig bodemontwikkeling, maar de terrasgronden zijn al meer ontwikkeld door een combinatie van processen zoals kleiverplaatsing, ferrolyse, gleyvorming en toenemende sodificatie. In de komgronden is argillipedoturbatie ook een belangrijk proces.

De voornaamste mineralen in de kleifractie zijn kaoliniet, smectiet, mica, palygorskiet, kwarts en kaliveldspaten. Volgens de criteria van Soil Taxonomy en de FAO legenda worden de oeverwalgronden geclassificeerd respectievelijk als Typic Ustifluvents en Eutric Fluvisols ; de komgronden als Entic Pellusterts en Pellic Vertisols en de terrasgronden als Typic Natrustalfs en Solodic Planosols.

Caractérisation pédologique de la Plaine Alluviale du Hadejia dans la région sémi aride du Nigéria

Résumé

Les sols des bourrelets de berge, dépressions et terrasses alluviales du Fleuve Hadejia ont été étudiés. Ces sols hydromorphes contiennent des micas, des nodules calcaires et des concrétions ferro-manganifères. Les bourrelets de berge et les terrasses sont caractérisés par une texture limoneuse, tandisque les dépressions sont de nature argileuse. Le carbone organique et les teneurs en

argile ont une distribution irrégulière avec la profondeur, reflètant ainsi l'origine fluviale et stratifiée du matériau parental. Les sols des bourrelets de berge et des dépressions sont peu évolués, mais les unités de terrasse ont atteint une certaine maturité, qui est exprimée par des phénomènes de migration d'argile, de ferrolyse, de gleyification et de sodification. L'argillipedoturbation également est un des processus majeurs dans les sols de dépression.

Les minéraux dominants de la fraction argileuse sont la kaolinite, la smectite, les micas, le palygorskite, le quartz et les feldspaths potassiques. Suivant les critères des classifications USDA-Soil Taxonomy et FAO-UNESCO, les bourrelets de berge sont caractérisés par des Ustifluvents typiques ou des Fluvisols eutriques: les sols de dépression correspondent à des Pellusterts entiques ou des Vertisols pelliques et les sols de terrasse se classent comme des Natraqualfs typiques ou des Planosols solodiques.

PEDOLOGIE, XXXIX-2, p. 191-207, 2 tab., 5 figs., Gand, 1989

ETUDE DE LA VARIABILITE SPATIALE DE QUELQUES PROPRIETES CHIMIQUES DU SOL EN FAGNE DE CHIMAY, BELGIQUE

P. GOOVAERTS
G. GERARD
R. FRANKART

Résumé

La variabilité spatiale de propriétés chimiques du sol (pH, conductivité électrique, teneurs en cations échangeables, CEC, teneurs en carbone organique et acidité d'échange) a été étudiée sous diverses affectations (prairies, bois, cultures) en Fagne de Chimay, Belgique. L'analyse de la variance a permis d'estimer les composantes inter et intra-parcellaire de la variance. Au sein des parcelles, les variations les plus importantes sont enregistrées pour les valeurs de conductivité électrique et les teneurs en cations échangeables.

La variabilité spatiale des valeurs de pH et de conductivité électrique a été analysée de façon plus approfondie. L'examen des variogrammes, calculés à partir des deux transects localisés respectivement en forêt et sous prairie, souligne le caractère restreint des échelles de variation, de l'ordre de quelques mètres pour les deux propriétés étudiées. L'interpolation de grilles de valeurs met en évidence une étroite relation entre la variabilité des mesures de pH et le type d'affectation.

Mots-clés

Variabilité spatiale, propriétés chimiques.

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1. INTRODUCTION

Le pédologue est souvent confronté au problème posé par le choix du nombre de prélèvements à effectuer dans une parcelle en vue de l'estimation d'une propriété donnée (Mc Bratney et Webster, 1983; Ruelle et al., 1986). D'après Webster et Burgess (1984), le nombre de prélèvements dépend de la précision recherchée, qui est fonction de l'objectif de la prospection, ainsi que de la variabilité inhérente à la surface inventoriée. Depuis une vingtaine d'années, l'étude de la variabilité spatiale des paramètres physico-chimiques et hydrodynamiques du sol s'est développée de manière considérable (Gajem et al., 1981; Uehara et al., 1984; Gascuel-Odoux, 1987). Les premiers travaux (Beckett et Webster, 1971) se caractérisaient par l'utilisation de méthodes d'analyse statistique basées sur l'hypothèse d'indépendance des observations. Mais les paramètres qui intéressent le pédologue sont des variables régionalisées, c'est-à-dire dont les valeurs dépendent de l'endroit étudié et ne sont donc pas indépendantes. L'existence de corrélations entre les valeurs prises par une propriété en différents points conduit à parler de structure spatiale. L'étude et la caractérisation de ces structures requièrent l'utilisation d'outils statistiques plus complexes tels le variogramme (Burgess et Webster, 1980; Yost et al., 1982; Bos et al., 1984; Riha et al., 1986) ou le corrélogramme (Webster et Cuanalo, 1975; Gajem et al., 1981; Lanyon et al., 1981; Miyamoto et Cruz, 1987).

Ces méthodes ont permis d'étudier, en Fagne de Chimay, Belgique , la variabilité spatiale de quelques propriétés chimiques du sol.

2. MATERIEL ET METHODES

2.1. Sites étudiés

Les parcelles étudiées, d'une superficie moyenne d'un hectare, sont localisées dans la partie occidentale de la Fagne de Chimay (sud de la province du Hainaut, Belgique). Elles furent échantillonnées en septembre 1986 et sont réparties en trois grandes classes d'affectation : cultures (céréales), prairies, futaie (chênaie) ou taillis sous futais (chênale charmée).

Les différents sites, choisis pour leur homogénéité tant pédologique que topographique, appartiennent à l'une des deux séries suivantes de la Carte des Sols de Belgique (Remy, 1981) : série Gbbf (Sols limoneux à charge schisteuse, à horizon B structural) et série Edx (Sols argileux modérément gleyifiés à développement de profil non défini). Selon le Soil Survey Staff (1975), la série Gbbf est un Typic Dystrochrept, clayey, mixed, udic, mesic et la série Edx est un Aquic Dystrochrept, clayey, mixed, udic, mesic.

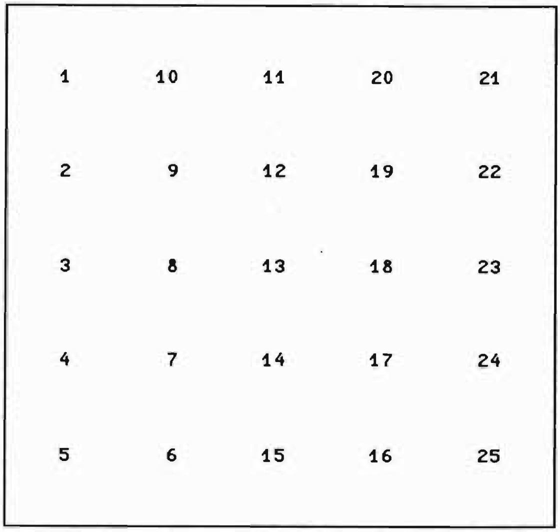

Fig. 1.
Dispositif 1 adopté pour l'échantillonnage d'une parcelle carrée d'un hectare.

2.2. Dispositifs d'échantillonnage

Trois dispositifs, caractérisés par une augmentation de l'échelle d'observation (diminution de l'intervalle d'échantillonnage), ont été utilisés.

1) Dispositif 1 : prélèvement de 25 échantillons selon un quadrillage régulier de 20 mètres de maille (figure 1). Après rejet d'un des 13 échantillons impairs, choisi de manière aléatoire, formation de 2 échantillons composites (pair et impair) de 12 prises. Dispositif appliqué à huit prairies et huit parcelles boisées.

2) Dispositif 2 : prélèvement de 64 ou 81 échantillons (dépendant de la taille de la parcelle) selon un quadrillage régulier de 10 mètres de maille. Dispositif appliqué à deux prairies, deux parcelles boisées et une culture.

3) Dispositif 3 : prélèvement de 100 échantillons selon un transect de 100 mètres de longueur et caractérisé par un intervalle d'échantillonnage d'1 mètre. Dispositif appliqué à une prairie et une parcelle boisée.

Sous prairie et en forêt, on préleva, après décapage des horizons holorganiques, les dix premiers centimètres de l'horizon minéral. Dans la parcelle cultivée, les vingt premiers centimètres furent échantillonnés.

2.3. Méthodes analytiques

Les composites (dispositif 1) ont été séchés à l'air, passés au tamis de 2 mm et analysés. Les mesures de pH(H_2O), pH(KCl) et conductivité électrique sont effectuées sur une suspension de terre fine (rapport 1/2.5). Les cations échangeables sont dosés par spectrophotométrie d'absorption atomique après extraction à l'acétate d'ammonium 1N pH 7. La CEC est déterminée après une première percolation à l'acétate d'ammonium 1N pH 7, suivie d'un lavage à l'alcool dénaturé et une deuxième percolation au KCl 1N pH 3 (Schollenberger et Simon, 1945). La teneur en carbone oxydable est obtenue par la méthode de Walkley et Black (1934). L'acidité d'échange est mesurée par titration après extraction au KCl 1N. L'ajout de NaF à la solution titrée provoque la transformation de l'Al^{+++} en un complexe stable avec production de NaOH dont la titration nous indique la quantité d'aluminium échangeable (Mc Lean, 1965).

Etant donné le grand nombre d'échantillons prélevés dans les dispositifs 2 et 3 (± 600), seules les mesures de pH(H_2O) et de conductivité électrique ont pu, grâce à leur rapidité d'exécution, être réalisées. Ces deux propriétés ont été mesurées sur des échantillons de sol frais.

2.4. Analyses statistiques

Les analyses statistiques (analyse de la variance, interpolation des grilles de valeurs) furent exécutées par le logiciel SAS (SAS Institute, 1985). Le calcul des variogrammes expérimentaux et l'ajustement des modèles théoriques correspondants furent réalisés à l'aide du logiciel GEO-EAS (Englund et Sparks, 1988).

3. RESULTATS ET DISCUSSION

3.1. Analyse des échantillons composites

Pour chacune des 2 séries pédologiques (Edx et Gbbf), 4 parcelles furent échantillonnées sous prairie et 4 autres sous couvert forestier; 11 propriétés chimiques furent mesurées sur les 32 composites obtenus. Pour ce dispositif, les distances entre points échantillonnés étaient au minimum de 20 mètres; nous avons dès lors considéré que les autocorrélations étaient négligeables. Ce fait s'est vérifié en ce qui concerne le pH et la conductivité électrique (chap. 3.2). Le traitement des données par les méthodes d'analyse de la variance a permis d'estimer, pour chaque propriété, les paramètres suivants :

- σ^2_p : mesure de la variabilité existant entre parcelles appartenant aux mêmes série pédologique et classe d'affectation;
- σ^2_c : mesure de la variabilité existant entre composites au sein d'une même parcelle.

En vue d'estimer la variabilité de l'erreur expérimentale (σ^2_{exp}), une seconde analyse a été réalisée sur dix composites.

3.1.1. *Etude de la variabilité de l'erreur expérimentale*

Quelques données concernant les erreurs analytiques sont disponibles dans la littérature. Jacob et Klute (1956) ont déterminé ces erreurs pour les mesures de pH(H_2O) (1/2) et de carbone organique (méthode de Peech). Les coefficients de variation obtenus sont 0.29 % pour le pH(H_2O) et 2.23 % pour le carbone organique. Gajem et al. (1981) mentionnent pour le pH(H_2O) (1/5) un C.V. de 0.5 % et pour la conductivité électrique (1/5) un C.V. de 1.6 %. Le rapport de la Commission des Sols de Wallonie (1988) cite, pour le dosage du K^+, Ca^{++} et Mg^{++} dans l'extractif acétate d'ammonium 0.5 M avec de l'EDTA 0.02 M à pH 4.65, les valeurs suivantes : K^+ (0.2-1.7 %), Ca^{++} (0.5-1.5 %) et Mg^{++} (0.2-3.7 %).

L'utilisation du coefficient de variation, nombre adimensionnel, permet la comparaison des différents types d'analyse (tableau 1).

Tableau 1.
Estimation de la variabilité de l'erreur expérimentale.

Propriétés mesurées	σ^2_{exp}	Coefficient de variation C.V. (%)
pH(H_2O) (10^{-1} unités pH)	0.12	0.69
pH(KCl) (10^{-1} unités pH)	0.01	0.28
conductivité (µS/cm)	6.45	2.18
Na^+ (10^{-2} méq/100 gr)	0.41	7.91
K^+ (10^{-2} méq/100 gr)	0.82	2.17
Ca^{++} (10^{-1} méq/100 gr)	1.43	2.46
Mg^{++} (10^{-2} méq/100 gr)	1.16	1.22
CEC (10^{-1} méq/100 gr)	14.60	2.40
carbone organique (10^{-2} % sol)	72.90	2.29
acidité d'échange (10^{-1} méq/100 gr)	1.78	4.02
Al^{+++} (10^{-1} méq/100 gr)	1.52	4.14

Ces estimations restent comprises dans la fourchette de valeurs habituellement citées. Notons encore que le pH est caractérisé par un coefficient de variation inférieur à celui des autres propriétés; ceci est dû au fait que le pH est une mesure logarithmique et donc que le zéro est arbitraire (Webster, 1977). Le coefficient de variation du Na^+ est supérieur à celui des autres cations échangeables et peut être attribué aux faibles teneurs dosées.

3.1.2. Etude de la variabilité intra-parcelle

Pour chaque type d'affectation, la variabilité intra-parcelle est estimée par la variabilité existant en moyenne entre composites, en n'oubliant pas que tout composite élimine partiellement la composante intra-parcellaire de la variance (Beckett et Webster, 1971). Les propriétés les plus variables sont le Na^{+} (C.V. : 10-26 %), l'acidité d'échange (C.V. : 6-12 %), la conductivité électrique (3-13 %) et le K^{+} (8-35 %) qui présentent une plus grande variabilité en prairie (10-35 %) qu'en forêt (3-8 %).

Beckett et Webster (1971) ont montré que la variabilité intra-parcelle de certaines propriétés chimiques du sol (particulièrement les teneurs en K^{+} et P) est plus importante en prairies, spécialement celles qui ont été pâturées récemment. En effet, si le prélèvement des éléments minéraux se fait de manière uniforme sur la parcelle, leur retour, sous forme de déjections solides ou liquides, présentent un caractère localisé. Ceci explique que la variabilité des teneurs en K^{+} est plus importante dans les prairies localisées sur Edx (C.V. : 35 %), pâturées de manière plus intensive que celles situées sur Gbbf (prairies de fauche ou pâtures pour chevaux) pour lesquelles le C.V. est de 10 %.

Les propriétés caractérisées par une variabilité intra-parcelle plus petite sont le pH (C.V. : 1 %), le pourcentage de carbone organique et la CEC (C.V. : 2-6 %), le Ca^{++} et le Mg^{++}.

3.1.3. Etude de la variabilité existant entre parcelles

Selon Beckett et Webster (1971), la composante inter-parcellaire de la variance est d'autant plus importante que la propriété mesurée est sensible à l'action anthropique. Ils distinguent, suivant leur coefficient de variation, trois groupes de propriétés :

- % sable, % argile, P total — C.V. : 10 %
- CEC, matière org., N total — C.V. : 25 %
- P, Mg^{++}, Ca^{++}, K^{+} disponibles — C.V. : 35-50 %

Dans notre travail, les propriétés les moins variables sont le pH (C.V. : 1-7 %), la CEC et le pourcentage de carbone organique (C.V. : 3-14 %), ce qui confirme les groupes de Beckett et Webster (1971). La conductivité électrique et le K^{+} montrent une variabilité plus importante entre prairies (30-45 %) qu'entre parcelles boisées (7-19 %). La coexistence de pâtures et de prairies de fauche, appartenant à différents propriétaires, entraîne une application hétérogène des amendements organiques (déjections solides et liquides) et minéraux (chaulage). Celle-ci influence la richesse minérale des sites (conductivité électrique) et plus particulièrement les teneurs en K^{+}.

Pour les autres cations échangeables, la variabilité (C.V.) entre parcelles boisées (Ca^{++} : 48-60 %; Mg^{++} : 35-47 %; Na^{+} : 27-38 %)

est supérieure à celle existant entre prairies (Ca^{++} : 7-11 %, Mg^{++} : 22-29 %, Na^{+} : 17-21 %).

3.2. Etude des transects

Toute variable distribuée dans l'espace est par définition "régionalisée" et présente deux caractéristiques apparemment contradictoires : une structure spatiale à laquelle s'ajoute un aspect aléatoire, imprévisible (Journel et Huijbregts, 1978). Cette structure spatiale peut être étudiée et modélisée lors d'une analyse structurale ou variographie, basée sur l'inférence du variogramme. Soit la propriété Z, localisée dans l'espace au point de coordonnées X=(x,y). La variabilité existant entre les variables régionalisées Z(X) et Z(X+h), séparées d'une distance h, peut être exprimée par la fonction $\gamma(h)$, appelée variogramme. Celui-ci est défini comme la moitié de l'espérance du carré des écarts entre valeurs distantes de h.

$$\gamma(h) = \frac{1}{2} E\left[(Z(X) - Z(X+h))^2\right]$$

Le graphe de $\gamma(h)$ en fonction de h (figure 2) montre comment l'information acquise en un point se détériore lorsqu'on s'en éloigne. L'estimation du variogramme à partir des données disponibles nécessite le respect de l'hypothèse intrinsèque, c'est-à-dire l'hypothèse de stationnarité d'ordre 2 des différences (Z(X) - Z(X+h)). Un estimateur de $\gamma(h)$ est alors la moyenne arithmétique

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z(X_i) - z(X_i+h))^2$$

où N(h) est le nombre de paires d'observations distantes de h.

L'analyse structurale débute par l'étude de quelques caractéristiques du variogramme, principalement son comportement à l'origine et à l'infini (figure 2). Par définition, $\gamma(h) = 0$ pour $h = 0$. Cependant, la plupart des variogrammes des propriétés du sol présentent une discontinuité à l'origine, appelée "effet pépite" (Burrough, 1983). Celle-ci peut être imputée soit aux erreurs de mesure, soit à l'existance de variations sur des distances inférieures à l'intervalle d'échantillonnage. La fonction $\gamma(h)$ peut croître indéfiniment avec h ou atteindre un palier à une distance appelée "portée". Un tel variogramme est dit de transition et la portée correspond à la distance au-delà de laquelle les observations deviennent spatialement indépendantes.

L'étape suivante consiste à ajuster au variogramme expérimental un modèle théorique (figure 2) qui rende compte des caractéristiques observées (Journel et Huijbregts, 1978). Les principaux modèles ajustés aux variogrammes de transition sont les modèles sphériques, exponentiels ou gaussiens. En absence de palier, le modèle linéaire est

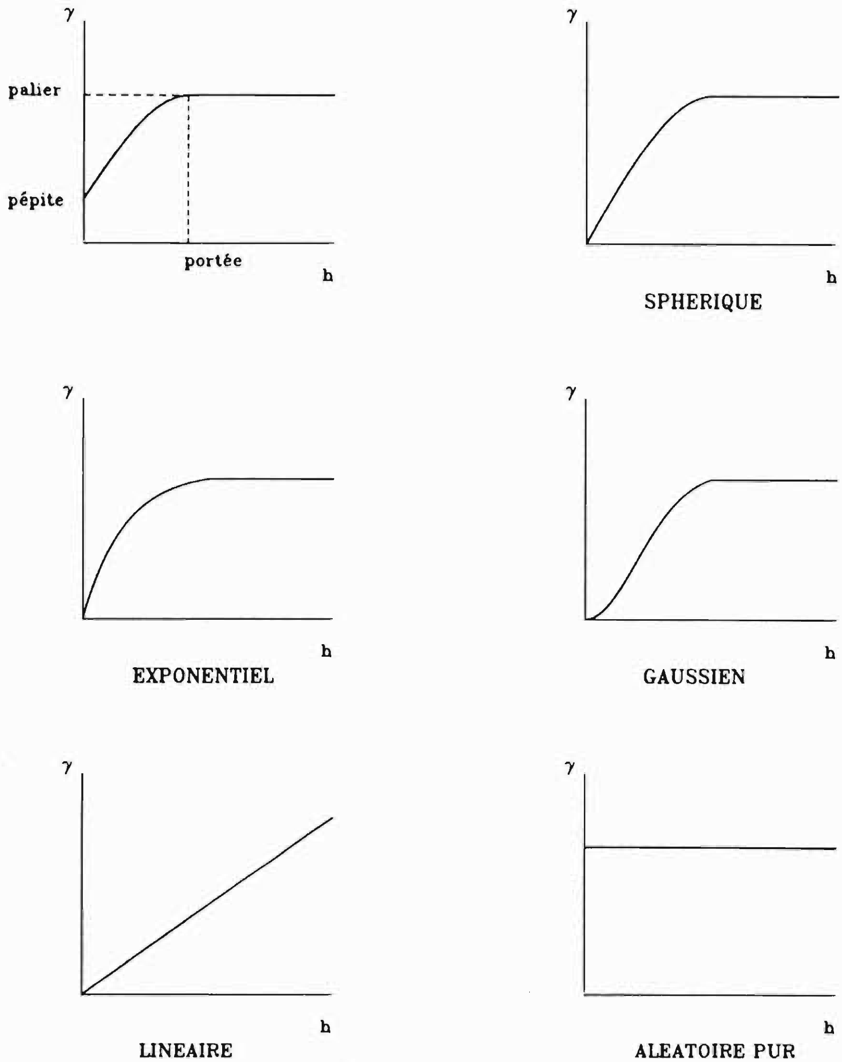

Fig. 2.
Exemples de modèles de variogrammes.

fréquemment utilisé. Le variogramme plat est caractéristique des phénomènes aléatoires purs où il n'existe aucune corrélation entre deux observations aussi rapprochées soient-elles.

Une analyse structurale a été réalisée sur les mesures de pH et de conductivité électrique effectuées le long de deux transects localisés respectivement en prairie et en forêt (figure 3). Le tableau 2 reprend les principales propriétés des variogrammes représentés à la figure 4. La majorité des variogrammes possèdent un palier qui est atteint plus ou moins rapidement et qui correspond généra-

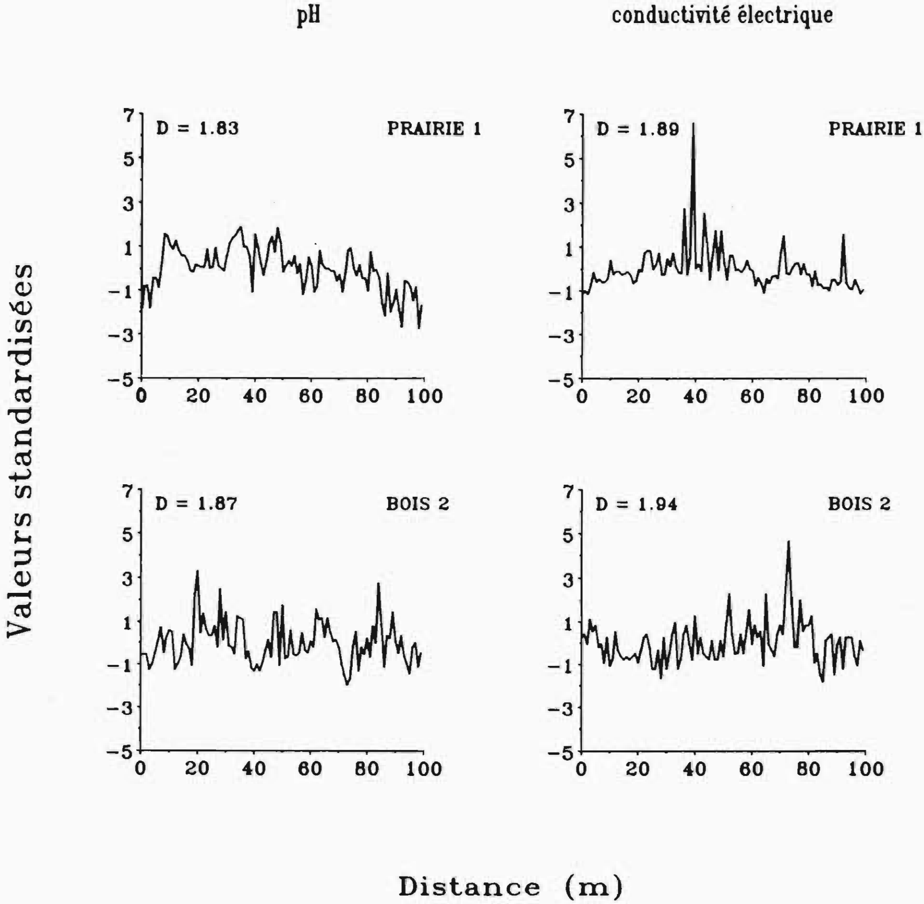

Fig. 3.
Evolution des valeurs standardisées de pH et de conductivité électrique le long de deux transects localisés respectivement dans les parcelles PRAIRIE 1 et BOIS 2 (D = dimension fractale).

lement à la variance globale de l'échantillon (tableau 2). Ce palier met en évidence l'existence de variances finies caractéristiques de processus stationnaires du second ordre. L'effet de pépite représente de 30 à 40 % de la variance spatiale maximale, traduisant une forte variabilité des mesures sur des distances inférieures à un mètre. En effet, la variabilité liée aux erreurs expérimentales (tableau 1) ne peut expliquer qu'en partie l'effet de pépite observé. Les mesures de pH présentent une structure spatiale dont la portée est de 10 mètres en prairie et 4 mètres en forêt. La zone d'influence des mesures de pH, c'est-à-dire l'aire dans laquelle les observations sont statistiquement associées au centre de l'aire (Campbell,

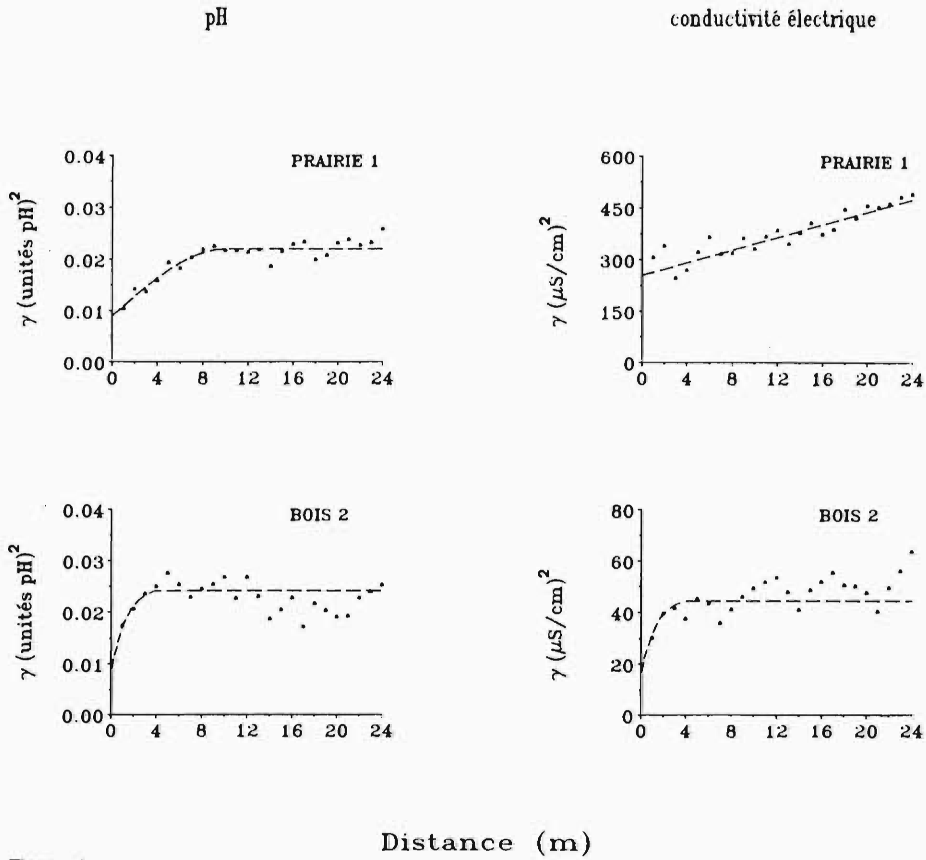

Fig. 4.
Variogrammes expérimentaux des mesures de pH et de conductivité électrique des deux transects localisés respectivement dans les parcelles PRAIRIE 1 et BOIS 2. Les traits discontinus symbolisent les modèles théoriques ajustés.

Tableau 2.
Caractéristiques des variogrammes.

Propriétés	Modèle	Portée	Pépite	Palier	σ^2
pH PRAIRIE 1 (unités pH)	sphérique	10 m	0.009	0.022	0.030
pH BOIS 2 (unités pH)	exponentiel	4 m	0.008	0.025	0.023
C.E. PRAIRIE 1 (µs/cm)	linéaire	-	255	-	394
C.E. BOIS 2 (µs/cm)	exponentiel	4 m	15	46	46

1978), est donc plus grande en prairie. Pour les mesures de conductivité électrique réalisées en forêt, le variogramme est exponentiel avec une portée de 4 mètres. Sous prairie, la croissance continue du variogramme est caractéristique d'un processus non stationnaire au second ordre. En effet, l'examen de ce transect (figure 3) montre l'existence d'une plus grande variabilité des valeurs de conductivité électrique (nombreux pics importants) sur la portion allant de 35 à 50 mètres.

Il convient d'insister sur l'importance prépondérante de l'échelle d'échantillonnage dans l'étude de la variabilité spatiale. Gajem et al. (1981) ont montré que l'estimation de la taille de la zone d'influence augmente avec l'intervalle d'échantillonnage. Pour Burrough (1983), le caractère aléatoire ou systématique des variations du sol dépend entièrement de l'échelle d'observation; une variation aléatoire peut presque toujours s'avérer structurée spatialement à une plus grande échelle. Les propriétés du sol sont donc des quantités fractales en ce sens que l'observation de leurs variations spatiales à des échelles croissantes révèlent de plus en plus de détails. Burrough (1983) utilise la valeur du paramètre D, variant de 1 à 2, comme mesure de l'équilibre existant entre les variations opérant sur de courtes distances (short-range variations) et celles agissant à de plus grandes échelles (long-range variations). Une grande valeur de D reflète la dominance d'effets opérant sur de courtes distances, ainsi que le caractère restreint des échelles de variation.

Pour les mesures de pH et de conductivité électrique réalisées le long des deux transects, le paramètre D a été estimé à partir de la formule $m=(4-2d)$ où m est la pente de la droite ajustée aux valeurs du variogramme (graphe $\log(\gamma(h))$ - $\log(h)$) situées avant le palier (Burrough, 1983). Les quatre séries sont caractérisées par des valeurs élevées de D (figure 3), soulignant l'importance des "short-range variations". Burrough (1983) mentionne, pour les propriétés du sol, des valeurs supérieures à 1.50.

3.3. Examen des grilles de pH

Le deuxième dispositif d'échantillonnage a permis une étude plus approfondie de la variabilité existant au sein de cinq parcelles. L'analyse des variogrammes démontre la dépendance spatiale des mesures de pH distantes de dix mètres, ce qui autorise l'application de méthodes d'interpolation conduisant à une cartographie thématique des surfaces. Le résultat de l'interpolation des grilles de pH est repris à la figure 5. La base de chaque graphe est définie par les axes géographiques X et Y, les valeurs de pH figurant sur l'axe vertical.

Ces graphes permettent de visualiser la variabilité existant dans chaque parcelle ainsi que son étroite relation avec le type d'affec-

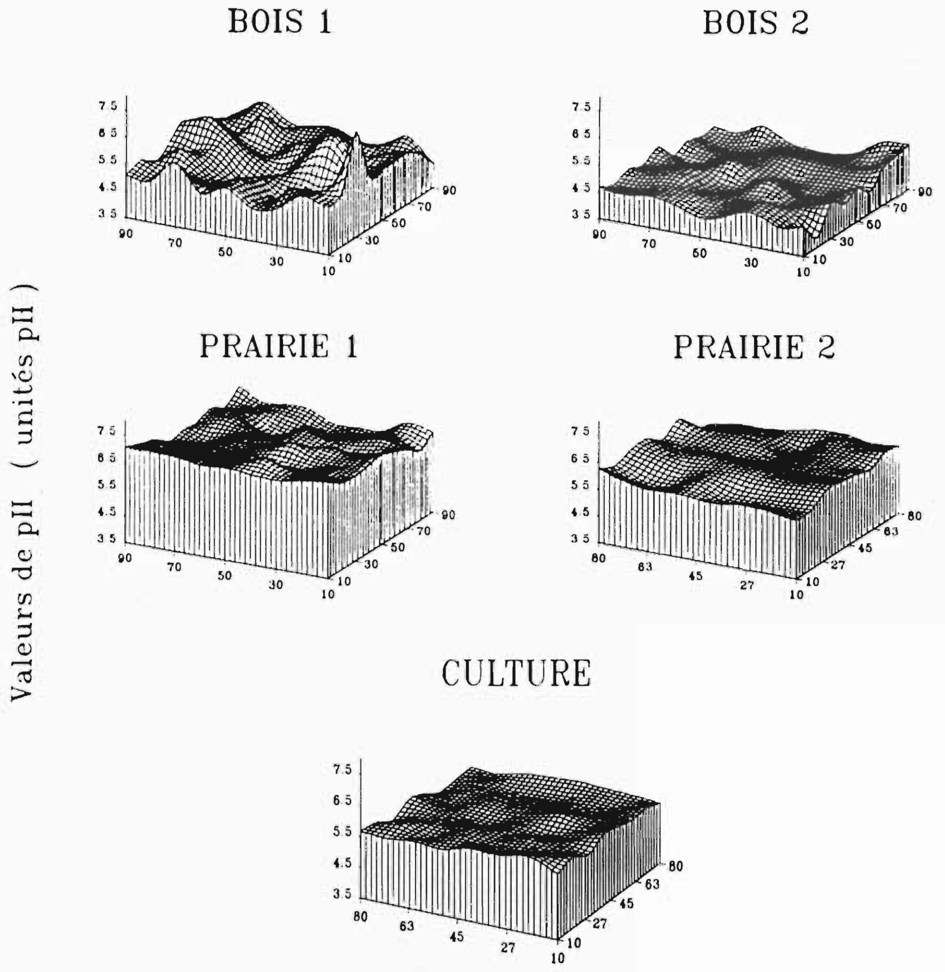

Fig. 5.
Diagrammes tri-dimensionnels des valeurs de pH obtenus par interpolation (procédure G3GRID du logiciel SAS) des mesures effectuées, dans 5 parcelles, selon un quadrillage régulier de 10 mètres de maille.

tation. La variabilité intra-parcelle des valeurs de pH présente la gradation suivante : cultures < prairies < bois. En effet, on observe sous bois une plus grande hétérogénéité de la couverture végétale, donc une plus grande variabilité de l'activité biologique productrice d'acides. La parcelle BOIS 2, caractérisée par un régime de futaie et une strate herbacée peu importante, est moins variable que la parcelle BOIS 1 où on note l'existence d'un taillis et d'un tapis herbacé fort diversifié. L'action homogénéisante des différentes méthodes phytotechniques est responsable de la moindre variabilité des valeurs de pH sous cultures.

4. CONCLUSIONS

Toute étude pédologique est incomplète si elle néglige les variations spatiales manifestées par la majorité des propriétés du sol. Cette variabilité, déjà importante sur quelques mètres carrés (During et Mountier, 1967), est fonction de la propriété mesurée et de l'affectation de la parcelle échantillonnée. Des propriétés telles le pH, le carbone organique et la CEC présentent une faible variabilité intra-parcelle comparé à d'autres paramètres tels les teneurs en cations échangeables ou la conductivité électrique. La nature et l'intensité de l'action anthropique ainsi que l'hétérogénéité de la couverture végétale contribuent soit à atténuer, soit à accentuer ces variations spatiales.

La similitude des coefficients de variation obtenus par Van den Hende et al. (1957) sur des parcelles de tailles diverses semble indiquer que les variations spatiales surviennent sur de très courtes distances. Le calcul et l'analyse des variogrammes confirment ces observations et permettent d'estimer cette distance à quelques mètres pour les valeurs de pH et de conductivité électrique.

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Study of the spatial variability of some soil chemical properties in "Fagne de Chimay" (Belgium)

Summary

The spatial variability of soil chemical properties (pH, electrical conductivity, exchangeable cations level, CEC, organic carbon content and exchangeable acidity) was studied, under various land uses (grazed field, forest, cultivated field), in "Fagne de Chimay" (Belgium). The analysis of variance led to the estimation of the between-plot and the within-plot components of variance. Within a plot, electrical conductivity and exchangeable cations level are the most variable properties.

The spatial variability of pH and electrical conductivity was analysed more in detail. The examination of variograms, computed from two transects located respectively in forest and in grazed field, shows the closeness of scales of variation, about some meters for the two properties of interest. Considering the result of interpolation of grid values, a close relation between pH measurements variability and land use type seems obvious.

Studie van de ruimtelijke variabiliteit van enkele chemische bodemeigenschappen in de "Fagne de Chimay", België

Samenvatting

De ruimtelijke variabiliteit werd bestudeerd van een aantal chemische bodemeigenschappen (pH, electrische geleidbaarheid, CEC en uitwisselbare cationen, gehalte aan organische koolstof en uitwisselbare zuurtegraad) onder verschillende gebruiksomstandigheden (weide, bos en akkerbouw) in de Fagne de Chimay, België. De variantie-analyse heeft toegelaten de inter- en intraparcellaire verschillen na te gaan. Binnen de percelen vertonen de electrische geleidbaarheid en de gehalten aan uitwisselbare basen de grootste variaties.

De ruimtelijke variabiliteit van de pH en electrische geleidbaarheid werd meer in detail bestudeerd. Onderzoek van de variogrammen berekend vanaf twee doorsneden uit resp. een bos en een weidegebied, toont het kleine variatiebereik aan - van de orde van enkele meters slechts - bij de studie van deze twee eigenschappen. Er wordt een duidelijke relatie vastgesteld, tussen de pH variabiliteit en het bodemgebruik.

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SPATIAL VARIABILITY OF SOIL TEXTURE IN A POLDER AREA
II. COKRIGING

M. VAN MEIRVENNE
G. HOFMAN

Abstract

In a first paper, the need to improve the punctual-kriging variance of the soil texture of a 1 ha polder soil was recognized. As an alternative to analysing more locations for their soil texture, a second variable was introduced : the -1.5 MPa water content. Since this variable is simpler, faster and cheaper to determine, it could be analysed more densely. The spatial cross correlation between the different textural fractions and the -1.5 MPa water content was used to cokrige soil texture. Compared with the kriging estimation, this resulted in a considerable reduction of the confidence interval of the estimation and a gain in detail, especially at locations where only a -1.5 MPa measurement was available.

Key-words

Cokriging, polder, texture, spatial variability.

1. INTRODUCTION

In the preceding paper, Van Meirvenne and Hofman (1989) analysed the spatial variability of the depth of the lithologic discontinuity, and the soil texture above (I) and below (II), of a 1 ha polder field in Belgium. They used the theory of regionalized variables as proposed by Matheron (1963, 1971). The structure of the spatial

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variability was characterized by the semivariogram and estimation of the variable of interest at unrecorded locations was done by punctual-kriging.

Due to the short ranges of the semivariograms of the different textural fractions (between 7.5 m and 51 m), a need for a more intensive sampling program was recognized to reduce the estimation variance.

To improve the precision of the estimation, the spatial correlation between soil texture and a second, more frequently sampled variable can be used as an alternative to more textural analyses. This technique is called cokriging (Matheron, 1971). The second variable can be selected to be simpler, faster and/or cheaper than soil texture. Meeting all these criteria, the water content of the soil at a matric potential of -1.5 MPa (-15 bar or pF 4.2) was chosen as second variable. The objective of this paper is to investigate the gain in accuracy obtained by cokriging the soil texture with the aid of the -1.5 MPa water content, in order to avoid more textural analyses.

Compared to kriging, cokriging has received far less attention in soil science. Nevertheless, Vauclin et al. (1983) used cokriging to estimate soil texture in relationship to available water content and water stored at -0.33 MPa. McBratney and Webster (1983) studied the spatial variability of the topsoil silt fraction with the aid of subsoil silt and sand measurements. Yates and Warrick (1987) estimated the gravimetric moisture content by cokriging using one or two additional variables : the bare soil surface temperature and the sand content. A comparison of different geostatistical methods to estimate a less sampled variable with the aid of a correlated denser sampled variable, is given in Ahmed and de Marsily (1987).

2. THEORY

The theory of regionalized variables, the assumptions involved and the punctual-kriging equations were discussed in the companion paper (Van Meirvenne and Hofman, 1989).

In-depth discussions of cokriging are given by Journel and Huijbregts (1978) and Vieira et al. (1983). Therefore, only a brief outline of the method will be given here.

Consider a field in which two second-order stationary regionalized variables z_1 and z_2 have been measured, with a number of samples n_1 and n_2 respectively. Suppose $n_1 < n_2$, so, z_1 has been less sampled compared to z_2.

Their semivariograms can be estimated by

$$\gamma^*_1(h) = \frac{1}{2N_1(h)} \sum_{i=1}^{N_1(h)} \{ z_1(i) - z_1(i+h) \}^2 \quad (1)$$

and

$$\gamma^*_2(h) = \frac{1}{2N_2(h)} \sum_{i=1}^{N_2(h)} \{ z_2(i) - z_2(i+h) \}^2 \quad (2)$$

in which $N_k(h)$ (k=1 or 2) is the number of pairs of observations $\{ z_k(i), z_k(i+h)\}$ and h is the distance lag.

The cross semivariogram can be estimated by

$$\gamma^*_{12}(h) = \gamma^*_{21}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{ z_1(i) - z_1(i+h)\} \{ z_2(i) - z_2(i+h)\} \quad (3)$$

where N(h) is the number of pairs of variables $(\{ z_1(i), z_1(i+h)\}, \{ z_2(i), z_2(i+h)\})$ separated by h. Notice that the cross semivariogram requires data points common for both variables. It is also required that the semivariograms and the cross semivariogram satisfy the Cauchy-Schwartz inequality, i.e. $|\gamma^*_{12}(h)| \leq |\gamma^*_1(h)\ \gamma^*_2(h)|^{\frac{1}{2}}$, for all h, to ensure that the variance will be positive (Yates and Warrick, 1987).

In the cokriging method, the estimator has the form

$$Z^*_1(x_0) = \sum_{i=1}^{N_1} \lambda_{1i} Z_1(x_{1i}) + \sum_{j=1}^{N_2} \lambda_{2j} Z_2(x_{2j}) \quad (4)$$

where N_1 and N_2 are the number of neighbours of Z_1 and Z_2 respectively, involved in the estimation of point x_0, and λ_{1i} and λ_{2j} are the weights associated with Z_1 and Z_2.

The unbiased condition is, similar to punctual-kriging,

$$E[Z^*_1(x_0) - Z_1(x_0)] = 0 \quad (5)$$

and the minimum variance of estimation requirement is

$$E[\{ Z^*_1(x_0) - Z_1(x_0)\}^2] = \text{minimum}. \quad (6)$$

The estimator will be unbiased if the sum of λ_{1i} equals unity and the sum of λ_{2j} equals zero. The minimum variance condition plus the constraint on the weights requires the introduction of two Lagrangian multipliers μ_1 and μ_2. This yields the cokriging system (Vieira et al., 1983)

$$\sum_{i=1}^{N_2} \lambda_{2i}\ \gamma_{12}(x_{2i}, x_{1l}) + \sum_{j=1}^{N_1} \lambda_{1j}\ \gamma_1(x_{1j}, x_{1l}) + \mu_1 = \gamma_1(x_{1l}, x_0),$$

$l = 1, ..., N_1$

$$\sum_{i=1}^{N_2} \lambda_{2i}\gamma_2(x_{2i},x_{2k}) = \sum_{j=1}^{N_1} \lambda_{1j}\gamma_{12}(x_{2k},x_{1j}) + \mu_2 = \gamma_{12}(x_{2k},x_0),$$

$$k = 1, ..., N_2$$

$$\sum_{i=1}^{N_1} \lambda_{1i} = 1,$$

and

$$\sum_{j=1}^{N_2} \lambda_{2j} = 0. \qquad (7)$$

The cokriging variance is given by

$$s_{ck}^2 = \sum_{i=1}^{N_1} \lambda_{1i}\gamma_1(x_{1i},x_0) + \sum_{j=1}^{N_2} \lambda_{2j}\gamma_{12}(x_{2j},x_0) + \mu_1. \qquad (8)$$

3. MATERIALS

In the frame of a research program, a 1 ha subarea situated in the Belgian polder area was sampled at 247 locations, as discussed in the preceding paper (Van Meirvenne and Hofman, 1989). The soil was described as coarse-loamy, illitic, calcareous, mesic Aquic Udifluvent displaying a lithologic discontinuity between loamy and sandy loam material, generally at a depth between 36 and 44cm. At all locations, a soil sample was taken of both the loamy material above and the sandy loam material below this discontinuity. These materials will be identified by I and II respectively. Of all soil samples, the gravimetric moisture content at a matric potential of -1.5 MPa was determined by the pressure membrane method. The repeatability of this analysis was tested by repeating the measurement 6 times for one loamy and one sandy loam soil sample. The coefficient of variation was 1.4 % and 2.0 % respectively. Texture analysis was done by the pipette method and was discussed in the first paper.

4. RESULTS AND DISCUSSION

4.1. Classical statistical analysis

This analysis presupposes all observations to be spatially independent.

Table 1 contains the population statistics of the -1.5 MPa data. The moisture content stored at -1.5 MPa of material I was found to be normally peaked (g_2 not significantly different from 3), but slightly negatively skewed ($g_1 < 0$ or extreme values tail off to the left). However, the difference with a normal frequency distribution was small. The -1.5 MPa data of material II were normally distributed.

Table 1.
Mean values (m), variances (s^2), extreme values, skewness (g_1) and kurtosis (g_2) of the -1.5 MPa data.

Material	m (% w/w)	s^2 ($\%^2$)	Extremes (%)	g_1	g_2
I	15.7	5.75	10.1-20.4	-0.42*	2.41
II	8.8	5.57	3.5-15.9	0.29	2.82

* significant at $\alpha = 0.05$

The linear correlation between the textural fractions (clay, silt, and sand) and the moisture stored at -1.5 MPa was calculated for both materials. The results are given in table 2 and shown in figure 1. The percent clay and silt are positively correlated with the -1.5 MPa moisture content, whereas the percent sand is negatively correlated. Since the slope of the regression is steepest for the clay to -1.5 MPa relationships, it can be concluded that the percent

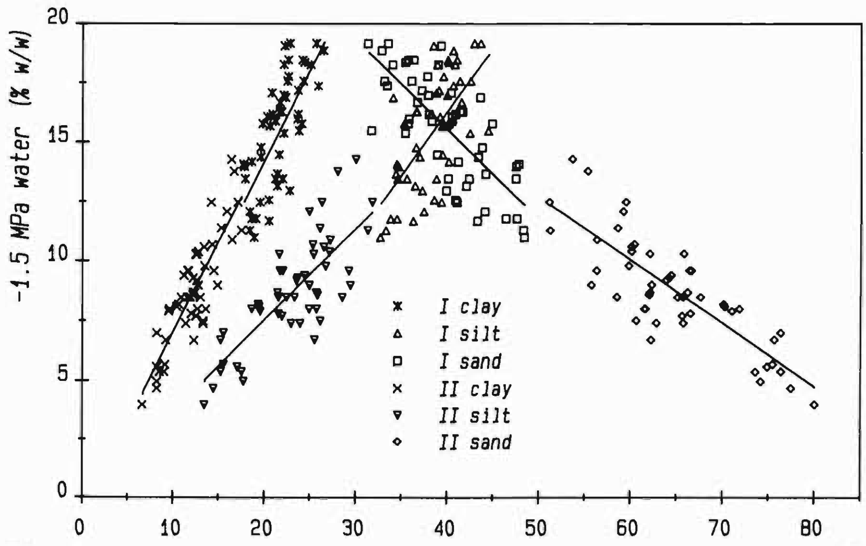

Fig. 1.
Linear regressions between the textural fractions of both materials and the -1.5 MPa water content (the coefficients of the regressions are given in table 2).

clay influences most the amount of water stored at this matric potential.

Table 2.
Coefficients of the linear regression model Y = A + BX and associated correlation coefficient r.

X	Y	A	B	r
I clay	-1.5 MPa	-1.09	0.768	0.73***
silt	-1.5 MPa	-5.07	0.535	0.66***
sand	-1.5 MPa	30.6	-0.379	-0.75***
II clay	-1.5 MPa	-0.488	0.757	0.86***
silt	-1.5 MPa	-0.0993	0.383	0.78***
sand	-1.5 MPa	25.9	-0.265	-0.83***

*** significant at $\alpha = 0.001$

4.2. Geostatistical analysis

Since a spatial structure of soil texture was identified in the first paper, geostatistical methods are more appropriate to investigate spatial dependence between soil texture and the moisture content at -1.5 MPa.

The experimental semivariogram, calculated by eq. (2), of both -1.5 MPa data sets was grouped per lag class of 5 m with the number of data pairs as weights. Both semivariograms were found to be best represented by an exponential model :

$$\gamma^*(h) = C_0 + (C_1 - C_0)\{1 - \exp(-h/b)\} \quad (9)$$

where C_0 is the nugget effect, C_1 the sill, a the range and h the distance lag. A practical range is used, defined as a=3b. The procedure to fit a theoretical model to the experimental semivariogram was described in the first paper. The values of these parameters are given in table 3 and the semivariograms are shown in figure 2. The largest distance over which the semivariogram should be considered is half the maximum dimension of the field on which it has been computed (Journel and Huijbregts, 1978). The sill of the theoretical semivariogram of material I corresponds with this maximum distance, indicating that the semivariogram still has a capability to increase beyond this largest lag distance. So, the spatial dependence of the -1.5 MPa water content of material I shows a spatial dependence greater than 70 m. The semivariogram of ma-

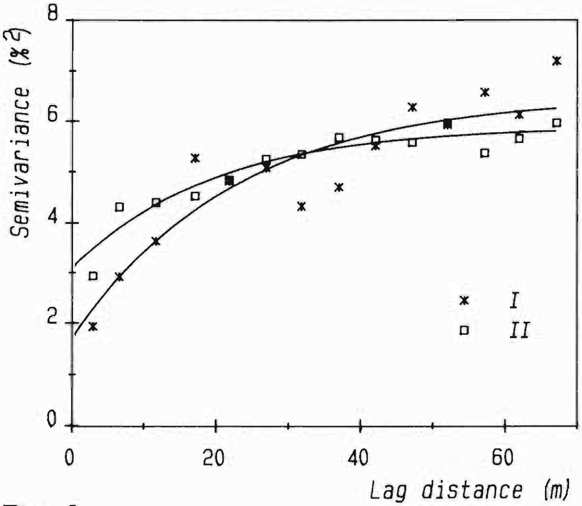

Fig. 2.
Experimental (points) and theoretical (lines) semivariograms of the -1.5 MPa data.

terial II reaches a sill at 58 m, thus its range of spatial dependence can be interfered within the dimensions of this field. Both semivariograms show large nugget effects. Therefore, a large part of the spatial variability occurred within the smallest sampling distance (2.5 m) or was due to measurement errors.

To visualize the water content stored at -1.5 MPa of material I and II they were punctual-kriged every 2.5 m, as described in the first paper (Van Meirvenne and Hofman, 1989). The results are given in figure 3. The ridges of the undulating surface of the data of material I correspond with the locations of former ditches which were used to drain this field before drain tubes were installed. One can still locate their position and orientation by observing the crop with aerial photographs. On the other hand, material II displays a more erratic spatial distribution.

The theoretical semivariograms of the texture data were discussed in the first paper.

To investigate the spatial cross correlation, the cross semivariograms between the three textural fractions and the -1.5 MPa data of the same locations were calculated for both materials, using eq. (3). The same procedure was followed as for the semivariograms to fit a theoretical model. The parameters of the theoretical cross semivariograms are given in table 3, the curves are shown in figure 4. Similarly as for the semivariograms, the cross semivariograms of material I show a tendency to increase beyond the largest lag distance, whereas they all reach a sill for material II. The cross se-

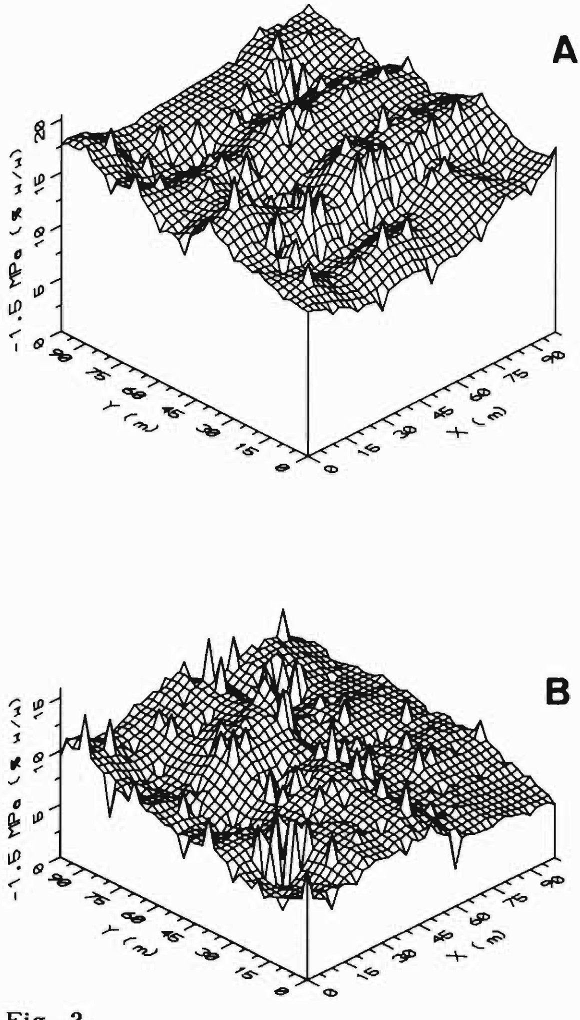

Fig. 3.
Punctual-kriged -1.5 MPa data of the loamy (A) and sandy loam (B) material.

mivariograms of the clay and silt content are positive, while they are negative for the percent sand, which is analogous with the linear regression analysis discussed before.

Using the -1.5 MPa water content as a second variable, co-kriging of the clay and sand content of both materials was done under the assumptions of second-order stationarity, ergodicity and point measurements. As in the first paper, a moving neighbourhood of 30 m was used for the texture data with an unlimited number of neighbours. For the -1.5 MPa data, the number of neighbours

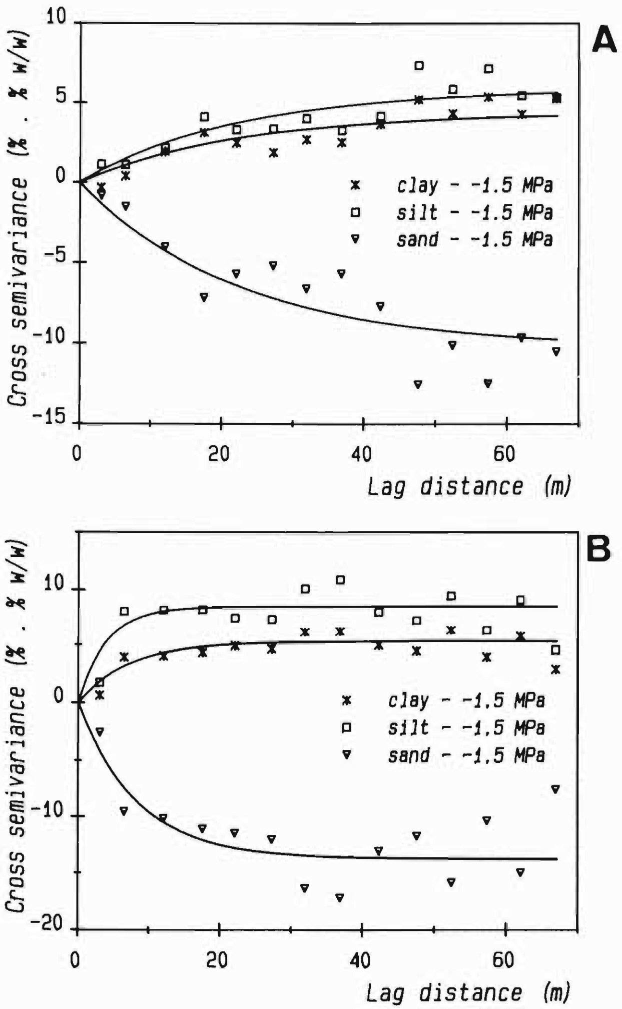

Fig. 4.
Experimental (points) and theoretical (lines) cross semivariograms of the texture - - 1.5 MPa data (A : material I, B : material II).

was restricted to 4 in order to reduce computational complexity. Contour maps of the cokriged texture fractions and twice the associated standard deviation (± $2s_{ck}$ can be taken as the 95 % confidence interval, assuming a normal distribution of this error) are given in figures 5 to 8.

Table 3.
Theoretical exponential (eq. no. 9) semivariograms of the -1.5 MPa data and cross semivariograms between the textural fractions and the -1.5 MPa data.

		C_0 (%^{2})	C_1 (%^{2})	a (m)
I	-1.5 MPa	1.7	6.5	67.0
II	-1.5 MPa	3.1	5.9	58.0
I	clay - -1.5 MPa	0.0	4.4	67.0
	silt - -1.5 MPa	0.0	5.9	67.0
	sand - -1.5 MPa	0.0	-10.3	67.0
II	clay - -1.5 MPa	0.0	5.3	21.0
	silt - -1.5 MPa	0.0	8.5	12.0
	sand - -1.5 MPa	0.0	-13.8	25.0

Both the kriged -1.5 MPa data and the cokriged texture data were jackknifed. The aim, as described in the first paper, is to investigate the validity of the assumptions involved and to test the ability to estimate known values with errors coherent to the predicted variances. The mean estimation error (MEE) should be close to zero and the reduced variance (RV) should be close to unity. The results are given in table 4 and it can be concluded that the options chosen and assumptions made were correct.

Table 4.
Mean estimation errors (MEE) and reduced variances (RV) of the kriged -1.5 MPa and cokriged texture data.

		MEE	RV
I	-1.5 MPa	-1.83E-02	0.84
II	-1.5 MPa	1.71E-03	0.86
I	clay - -1.5 MPa	-1.65E-01	1.35
I	sand - -1.5 MPa	2.89E-01	1.17
II	clay - -1.5 MPa	5.29E-05	1.29
II	clay - -1.5 MPa	-9.02E-02	1.19

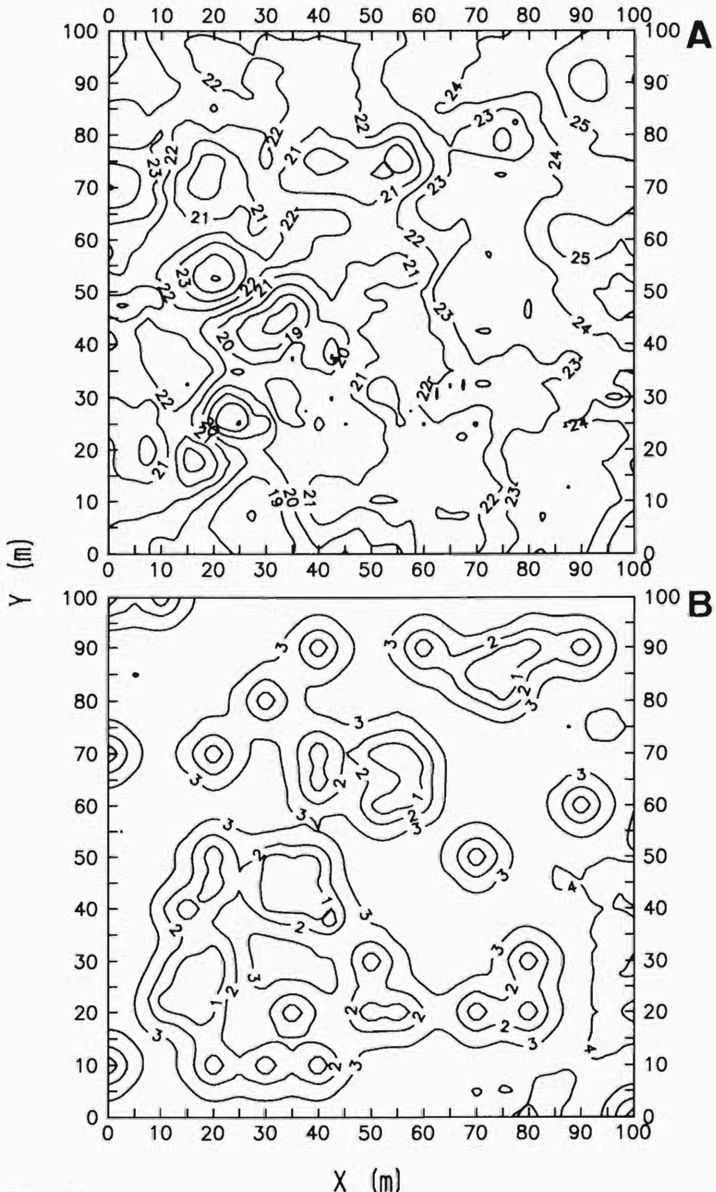

Fig. 5.
Cokriged values (A) and twice the cokriging standard deviation (B) of I clay (%).

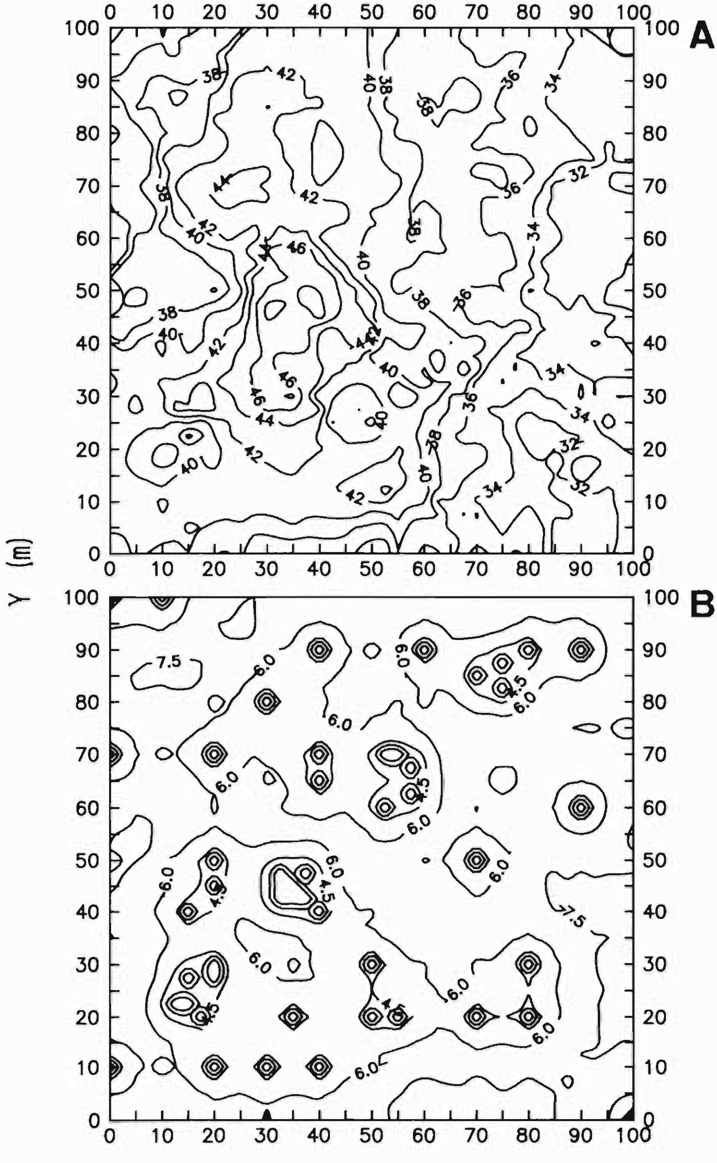

Fig. 6.
Cokriged values (A) and twice the cokriging standard deviation (B) of I sand (%).

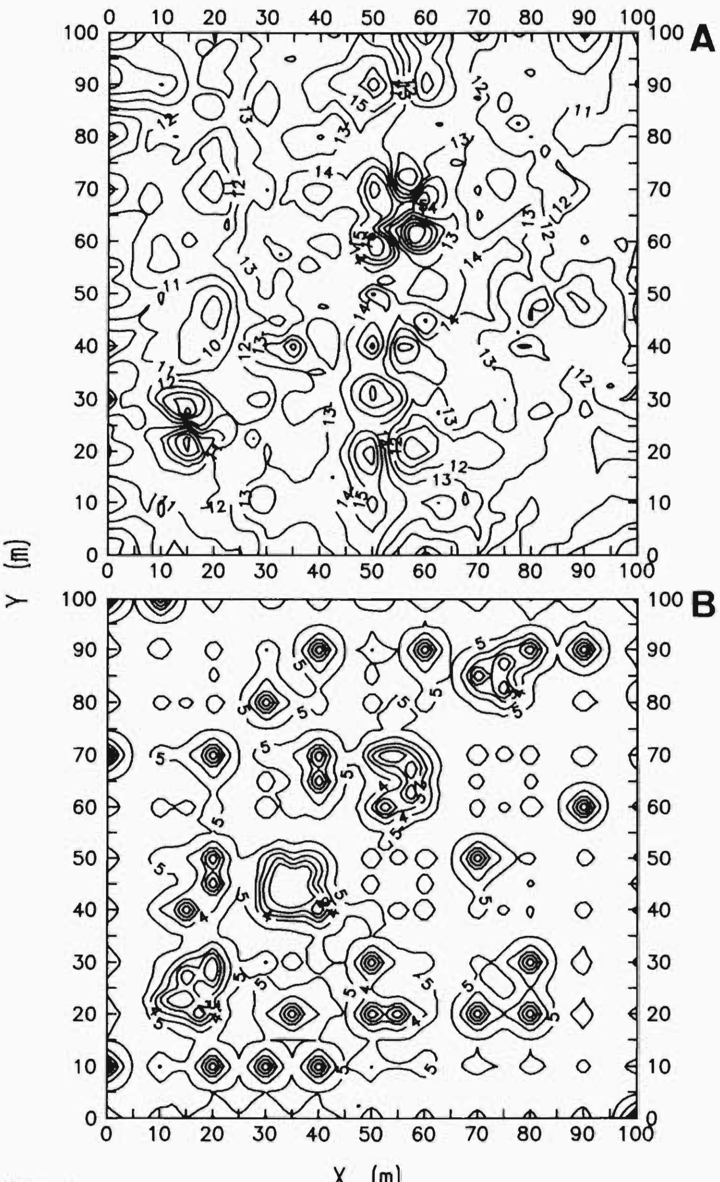

Fig. 7.
Cokriged values (A) and twice the cokriging standard deviation (B) of II clay (%).

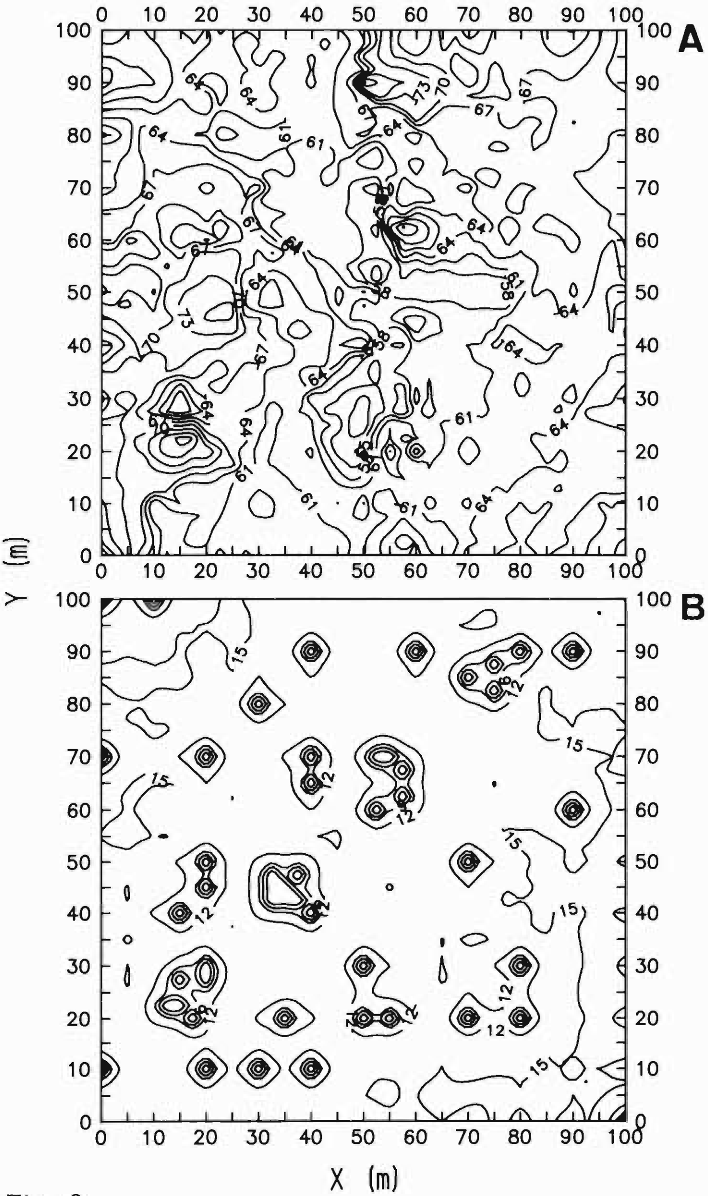

Fig. 8.
Cokriged values (A) and twice the cokriging standard deviation (B) of II sand (%).

To investigate the gain in accuracy obtained by cokriging compared to kriging, the average 95 % confidence intervals associated with each estimation technique were calculated and compared (table 5). These average differences show a 4.7 % to 9.5 % improvement of cokriging over kriging. However, since the kriging estimation variance was already small at locations close to texture measurement points, the average differences calculated for the entire field mask the larger reductions of the confidence interval at locations far from measurement points. Table 6 gives the largest difference between a kriging and cokriging 95 % confidence interval. Out of these values, it can be concluded that at a particular location, a considerable gain (19 % to 42 %) can be obtained by applying cokriging.

Table 5.
Average 95 % confidence intervals of the kriging ($\overline{2s_k}$) and cokriging ($\overline{2s_{ck}}$) estimation and their absolute and relative differences.

	$\overline{2s_k}$ (%)	$\overline{2s_{ck}}$ (%)	$\overline{2s_k} - \overline{2s_{ck}}$ (%)	% gain
I clay	3.11	2.95	0.16	5.1
I sand	6.84	6.19	0.65	9.5
II clay	5.20	4.86	0.34	6.5
II sand	14.37	13.69	0.68	4.7

Table 6.
Absolute and relative differences between the kriging ($2s_k$) and cokriging ($2s_{ck}$) 95 % confidence interval at location X = 100 m and Y = 100 m.

	$2s_k$ (%)	$2s_{ck}$ (%)	$2s_k - 2s_{ck}$ (%)	% gain
I clay	4.43	3.58	0.85	19
I sand	9.56	6.88	2.68	28
II clay	6.07	3.55	2.52	42
II sand	16.84	11.70	5.14	31

5. CONCLUSIONS

In a first paper, Van Meirvenne and Hofman (1989) recognized a need for more textural analyses to reduce the punctual-kriging estimation variance. This paper investigated the ability to use cokriging to improve the estimation of soil texture, by using a second, simple, cheap and fast to determine, cross-correlated variable : the -1.5 MPa water content.

A classical statistical analysis indicated that the frequency distribution functions of the -1.5 MPa data sets could be considered to be normal. Also, highly significant correlations were found between all textural fractions and the -1.5 MPa data. This correlation was positive for the clay and silt fractions and negative for the sand fraction. The -1.5 MPa water content was influenced most by the percent clay. This is in agreement with earlier investigations in the Belgian polder areas (De Leenheer and Van Ruymbeke, 1960).

A geostatistical study included semivariogram and cross variogram analyses. For material I the semivariogram of the -1.5 MPa data and the cross semivariograms with all textural fractions showed an increasing variability beyond the largest lag distance recommended to calculate these functions (70 m). For material II, all these functions reached a sill within this distance. Therefore, if independent samples are required to investigate the moisture retention of the soil of this field, samples should be further apart than 70 m for the loamy material (I), and at least 58 m apart for the sandy loam material (II).

A comparison of the 95 % confidence interval associated with the kriging and cokriging interpolation shows an average improvement ranging between 4.7 % and 9.5 % when applying cokriging. These values are in agreement with the results found by Yates and Warrick (1987). They reported average gains ranging between 0.2 % and 13 % when kriging and different cokriging results were compared. However, the advantage of using a second variable to estimate a first one is largest at locations far from measurement points of the first variable and at locations where only the second variable is known (Vauclin et al., 1983). The largest gain of cokriging over kriging at a particular point was between 19 % (I clay) and 42 % (II clay). Moreover, all the cokriging contour maps of the different textural fractions contain much more detail if compared to the kriging maps of the preceding paper. These findings suggest a considerable improvement of the estimation of soil texture at unrecorded locations. This conclusion confirms the recommendations made by Yates and Warrick (1987). These authors concluded that cokriging should provide improved estimates when the magnitude of the correlation coefficient between the two variables considered is greater than 0.5 and the second variable is over-sampled, which was the case in this study.

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Yates, S.R. & Warrick, A.W. (1987)
Estimating soil water content using cokriging.
Soil Sci. Soc. Am. J., 51 : 23-30.

Ruimtelijk variabiliteit van de bodemtextuur in een poldergebied : II. Cokriging

Samenvatting

In een eerste artikel werd de behoefte om de variantie van de punt-kriging van de bodemtextuur te verbeteren onderkend. Als een alternatief voor meer textuuranalysen werd een tweede variabele geïntroduceerd : het vochtgehalte bij -1, 5 MPa. Aangezien deze variabele eenvoudiger, sneller en goedkoper te bepalen is, kon hij op meer lokaties bepaald worden. De ruimtelijke wederzijdse korrelatie tussen de verschillende textuurfrakties en het vochtgehalte bij -1,5 MPa werd gebruikt om de bodemtextuur te interpoleren via cokriging. Vergeleken met kriging, leidde dit tot een aanzienlijke verkleining van de betrouwheidsintervallen van de interpolatie en een winst in detail, voornamelijk op deze plaatsen waar enkel een -1,5 MPa bepaling beschikbaar was.

La variabilité spatiale de la texture du sol des polders : II. Cokrigeage

Résumé

Dans un premier article il a été établi qu'il était nécessaire d'améliorer la variance du point-krigeage de la texture du sol. Comme alternative pour un plus grand nombre d'analyses de texture, une seconde variable a été introduite : la teneur en eau à -1,5 MPa. Etant donné que cette variable peut être déterminée de façon plus aisée, plus rapide et meilleure marchée, le nombre d'emplacements peut être augmenté. La corrélation réciproque dans l'espace entre les différentes fractions texturales et la teneur en eau à -1,5 MPa a été utilisée pour interpoler la texture du sol par cokrigeage. Comparée au krigeage, cette méthode conduit à une diminution appréciable des intervalles de confiance de l'interpolation et un gain de détail, principalement aux emplacements où l'on ne dispose que d'une détermination à -1,5 MPa.

D. Baize
Guide des analyses courantes en pédologie
Publication INRA, Versailles, 1988, 172 p., ISBN 2-7380-0075-4.
Prix : 100,00 FF.
Commandes à : INRA Publications, Route de Saint-Cyr, F-78026 Versailles Cedex, France.

Ce livre, conçu comme un guide pratique, essaie de répondre à la nécessité de rendre plus accessible la Science du Sol aux utilisateurs des analyses pédologiques. Ce n'est donc ni un cours de pédologie générale, ni un traité d'agronomie.

Bien choisir ses analyses et maitriser les modes d'expression des résultats, les interpréter de manière correcte et bien les présenter, telle est l'ambition de cet ouvrage. Ainsi, dans un langage simple et direct, et illustré avec beaucoup d'exemples, l'auteur a pu regrouper dans 20 chapîtres bien délimités les principales analyses pédologiques, commentariant successivement et pour chacune d'elles les principes de la méthode, l'utilité du test et l'interprétation des données obtenues.

Après une introduction générale, ce volume traite successivement le carbone et la matière organique (ch. 4), la perte au feu (ch. 5), la granulométrie (ch. 6, 7 et 8), le calcaire total et actif (ch. 9), le pH (ch. 10), la CEC et les bases échangeables (ch. 11 et 12), le fer, l'aluminium et le manganèse (ch. 13), les analyses chimiques totales (ch. 14), la diffractométrie X (ch. 15), la densité apparente et la porosité (ch. 16), les humidités caractéristiques (ch. 17) et la stabilité structurale (ch. 18). Les chapîtres 19 et 20 sont réservés à la discussion des sols posant des problèmes particuliers et à des remarques finales. Dans les annexes, un certain nombre de données pratiques sur la préparation des échantillons et sur la réconversion des mesures chimiques sont données. Une bonne bibliographie, malheureusement un peu trop limitée aux ouvrages français, et un index alphabétique des matières clôture cet excellent ouvrage.

Ce livre s'adresse à tous ceux qui ont à caractériser ou qui veulent étudier ce que l'on appelle couramment les sols, c'est à dire aux pédologues, qu'ils soient cartographes, chercheurs ou étudiants, aux forestiers, aux agronomes, agro-pédologues et techniciens agricoles. En plus, il peut intéresser les enseignants et tous les spécialistes des disciplines voisines telles que la biologie des sols, la phyto-écologie, la botanique et la géographie physique...

W. VERHEYE

J. Szegi (eds)
Proceedings of the 9th International Symposium on Soil Biology and Conservation of the Biosphere.
Akademiai Kiado, Maison d'édition de l'Académie des Sciences de Hongrie, H-1361 Budapest, P.O.B. 36, 1987, Volume 1 and 2, 945 p., ISBN 963-05-4759-7.
Price : 89.00 US dollars.

These proceedings assemble papers presented at the 9th International Soil Biological symposium organized by the Hungarian Society of Soil Science and held at the Sopron University of Forestry and Timber Industry in August 1985.

The papers are grouped into the following sections : the effect of fertilization on soil biological processes, interaction between pesticides and soil organisms, importance of biological nitrogen fixation in soil fertility, the role of soil organisms in the decomposition and synthesis of organic matter, the role of soil organisms in the soil forming processes, soil organisms and their role in the soil ecosystem, interrelations between soil properties and biological activity and relationships between higher plants and soil organisms.

Throughout the different papers, it becomes clear that the soil is not only a scene of physical and chemical events but also a biotope wherein different biological processes go on. During the symposium several papers covered the relation between fertilization and microbial activity. A lot of attention went into biological nitrogen fixation and microbiological transformations of organic matter. Next to general papers also specific papers were presented on different fixing microorganisms, the influence of fertilization on fixation and several aspects of symbiosis. Formation and decomposition of organic matter in combination with soil respiration, and other soil characteristics was amply covered. A lot of papers discussed the different aspects of the nitrogen cycle and brought them in relation to fertility problems. Research on the use of agrochemicals, especially pesticides, was also presented.

The two volumes are of particular interest to scientists active in soil biology, microbiology, fertility and chemistry. A subject index is provided at the end of part 2.

O. VAN CLEEMPUT

Z. Prusinkiewicz
Multilingual dictionary of forest humus terms.
Panstwowe Wydawnictwo Naukowe, Warszawa, 1988, 195 p., ISBN 83-01-07582-1.
Price : 400 Zlotys (env. 200FB).

Le Professeur Z. Prusinkiewicz nous présente un ouvrage qui peut, vraiment, être qualifié de dictionnaire multilingue. Nous sont proposées, ici, les définitions de quelque 125 termes relatifs aux humus forestiers, en pas moins de sept langues différentes : polonais, russe, anglais, français, allemand, espagnol et suédois, ainsi que la traduction du terme lui-même (sans définition), en tchèque, estonien, hongrois, lettonien, lithuanien, roumain et serbo-croate.

L'idée de départ fut que la terminologie, dans le domaine de l'humus forestier, est l'une des plus confuses de la pédologie et de l'édaphologie. Le but de l'entreprise mise sur pied par le Professeur Prusinkiewicz est de faciliter la compréhension des écrits scientifiques et les discussions lors des rencontres internationales et, d'autre part, d'aider à rapprocher les idées concernant la caractérisation de la matière organique édaphique et la systématique des humus forestiers. En outre, cet ouvrage doit permettre aux pays qui n'en disposent pas encore, de développer leur terminologie propre, aussi proche que possible des conceptions internationales admises.

Pour mener cette tâche à bien, le Professeur Prusinkiewicz s'est entouré, outre ses collaborateurs. immédiats, des avis d'une équipe de quelque trente spécialistes européens où manque, peut-être, l'un ou l'autre "humologue" de la République Fédérale d'Allemagne.

Ce léger reproche ne diminue en rien tout le bien que nous pensons de cet ouvrage qui ne peut que faciliter les contacts entre spécialistes de pays différents. La modicité du prix de ce livre ne peut que nous inciter à encourager nos collègues à en faire l'acquisition.

F. DELECOUR

NN
Agrométéorologie des régions de moyenne montagne.
Les Colloques de l'INRA, vol. 39 (Agrométéorologie), INRA-Versailles, 1987, 443 p., ISBN 2-85340-976-7.
Prix : 220,00 FF.
Commandes à : Service des Publications, CNRA, Route de Saint-Cyr, F-78000 Versailles, France (réf. C039).

Consciente de l'impérieuse nécessité du maintien d'une activité agricole en montagne et du rôle que jouent les conditions climatiques à cet égard la Commission d'Agrométéorologie de l'INRA et la Météorologie Nationale ont jugé nécessaire de faire le point dans ce domaine à l'occasion d'un colloque tenu en avril 1986 à Toulouse. Ce colume constitue le compte rendu des communications présentées à cette occasion.

Cet ouvrage comporte 33 contributions scientifiques, réparties autour de quatre thèmes majeurs. Après une introduction sur les besoins (première partie avec 3 communications) et sur l'inventaire des données climatiques et pédologiques immédiatement disponibles (deuxième partie avec 12 articles), les nouvelles approches permettant d'élargir le contexte de la variabilité topoclimatique en moyenne montagne sont évoquées (troisième partie avec 7 articles). Ceci conduit ultérieurement à l'estimation des potentialités agricoles (quatrième partie avec 11 articles), l'accent étant mis en premier lieu sur les surfaces herbagères.

Pour l'agropédologue en particulier cette dernière partie contient quelques communications intéressantes faisant la liaison entre les facteurs climatiques et la croissance ou la potentialité de production, notamment de la main de M. Lafarge (pp. 287-302) sur les céréales, de M. Duru (pp. 317-333 et 335-349) et A. Mathieu et al. (pp. 351-365) sur les fourrages, et de R. Marocke (pp. 391-406) sur les plantes médicinales.

W. VERHEYE

G.C. Marten, A.G. Matches, R.F. Barnes, R.W. Brougham, R.J. Clements and G.W. Sheath (eds.)
Persistence of forage legumes.
American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison, USA, 1989, 596 p., ISBN 0-89118-089-2.
Price : 19 US dollars (+ 1.90 US dollars per book for postage on all orders outside the US).
Orders to : ASA, CSSA and SSSA Headquarters Office, att. Book Order Dept., 677 South Segoe Road, Madison, WI, 53711 USA.

This volume contains the proceedings fo a trilateral US-Australia-New Zealand workshop held in July 1988 in Hawaii on the problems of poor persistence of forage legumes. The objectives of this meeting were to : (1) document problems of poor forage legume persistence in each country and their economic consequences, (2) review what is known of the constraints to forage legume persistence in each country, (3) exchange information on concepts, methods, approaches and recent advances regarding forage legume persistence, (4) compile, interpret and document pertinent data on persistence of forage legumes, (5) develop a consensus on important gaps in biological information needed to allow modelling of forage legume persistence, and (6) enable scientists in Australia, New Zealand and the United States who are conducting research in this matter to meet and exchange information. Those objectives have been covered in the book by 33 contributions, regrouped into 7 sections and themes.

The first section (4 papers), dealing with an overview of the problems with legumes, is followed by a series of 6 papers on the development and the growth characteristics of legumes. The major edaphic and climatic stress phenomena (4 papers), cultural practices and plant competition (6 papers) and plant-animal interfaces (4 papers) constitute the leading topics for sections 3, 4 and 5. Major pests and diseases (5 papers) and genetics and breeding for persistence (3 papers) cover the remaining chapters.

All papers in this book include a well-documented reference list for further in-depth reading. Ample space has moreover been reserved for discussion topics, both at the level of each individual contribution as at the general discussion per topic as a whole.

Rural land use planners and agronomists, dealing with forage legumes will find in this book interesting and up-to-date information on this particular topic.

W. VERHEYE

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SUMMARY SOMMAIRE INHOUD