

## **5.3 Soil data**

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### **5.3.1 *Soil physical data***

Soil physical data can be obtained from two main sources: field observations and laboratory analyses. The two types of data are complementary. Field data are collected in soil surveys and presented in soil survey reports. Such reports contain descriptions of representative observation sites and soil profiles. Soil profile descriptions specify for each individual layer, or 'horizon', in a soil, the depth of the horizon, its colour, texture, structure, porosity, mottling and foreign inclusions. Two profile descriptions from Sierra Leone are presented in Tables 51 and 52, as examples.

A profile description is thus a field record of observed (and measured) soil characteristics. The information that such a profile description provides is at best semi-quantitative but nonetheless valuable as it is indicative of important physical and chemical soil conditions. Examples are soil texture estimates ('field texture') which are indicative of a score of physical soil parameters – see Tables 16, 17 and 18 – and soil colour estimates, which contain implicit information on the contents and distribution of soil organic matter, oxides, etc. The interpretation of such evidence is not always easy and is best entrusted to a skilled soil scientist with ample local experience.

Profile descriptions are normally supplemented by analyses of soil samples from one or more of the horizons distinguished in the profile description. Such analysis data are always quantitative and reproducible but, here again, data interpretation is not always easy. One difficulty is that the sample material is disturbed and sometimes modified prior to analysis. An example of this is the drying, sieving and decalcification of soil material prior to the determination of its particle size distribution in the laboratory. (This is one reason why field texture estimates do sometimes differ from texture class estimates based on laboratory analysis).

In all cases, soil data are determined on the basis of a limited quantity of soil material. As soils are rarely homogeneous, even accurately determined quantitative data give only an indication of the properties of an entire soil body. An additional difficulty is presented by the translation of soil data into land characteristics, because a tract of land includes normally more than one soil type. This regional variability among soils introduces a need for aggregation of individual soils in soil (map) units. The map unit criteria, and therewith the range and significance of the provided soil information, are commen-

Table 51. Profile description of Profile P9, Masuba, Sierra Leone. Described by R. Miedema and A. A. Thomas on March 20, 1968

Location	Topographic map of Sierra Leone, scale 1:50000, sheet 43, coordinates HE27 <sub>8</sub> -87 <sub>2</sub>		
Physiography	Lower part of streambed near valley edge.		
Relief	Slope 0 to 3 percent		
Vegetation	Farm with cassava, Kandi trees and weeds, and many wild oil palms.		
Drainage	Moderately well drained.		
Parent material	Gravel-free, transported alluvial/colluvial material.		
Hor. code: A <sub>p</sub> Hor. depth: 0-19 cm Lab. No.: S29810	Very dark grayish brown (10YR 3/2); sandy clay loam; weak fine to medium angular blocky; very hard; common macro- and many mesopores; few distinct fine charcoal mottles; many coarse, medium, and fine roots; many large and medium ant holes; clear, smooth boundary to horizon below.		
Hor. code: B <sub>1</sub> Hor. depth: 19-57 cm Lab. No.: S29811	Pale brown (10YR 6/3); sandy clay loam; weak fine to medium angular blocky; very hard; many macro-and mesopores; few distinct fine charcoal mottles; common fine distinct reddish-yellow to strong brown (7.5YR 5.5/8) to red (2.5YR 5/8) iron mottles; common coarse, many medium and fine roots; less than 10% uncoated, nodular, coarse, porous, red, hardened plinthite glaebules <sup>a</sup> , with few quartz grains; many large and medium ant holes; gradual, smooth boundary to horizon below.		
Hor. code: B <sub>2</sub> Hor. depth: 57-170 cm Lab. No.: S29812	Very pale brown (10YR 6.5/3); sandy clay loam; weak fine angular blocky; firm; many macro- and mesopores; many distinct fine and medium yellowish-red (5YR 5/8) and reddish-yellow (7.5YR 6/8) iron mottles; common distinct fine and medium charcoal mottles; few coarse, common medium, and many fine roots, less than 10% gravel, and one quartz stone; common worm holes with dark coatings.		
Soil physical and soil chemical data.			
Classification: 'Plinthic' Udoxic Dystropept			
Horizon code	A <sub>p</sub>	B <sub>1</sub>	B <sub>2</sub>
Depth of horizon (cm)	0-19	19-57	57-170

Table 51. (continued)

Fraction of entire sample	>2 mm (g g <sup>-1</sup> )	0.0009	0.018	0.020
Particle-size distribution	<2 mm (%)			
Total sand	2.0-.05 mm	64.0	59.6	60.4
Total silt	.05-.002 mm	12.6	13.6	13.9
Total clay	<.002 mm	23.4	26.8	25.7
Bulk density (g cm <sup>-3</sup> )		1.1	1.3	1.3
Moisture: SM <sub>333</sub> (cm <sup>3</sup> cm <sup>-3</sup> )		0.16	0.15	0.16
SM <sub>16000</sub> (cm <sup>3</sup> cm <sup>-3</sup> )		0.10	0.10	0.10
Organic carbon (g g <sup>-1</sup> )		0.0125	0.006	0.005
Total P (ppm)		n.d. <sup>b</sup>	n.d.	n.d.
Total CaO (%)		0.133	0.078	0.078
Total Fe <sub>2</sub> O <sub>3</sub> (%)		2.67	3.13	3.18
Total K <sub>2</sub> O (%)		1.361	1.277	1.200
Available K (kg ha <sup>-1</sup> )		67	73	121
P-Bray No. 1 (kg ha <sup>-1</sup> )		9.0	3.4	3.4
C.E.C. (me(100 g) <sup>-1</sup> )		5.71	3.79	3.14
exchangeable Ca me(100 g) <sup>-1</sup>		0.47	0.16	0.21
exchangeable Mg me(100 g) <sup>-1</sup>		0.37	0.16	0.16
exchangeable K me(100 g) <sup>-1</sup>		0.03	0.02	0.01
exchangeable Na me(100 g) <sup>-1</sup>		0.08	0.08	0.08
exchangeable Al me(100 g) <sup>-1</sup>		0.99	1.09	1.05
Base saturation (%)		16.6	11.1	14.6
pH-H <sub>2</sub> O		4.7	4.6	4.8

Source: Odell et al., 1974.

a laterite gravel

b n.d. is not determined

Table 52. Profile description of Profile Kpuabu 1, Manowa, Sierra Leone  
Description after Sivarajasingham.

Location	Kpuabu Cocoa Experiment Station; about 450 feet (137 m) from the Kenema-Joru road on the road to the Station Office, and about 150 feet (46 m) on the right-hand side from the Station Office road.
Physiography	Accordant, flat-topped hill of the dissected lateritic upland.
Relief	Upper, convex 5 percent slope.
Vegetation	Cocoa plantation under many tall trees of original secondary vegetation; good grass cover.

Table 52. (continued)

Drainage	Moderately well drained.
Parent material	A thin layer of gravel-free material over a thick, very gravelly layer of locally transported material.
Hor. code: A <sub>1</sub> Hor. depth: 0-25 cm Lab. No.: S28558	Very dark grayish brown (10YR 3/2); sandy clay loam; moderate medium and fine subangular blocky; porous; friable, slightly sticky, slightly plastic; common fine, few medium, and very few coarse roots; clear, smooth boundary to horizon below.
Hor. code: A <sub>3</sub> Hor. depth: 25-53 cm Lab. No.: S28557	Dark brown (10YR 3/3); very gravelly sandy clay; 70% yellow-coated, nodular, coarse and medium, dense, red and yellow, hardened plinthite glaeboles <sup>a</sup> ; weak fine subangular blocky aggregates with no strong interface; friable, sticky, slightly plastic; few fine and very few medium roots; gradual, smooth boundary to horizon below.
Hor. code: B <sub>21</sub> Hor. depth: 53-89 cm Lab. No.: —	Dark yellowish brown to yellowish brown (10YR 4/4-5/6); very gravelly sandy clay; 60% yellow-coated and uncoated, round, fine, dense, red and black, hardened plinthite glaeboles <sup>a</sup> ; weak fine subangular blocky aggregates with no strong interface; friable, sticky, slightly plastic; very few fine and medium roots; gradual, smooth boundary to horizon below.
Hor. code: B <sub>22t</sub> Hor. depth: 89-178 cm Lab. No.: S28556	Strong brown (7.5YR 5/8); very gravelly clay; 75% yellow-coated, nodular, coarse, dense, red and yellow, hardened plinthite glaeboles <sup>a</sup> ; weak fine subangular blocky aggregates with no strong interface; porous; friable, sticky, slightly plastic; very few fine and medium roots.
Remarks	This soil is very gravelly and droughty and would be expected to be unsuitable for cocoa. The cocoa planted in 1959 appears as stunted trees of very poor health, with many vacant patches because of low survival rate of the planted seedlings. Management is very good, but shade appears to be excessive.

Soil physical and soil chemical data.

Classification: Orthoxic Palehumult (or Typic Umbriorthox)

Table 52. (continued)

Horizon code		A <sub>1</sub>	A <sub>3</sub>	B <sub>22t</sub>
Depth of horizon (cm)		0-25	25-53	89-178
Fraction of entire sample	> 2 mm (g g <sup>-1</sup> )	0	0.70	0.75
Particle-size distribution	< 2 mm (%)			
Total sand	2.0-.05 mm	57.4	49.2	38.9
Total silt	.05-.002 mm	11.8	12.4	13.3
Total clay	<.002 mm	30.8	38.4	47.8
Bulk density (g cm <sup>-3</sup> )		1.2 <sup>c</sup>	1.4	1.5
Moisture: SM <sub>333</sub> (cm <sup>3</sup> cm <sup>-3</sup> )		0.19	0.17	0.22
SM <sub>16000</sub> (cm <sup>3</sup> cm <sup>-3</sup> )		0.13	0.13	0.18
Organic carbon (g g <sup>-1</sup> )		0.027	0.019	0.007
Total P (ppm)		390	370	n.d. <sup>b</sup>
Total CaO (%)		0.076	0.074	0.069
Total Fe <sub>2</sub> O <sub>3</sub> (%)		8.10	8.99	11.19
Total K <sub>2</sub> O (%)		0.169	0.180	0.215
Available K (kg ha <sup>-1</sup> )		10.0	3.4	1.1
P-Bray No. 1 (kg ha <sup>-1</sup> )		5.6	2.2	0
P-Bray No. 2 (kg ha <sup>-1</sup> )		9.0	4.5	2.2
C.E.C. (me(100 g) <sup>-1</sup> )		11.79	9.29	6.00
exchangeable Ca (me(100 g) <sup>-1</sup> )		0.01	0.07	0
exchangeable Mg (me(100 g) <sup>-1</sup> )		0.10	0.08	0.08
exchangeable K (me(100 g) <sup>-1</sup> )		0.10	0.07	0.06
exchangeable Na (me(100 g) <sup>-1</sup> )		0.04	0.05	0.04
exchangeable Al (me(100 g) <sup>-1</sup> )		3.06	2.50	0.67
Base saturation (%)		2.1	2.9	3.0
pH-H <sub>2</sub> O		4.3	4.5	4.8

Source: Odell et al., 1974.

<sup>a</sup> laterite gravel

<sup>b</sup> n.d. is not determined

<sup>c</sup> Estimated

surate with the map scale, which is dictated by the number of observations per unit surface area. In other words: there are detailed soil maps and less detailed ('semi-detailed' and 'reconnaissance') soil maps and the information that can be extracted from a soil survey report depends on the observation density and aggregation level of the soil map units.

The following sequence of taxonomic aggregation levels is widely used in

soil science:

Soil	Orders
Soil	Suborders
Great	Soil Groups
Soil	Subgroups
Soil	Families
Soil	Series
(Soil	Types)

In this hierarchy, soil orders are the least specific with regard to soil properties, soil types are the most specific. At the lowest, most detailed level, soil types are distinguished within soil series on the basis of texture, a single characteristic (USDA, 1975). Most detailed soil surveys define only soil series, without subdivision in types, because a series is commonly already homogeneous with regard to texture. Detailed soil maps and reports describing individual soil series are valuable sources of soil physical and chemical information. Less detailed soil inventories provide less specific information and are consequently less useful for quantitative crop production analysis.

Even if reliable quantitative data are available, they cannot always be used in an indiscriminate way. Much of the soil physical information required for the modelling of a crop's production environment is related to the geometry of the soil matrix and correlated with the matrix texture. Quantitative correlations have been established for standard soils from the Netherlands with a normal mineral composition for Dutch conditions. A different situation may exist in the tropics and this may affect the relation between soil texture and soil physical characteristics. It is also possible that the matrix geometry itself differs from the typical situations studied in the Netherlands. This is the case in compacted soils or in soils with a very loose matrix, in soils with very high organic – matter content or in very gravelly or stony soils. The most important factors that disturb the tabulated relation between matrix texture and soil physical parameters (Tables 17, 18 and 19) will be discussed in the following. When such deviations occur, measured relations and variables must be used instead of tabulated standard values.

### *The relation between matrix geometry and physical soil properties*

#### – The influence of the packing density

Normally, soil is a three – phase system. It is composed of a solid component (minerals and/or soil organic matter), a liquid component (soil moisture) and a gaseous component (soil air):

$$V_t = V_s + V_l + V_g \quad (87)$$

where

- $V_t$  is the sample volume ( $\text{cm}^3$ )
- $V_s$  is the volume of solid soil materials ( $\text{cm}^3$ )
- $V_l$  is the volume of soil moisture ( $\text{cm}^3$ )
- $V_g$  is the volume of soil air ( $\text{cm}^3$ )

The fraction of the soil volume not occupied by the solid phase is the total pore space,  $SM_0$  ( $\text{cm}^3 \text{ cm}^{-3}$ ), which may be expressed as:

$$SM_0 = (V_t - V_s)/V_t \quad (88)$$

The actual value of  $SM_0$  is largely determined by the 'bulk density' (BD, expressed in  $\text{g cm}^{-3}$ ) of the soil material. The bulk density is basically the weight per unit volume of dry soil material:

$$BD = W_t/V_t \quad (89)$$

where

$W_t$  is the dry sample weight (g)

In 'normal' soils, bulk density values vary between 0.9 and 1.5  $\text{g cm}^{-3}$ . The solid component,  $V_s$ , has a weight that is almost identical to  $W_t$ , because the weight of a unit of soil air is negligible when compared with the weight of a similar unit of solid soil material. The weight of one volume unit of the solid component is called the specific density (SD, expressed in  $\text{g cm}^{-3}$ ) of the soil material; it may be expressed as:

$$SD = W_t/V_s \quad (90)$$

Combination of Equations (88), (89) and (90) yields:

$$SM_0 = 1 - BD/SD \quad (91)$$

The overall specific density of composite (i.e. mineral and organic) soil material depends to some extent on the mineral composition of the solid phase, but is much more influenced by the soil organic – matter content. Soil minerals normally have a specific density of approximately 2.60  $\text{g cm}^{-3}$ ; the specific density of organic matter ranges between 1.30 and 1.50  $\text{g cm}^{-3}$ , with a typical value of 1.43  $\text{g cm}^{-3}$ . Consequently, the compounded specific density of an organic matter containing soil material can be approximated by:

$$SD = 1/((1 - O_m)/2.6 + O_m/1.43)$$

or

$$SD = \frac{3.72}{1.43 + 1.17 \times O_m} = \frac{1}{0.38 + 0.31 \times O_m} \quad (92)$$

where

$O_m$  is the weight fraction of organic matter in soil ( $\text{g g}^{-1}$ )

In some soil survey reports, the organic matter content of the soil is expressed as the carbon content of the matrix material ( $C_m$ , expressed in  $\text{g g}^{-1}$ ). As most soil organic matter consists for approximately  $0.55 \text{ g g}^{-1}$  of carbon, the overall specific density can also be established with:

$$SD = \frac{3.72}{1.43 + 2.13 \times C_m} = \frac{1}{0.38 + 0.57 \times C_m} \quad (93)$$

Compression of soil material does not affect SD, but increases BD. Consequently, it lowers  $SM_0$  (Equation 91). Total pore space values, which deviate from values typical for soils within a given texture class, are associated with a – typical hydraulic soil properties ( $k_v - \psi$  and  $SM_v - \psi$  relations) and this directly affects plant performance in situations where water availability to the plant is suboptimal.

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### Exercise 65

Reconstruct the  $SM_0$  values of the three soil horizons distinguished in profile P9 (Table 51).

Compare the calculated  $SM_0$  values with the indicative  $SM_0$  value for sandy clayloam as tabulated in Table 16 (Section 3.2).

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#### – High soil organic matter contents

Equation 92 demonstrates that the presence of soil organic matter decreases the overall specific density of soil material. However, it lowers the bulk density even more, because organic matter cements individual soil particles together to form loosely structured aggregates. The overall result of organic – matter accumulation in a soil is therefore generally an increase in total pore space. The quantity of organic matter in a soil is determined by the supply rate of plant litter and by the rate at which this litter is decomposed by soil organisms. Equilibrium between supply and decomposition of organic material may be approached in soils under a natural vegetation cover and in agricultural soils long cultivated under steady management. High organic – matter



contents build up where the decomposition of organic material is reduced by factors that hamper or preclude the activity of soil organisms, such as low soil temperature, low soil pH, prolonged periods of waterlogging or the formation of toxins or compounds with a high resistance to microbial attack. In general, tabulated soil physical parameters cannot be applied if organic carbon contents exceed  $0.04 \text{ kg kg}^{-1}$  in more than one – third of the rootable surface soil.

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### Exercise 66

Explain why the upper 19 cm layer of soil profile P9 has a lower BD and higher  $SM_0$  than the two subsurface horizons of this profile.

The bulk density of high moor peats varies commonly between  $0.05$  and  $0.15 \text{ g cm}^{-3}$ ; the mineral content of such peats is low, say between  $0.01$  and  $0.05 \text{ g g}^{-1}$ . Calculate  $V_s$  of such peats.

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#### – Dominance of swelling and shrinking clay minerals

Certain types of clay minerals, known as ‘smectite’ clays, shrink in volume upon drying. This causes the formation of deep soil cracks during droughts. The clays swell again in a subsequent wet period, which results in the destruction of voids and pores. Smectite – rich ‘Vertisols’, also known as ‘Regur’ or ‘Black Cotton Soils’, are notorious in this respect. Drying of their topsoil causes the formation of a thin granular surface layer of hard clay aggregates on top of dense (BD around  $1.55 \text{ g cm}^{-3}$ ) polygonal structures, separated by deep, wide cracks. Swelling of the clays in wet periods causes smearing of the surface soil during tillage and shearing phenomena at some depth. Clearly, this affects  $SM_\psi - \psi$  and  $k_\psi - \psi$  relations. The mathematical description of the water regime of Vertisols is therefore virtually impossible.

#### – High contents of sesquioxides in the clay fraction

Many genetically old, red and yellow soils in the humid tropics have a clay fraction ( $< 0.002 \text{ mm}$ ) dominated by aluminium oxides and iron oxides (‘sesquioxides’). Such soils are classified as ‘Oxisols’ or bear a name in which the prefix ‘ox’ occurs. Profile P9, classified as a ‘Plinthic Udoxic Dystropept’, is an example of such a soil rich in sesquioxides (Table 51). The oxides cement individual clay particles together to stable sand – sized aggregates that have fine pores inside. In the low suction range, these fine pores remain filled with water and do not influence the  $SM_\psi - \psi$  relation, which resembles that of a sand. In the high suction range, coarse soil pores are all empty. A normal sand with solid particles has then lost virtually all of its water because very few fine pores occur between the coarse sand grains. A cemented Oxisol, however, has fine pores inside the cemented aggregates. This explains why its  $SM_\psi - \psi$  relation resembles that of a loam soil in the high suction range. Soils high in

sesquioxides have typically compound  $SM_{\psi} - \psi$  relations; in water – balance calculations for Oxisols one has to approximate the required  $SM_{\psi} - \psi$  combinations by linear interpolation between measured values.

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### Exercise 67

Calculate  $SM_{333}$  and  $SM_{16000}$  for a sandy clay loam (use Equation 27 and Table 16; Section 3.2). Compare the calculated values with values measured for profile P9 (Table 51).

Calculate  $SM_{333}$  for profile P9, using  $SM_0$  as calculated in Exercise 65 and  $\gamma = 0.035 \text{ cm}^{-2}$  (a value appropriate for medium coarse sand). Compare the result with the measured  $SM_{333}$  value (Table 51).

Calculate  $SM_{16000}$  for profile P9, using  $SM_0$  as calculated in Exercise 65 and  $\gamma = 0.017 \text{ cm}^{-2}$  (a value appropriate for loam soils). Compare the result with the measured  $SM_{16000}$  value (Table 51).

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#### – Slaking soils

A low structure stability of the uppermost soil layer may lead in some soils to dispersion of the individual soil particles in times of excessive wetness and to subsequent formation of a hard surface crust upon drying. This phenomenon is known as ‘slaking’ of the soil; it is associated with clogging of pores and it lowers the infiltration capacity and surface storage capacity of water. Slaking is particularly prominent in fine sandy soils that are low in organic matter and calcium. Slaking is aggravated by unnecessary tillage operations, which enhance the destruction of aggregates and intensify the breakdown of soil organic matter.

#### – Gravelly and stony soils

Soil texture determinations – both in the laboratory and in the field – disregard the presence of any component with a diameter in excess of 2 mm. In some soils, such inclusions make up a considerable part of the matrix. The presence of gravel reduces the volume of soil material that can be explored by the roots and consequently the quantity of water that the soil can supply to a crop. Normally, gravel contents are estimated in the field and expressed as a fraction of the volume of each soil horizon. An example is the soil description of profile Kpuabu 1, presented in Table 52. In some cases, gravel contents are determined in the laboratory. This is the case for soils in which gravel contents are low and cannot be estimated in the field with any measure of accuracy. In that case, gravel is separated from the sample material by sieving and is subsequently weighed. The gravel content is then often expressed as a weight fraction (i.e. in  $\text{g g}^{-1}$ ); profile P9, presented in Table 52, is an example. Weight fractions are easily converted to volume fractions (i.e. in  $\text{cm}^3 \text{ cm}^{-3}$ ) by multi-

plying the weight fraction by BD/SD (cf. Equation 91). Clearly the quantity of ultimately available water in the soil ( $W_a$ , see Equation 52 in Section 3.2) is affected if the rooted surface soil contains gravel. A soil which contains a fraction 'X'  $\text{cm}^3 \text{cm}^{-3}$  of gravel contains only  $(1 - X) \cdot W_a$  cm available water. As a consequence, water shortage develops more rapidly on gravelly soils than on similar soils without gravel. This statement is illustrated by a remark on the description form of profile Kpuabu 1, a gravelly soil in the Manowa Series, Sierra Leone (Table 52).

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### Exercise 68

Calculate SD and  $SM_0$  for the analysed horizons of profile Kpuabu 1, Table 52. Use Equations 93 and 91.

Approximate for each of the analysed horizons a value of  $\gamma$  that applies under conditions of low suction. Use the equation

$$SM_{333} = SM_0 \cdot e^{-\gamma \times (\ln 333)^2}, \text{ or } \gamma = 0.03 \cdot \ln(SM_0/SM_{333})$$

Calculate  $SM_{100}$  for each horizon with the low suction  $\gamma$  and  $SM_0$  values established. Use Equation 27.

Calculate the fraction of ultimately available water contained in each horizon ( $= SM_{100} - SM_{16000}$ ).

Convert fraction to cm (multiply each fraction by the depth of the horizon in cm).

Correct for the presence of gravel in each horizon.

Calculate the quantity of ultimately available water in the upper 178 cm of soil (assume that horizon B21 has 2.8 cm available water, before correction for gravel, and a gravel content of  $0.6 \text{ cm}^3 \text{cm}^{-3}$ ).

Calculate the quantity of water that would have been available to the crop if the soil contained no gravel.

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### *Soil morphological indicators*

Detailed examination of a soil profile can produce valuable information on soil rootability, homogeneity and water regime. Although it requires much experience to benefit fully from the interpretation of soil morphology, some profile characteristics are rather straightforward reflections of important soil physical conditions. A few morphological clues to maximum and minimum groundwater depths over the year, to past rooting depths and to the intensity of biological soil homogenization will be discussed briefly.

#### – Iron mottling and water table fluctuation

Most soils contain iron, originating from rock weathering or from influx

from outside. Depending on the aeration status of the soil material, iron ions occur in a trivalent ( $\text{Fe}^{3+}$ , 'ferric') or in a bivalent ( $\text{Fe}^{2+}$ , 'ferrous') form. Well aerated soil layers contain ferric oxides ('rust') which are stable and immobile as long as oxidized conditions persist. However, under conditions of prolonged water saturation of the soil, ferric ions are transformed to ferrous ions, which are easily transported with moving water. This ferrous iron is reconver-  
 ted to the immobile ferric form near air – filled pockets in the otherwise reduced soil mass. Thus, accumulation of iron oxides takes place at these places and this shows up as red, brown or yellow rust mottling. The abundance, size, colour, shape and contrast of these mottles are indications of the intensity of groundwater – table fluctuations in the past. For our purposes a few rules suffice:

- In subsoil horizons which are permanently below groundwater, rust mottling is completely absent and matrix colours are commonly greyish.
- Surface horizons that are not saturated commonly have reddish or brownish matrix colours, witnessing evenly distributed ferric oxides. (Organic matter accumulation may cause dark brown colours but there are no signs of iron redistribution).
- Distinct iron mottling indicates the zone of past groundwater – table fluctuations. (A groundwater table shallower than a few metres at the time of the soil examination is recorded in the profile description).

### Exercise 69

Check the profile descriptions of profiles P9 and Kpuabu 1 for depth and abundance of reddish mottles. Which one of these two profiles has the deeper groundwater table?

Figure 53 presents the groundwater table level in P9 during the second half of 1968. Are the groundwater table depths recorded in that period exceptional?

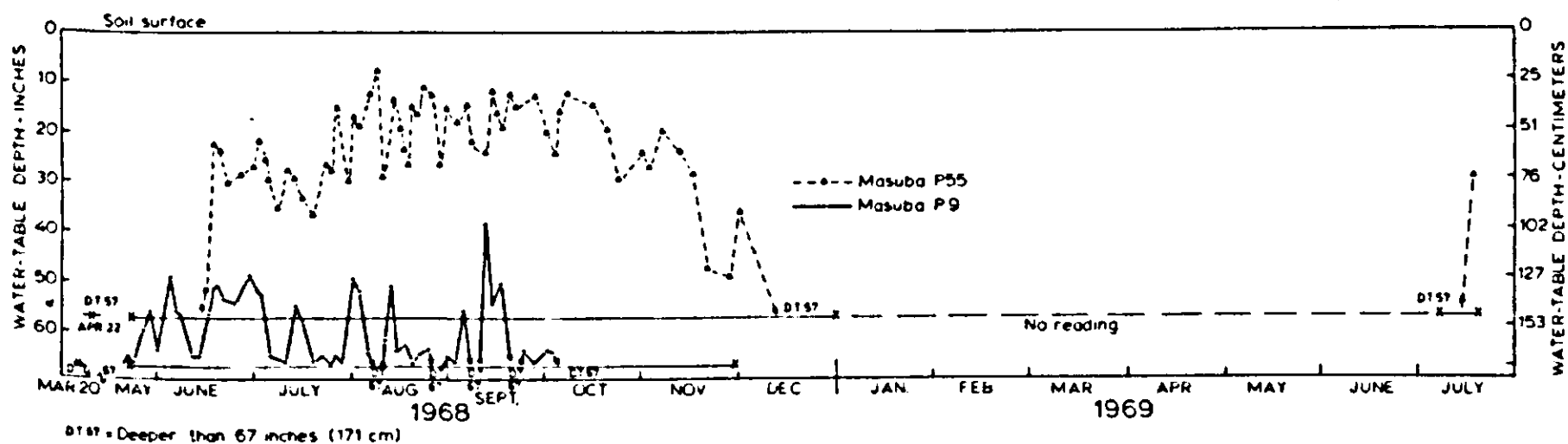


Figure 53. Water table fluctuations at site Masuba P9 during the second half of 1968. (Source: van Vuure & Miedema, 1973)

– Depth of undisturbed subsoil and root prints

Surface soil homogeneity is an important assumption in the crop production model presented here. This condition may result from deep weathering of homogeneous parent rock or from prolonged sedimentation in a stable environment. More commonly, however, soil homogeneity results from biological mixing of the surface soil by the soil fauna and plant roots. The depth and intensity of homogenization processes can be inferred from soil descriptions.

Soils that are intensively homogenized by biological activity lack abrupt horizon boundaries and have a comparatively uniform matrix texture throughout the root zone. A well homogenized surface soil is porous with many ‘macropores’ and ‘mesopores’, as a result of the activity of small organisms, and is perforated by worm holes, ant holes, etc. Plant roots also contribute to the biological mixing of soil material. When roots die, they desintegrate and leave voids in the soil matrix. Dark coloured surface soil material often leaches to deeper strata along these former root channels. Under wet conditions, the channels act as air ducts bringing atmospheric oxygen to the poorly aerated subsoil. Transformation of soluble ferrous iron to ferric oxides can then produce a reddish lining of rust along the channel walls which become visible as ‘root prints’. The number and size distribution of root prints in a soil reflect the intensity of root activity in the past. Where biopores and root prints are absent, the soil is called ‘undisturbed’. If the upper boundary of the undisturbed subsoil is deeper than approximately one metre below soil surface and evidence of surface soil homogenization is clear, it is not to be expected that the root activity of crops will meet any mechanical impediment. Absolute criteria for the degree of soil homogenization cannot be given because soil homogeneity depends not only on the intensity of mixing but also on the uniformity and stratification of its parent material, which is a geological datum.

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**Exercise 70**

Check the profile descriptions of profiles P9 and Kpuabu 1 for depth and abundance of roots. Pay also attention to evidence of ant and worm activity. Is rooting impeded in any of the two soils?  
In which of the two soils is biological soil homogenization more intense?

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**5.3.2 Soil chemical data**

Chemical analysis of soil samples is a routine part of the study of soils and of soil suitability for agricultural use. Chemical analyses are particularly needed to establish the approximate fertility status of the soil. For that purpose, the following issues must be dealt with:

- what are the total quantities of plant nutrients in the soil?
- to what extent are these nutrients available for uptake by plants?
- what is the capacity of the soil to temporarily store nutrients for later release to the soil solution and then to the crop?
- are there soil chemical anomalies that hamper crop production?

Soil chemical data as such are of very limited value. In association with measured plant performance they gain significance, but reliable and generally applicable correlations between soil chemical data and crop production cannot be expected. Exogenous conditions that differ each year (e.g. the weather) obscure such correlations and allow at best the identification of generally safe ranges in the chemical status of the soil. Outside these ranges, plants are exposed to either nutrient deficiency or to excess levels of elements in the soil solution, which have a toxic effect on crops.

In this subsection those soil chemical data will be discussed that are routinely collected for soil profiles representing the major soils of important land units. The significance of soil chemical data as indicators of nutritional disorders will be explained to identify soil chemical constraints on plant production in a number of situations.

### *Total element contents*

The determination of total element contents helps to indicate structural nutrient deficiency (e.g. in mineralogically poor soils or in exploited and chemically exhausted soils) but supplies no information on the exact quantities of nutrients that crops can actually take up from the soil. Total nutrient contents are normally determined after digestion of a soil sample with a strong agent such as nitric or perchloric acid. Modern analysis techniques, e.g. X-ray spectroscopy, permit non-destructive determination of total element contents. In view of the limited significance of total element data for practical agriculture, this subject will not be treated any further.

### **Exercise 71**

Calculate the total quantity of phosphorus (P, expressed in  $\text{kg ha}^{-1}$ ) contained in the upper 53 cm of soil profile Kpuabu 1, Sierra Leone. For soil chemical data and BD values of this profile see Table 52.

Repeat the calculations for potassium (K, expressed in  $\text{kg ha}^{-1}$ ).

Note: 1 kg  $\text{K}_2\text{O}$  is equivalent to 0.83 kg K.

### *Contents of 'available' nutrients*

Only a limited part of all nutrients in a soil can actually be taken up by crops in the course of one growth cycle. The other part is lost or tied up in minerals and/or in stable organic and organo-mineral compounds and beco-

mes available to plant roots only after weathering or biochemical decomposition of organic structures ('mineralization'). Soil fertility specialists have long tried to find extraction agents that mimic the action of plant roots. Such agents should remove available nutrients from the soil while leaving the unavailable fraction untouched. Their quest has not been entirely unsuccessful. Many 'mild' (i.e. weakly acid or alkaline) agents have been identified, which give, under specific conditions, a reasonable correlation between element extraction from a soil and total contents of the same element in the tissue of plants grown on that soil. An extractant that reflects nutrient availability to any crop under all conditions does not exist, because the demand of a crop for nutrients and its competitive position relative to other consumers is partly dependent on exogenous factors. In practice, preference for the use of a certain extractant is based on local experience. Extractants that are often used are listed in Table 53. As this table suggests, there are no extractants for estimating the availability of nitrogen in soils.

Sections 4.1 and 4.2 contain the implicit information that there is inorganic nitrogen in the plant – soil – atmosphere system, e.g. fertilizer N, as well as organic nitrogen, incorporated in soil organic matter and in soil micro – organisms. Nitrogen losses through leaching, denitrification or volatilization act mainly on nitrogen in its inorganic form. Organic nitrogen is largely responsible for the N status of unfertilized soils; it becomes available for uptake by plants through mineralization during decomposition of the organic matter. The quantity of nitrogen that is mineralized from the organic structures in the course of decomposition is a function of the quantity of carbon used by soil micro – organisms to support their metabolic activities (Bouldin et al., 1980). This is the reason that in some soil survey reports the C/N ratio of the soil organic matter is specified in addition to the organic matter or organic carbon content. A C/N ratio lower than 15 indicates a situation in which decomposition of soil organic matter yields appreciable quantities of mineral nitrogen; a

Table 53. Some common extractants used for the determination of available phosphorus or potassium.

Element extracted	Name of extractant	Chemical composition of extractant
P	Bray No. 1	0.03 N $\text{NH}_4\text{F}$ + 0.025 N HCl
P	Bray No. 2	0.03 N $\text{NH}_4\text{F}$ + 0.01 N HCl
P	Truog	0.002 N $\text{H}_2\text{SO}_4$ (pH 4.8)
P	Olsen	0.05 N $\text{NaHCO}_3$ (pH 8.5)
P	Modified Olsen	0.5 N $\text{NaHCO}_3$ + 0.5 N $\text{NH}_4\text{F}$ (pH 8.5)
K	—	23% $\text{NaNO}_3$
K	—	1 N $\text{NH}_4$ — acetate

(Sources: Dabin, 1980; Odell et al., 1974)



high C/N ratio of 30 or more is indicative of low nitrogen levels in unfertilized soils.

In many traditional agricultural systems an equilibrium situation exists in which inputs of nitrogen equal losses by crop removal, denitrification, leaching, etc. In such situations, the quantity of nitrogen furnished by natural soil fertility can be reliably estimated with the procedures presented in Sections 4.1 and 4.2. However, when this equilibrium is disturbed, e.g. by a change in management system, a non-steady state occurs in which the soil organic-nitrogen content changes towards a new equilibrium level. This involves changes in the rates of decomposition and resynthesis of soil organic matter. Both these processes are extremely complicated and depend on quantity and composition of the organic matter in the soil and also on environmental conditions such as soil moisture content, soil pH and soil temperature. Consequently, there are no generally valid guidelines for estimating, by tests on soil samples, the ability of soil organic matter to supply nitrogen to plants.

Available phosphorus in the soil originates from weathering rock, dissolving phosphorus compounds and also from the organic soil component, but the latter plays a less prominent role than in the case of nitrogen. Tropical soils at an advanced degree of development have lost most of their weatherable minerals and have therefore a high probability to be structurally low in phosphorus. However, P deficiency is also widespread in younger soils because dissolved phosphorus may be inactivated by the solid soil phase (phosphorus fixation), precipitate as an insoluble phosphate or be (temporarily) tied up in microbial bodies. Dabin (1980) quotes a study by Roche et al. (1978), indicating that the phosphorus fixation capacity of 140 soils from 20 different countries correlated with the contents of clay and fine silt ( $r = 0.51$ ), organic matter ( $r = 0.7$ ), total aluminium ( $r = 0.63$ ), 'exchangeable' aluminium ( $r = 0.86$ ), and total iron ( $r = 0.55$ ), all significant at the 0.1% level. With so many variables involved (and there are more!), it is to be expected that the correlation between extractable phosphorus and phosphorus taken up by a crop varies among soils and extractants. In other words, different extractants give different results and locally established correlations are not transferable to other areas. In many countries, Olsen-type extractants are preferred for the determination of phosphorus availability; soil fertility specialists in Sierra Leone (Tables 51 and 52) use Bray No. 1 and/or Bray No. 2. Table 54 illustrates the limited significance of 'available P' - figures without thorough local experience. The table presents the phosphorus uptake by rice from a number of important soil series in Thailand, and 'available P' in these soils obtained with different extractants (Puh & Khunathai, 1971).

The difficulty in interpreting such values is increased by the necessity to judge the availability of phosphorus in relation to the contents of other essential elements, because crop response to the presence of a specific nutrient in the soil depends very much on the balance or imbalance of the total nutrient supply (Section 4.1). Dabin (1980) states that the critical values of extractable



**Table 54. Phosphorus uptake by rice and available phosphorus (ppm) by four methods**

Soil Series Code	P content of control plants (mg P per pot)	Bray No. 1	Bray No. 2	Truog	Olsen
Bn (1)	59	6.6	9.0	2.7	7.3
Bn (2)	40	1.2	6.0	0.9	8.0
Db	65	3.0	6.9	5.4	4.6
Sb (1)	176	6.1	12.8	6.9	9.9
Cn	143	2.3	8.8	3.6	13.1
Ok (1)	4	2.8	7.8	2.2	3.3
Sm	88	0.6	9.0	3.3	5.8
Np (1)	119	3.8	16.0	5.4	12.2
Hd	56	2.3	7.2	5.1	5.5
Re (1)	33	4.2	8.5	2.2	6.2
Bn (3)	222	4.4	21.8	9.1	8.4
Rs	52	7.1	26.0	5.8	2.9
Ok (2)	68	10.7	29.5	9.1	6.6
Sb (2)	49	3.3	8.4	2.9	3.2
Re (2)	135	9.2	11.9	2.9	3.6
Ub	47	8.2	8.8	1.0	1.6
Lp	63	5.3	7.3	2.9	2.3
Np (2)	135	7.5	13.8	3.5	3.2
Pb	93	15.7	53.2	11.3	9.6
Bk	—	4.7	5.9	2.9	2.5

Source: Puh & Khunathai, 1971.

soil P are co – determined by the soil's total nitrogen content. For modified Olsen P he gives the following empirical rule: for soils with average to low fixation capacity of phosphorus (i.e. roughly Class I and the upper half of Class II in Table 47), the critical phosphorus level is estimated at 0.025 times the total nitrogen content. For soils with a moderate to high fixation capacity (lower half of Class II in Table 47) that level can be twice as high and in the case of soils with very high phosphorus immobilization capacity the level can be increased even further.

Phosphorus immobilization is particularly prominent in certain young volcanic soils with a high content of hydrated iron and aluminium oxides in the clay fraction ('allophane' – rich soils) and is also widespread in old reddish and yellowish tropical soils with a high sesquioxide content. As explained in Subsection 5.3.1, the profiles Masuba P9 and Kpuabu 1 from Sierra Leone (Tables 51 and 52) are examples of such soils, which formed as a result of progressive weathering of rock in the absence of rejuvenation through mineral influx from elsewhere.

Immobilization of potassium also occurs, but the process is different from

phosphorus fixation. In the case of potassium, the ions are incorporated in the lattice of certain clay minerals. Many crops take up similar quantities of potassium and of nitrogen, particularly root and tuber crops and many vegetables and fruits. Soil potassium originates from weathering clay minerals (biotite, hydrous mica, illite) and – at a much slower rate – from the breakdown of feldspar and mica. Flood water or irrigation water is another source of K. Many weathered tropical soils, such as quartzitic sands and red or yellow residual soils on geologically old parent rock, are structurally deficient in potassium. Immobilization of potassium by clay minerals with a high selectivity for potassium can be of importance to practical agriculture. Mitra et al. (1958) working with pure clays from India found that the clay minerals bentonite and illite fixed some  $4 \text{ mg K g}^{-1}$ . The most common clay mineral in tropical soils, kaolinite, fixed only some  $0.13 \text{ mg K g}^{-1}$ . This, and the fact that the K – fixation capacity is lower in acid soils than in neutral or alkaline soils, explains why potassium fixation is less prominent – and less well researched – in tropical soils than in certain soils in temperate regions. Data by Kemmler (1980) suggest that available potassium levels are ‘low’ where extraction with 1 N ammonium acetate removes less than  $6 \text{ mg K}$  per 100 g soil material.

‘Minor elements’ such as calcium and magnesium, and/or ‘trace elements’, such as copper, zinc and manganese, are often in short supply in old, leached tropical soils. Calcium deficiency is associated with soil acidity ( $\text{pH} < 5$ ); application of lime (Ca) or ground magnesium limestone (Ca, Mg) remedies the situation. Sulfur deficiency also occurs, but published information indicates no association between sulfur deficiency and soil or climatic factors that would be useful in predicting areas of likely deficiency (Blair et al., 1980).

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### Exercise 72

Compare the total quantity of phosphorus contained in the upper 53 cm of profile Kpuabu 1 (Exercise 71 and Table 52) with the quantity of available P extracted with Bray No. 1. Can you explain the difference?

Suppose that 3000 kg of rice grain was to be produced on a soil like Kpuabu 1. Would P fertilization be necessary? Explain your answer. (Recall that the slope of the yield – uptake curve is 50 to 70 kg grain per kg N and the P/N ratio in the tissue is around 0.1 under balanced supply).

Is there a need for K – fertilizers on Kpuabu 1? Explain your answer.

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### *Ion adsorption in soils*

Plants take up nutrients from the soil solution which is essentially a low concentration solution of a mixture of ions. This ‘soil solution’ would be rapidly exhausted if ions, taken up by the crop, were not replenished. Fortunately, most soils have a capacity to maintain a stock of positive ions (cations)

adsorbed at the negatively charged surfaces of solid soil particles (both mineral particles, particularly in the clay fraction and organic matter). The most important cations in this respect are Ca, Mg, K, Na and H. These ions enter the soil solution if the existing equilibrium between the concentration of a certain ion in the soil solution and the quantity adsorbed at the 'exchange complex' of the soil is disturbed, e.g. through nutrient removal by plant roots. A new equilibrium will then be established. The reverse also applies: an increase in the concentration of a certain ion in the soil solution induces adsorption of that ion at the exchange complex. This implies that cations added to the soil, for instance with fertilizers, are not necessarily lost if not instantly taken up by a crop, because part of the ions become available over a longer period via a process of exchange between the exchange complex and the soil solution. The capacity of a soil to adsorb cations depends mainly on the surface properties of the solid soil particles, notably their specific surface (i.e. the total surface area per unit weight of soil) and the electric charge per unit surface area. Finely textured (clay) soils have a high specific surface and therefore a higher cation exchange capacity — 'C.E.C.', expressed in milli — equivalents per 100 g soil — than coarser — textured soils. The mineralogical composition of the solid soil phase is also of influence because clay minerals vary in their surface charge. Table 55 presents typical values for the specific surface and C.E.C. of some common solid phase components. It shows that soil organic matter has a comparatively high cation exchange capacity, therefore the overall C.E.C. of soil material is often higher in the organic matter containing surface horizon than lower in the profile.

The cation exchange complex plays an important role in the determination of soil acidity, i.e. the concentration of hydrogen ions in the soil solution. Often in field situations, a substantial part of the exchange complex may be occupied by hydrogen ions, even at relatively low concentrations of that element in the soil solution, because these ions are adsorbed preferentially. This

Table 55. Specific surface area and C.E.C. of selected solid phase components.

	surface area (m <sup>2</sup> g <sup>-1</sup> )	C.E.C. me (100 g) <sup>-1</sup>
Clay minerals:		
kaolinite	10-20	1-10
montmorillonite	600-800	80-120
vermiculite	600-800	120-150
mica	70-120	20-40
chlorite	70-150	20-40
allophane	70-300	10-150
Soil organic matter	800-900	100-300

(Source: Bohn et al., 1979).

preferential adsorption is on the one hand associated with replacement of Al and Mg ions in the clay minerals by H ions, and on the other hand with the surface properties of the soil organic matter. The result of these processes is that soils exhibit an extended buffering range, i.e. addition of relatively large amounts of H ions will only slightly increase their concentration in the soil solution. Hence, the pH (defined as  $-\log(\text{concentration H}^+ \text{ ions})$ ) will only decrease very little. On the other hand, if the soil has a low pH value, and thus a high concentration of H ions in the soil solution, considerable quantities of a competitive cation, such as calcium, may be necessary to increase the pH. That quantity expressed in kilograms of CaO required to change pH by 0.1 unit is referred to as the 'liming factor'.

To characterize soils with respect to the composition of the adsorbed ions, the sum of adsorbed calcium, magnesium, potassium and sodium – in me per 100 g soil – expressed as a fraction of the total exchange capacity of the soil, is defined as the soil's 'base saturation'. A low base saturation, i.e. less than 0.4 is typical for most cultivated soils in the tropics. The remainder of the exchange complex is occupied by such ions as hydrogen, aluminium, iron, etc.

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### Exercise 73

Approximate the C.E.C. of the mineral soil material in the surface horizon of Kpuabu 1 (Table 52). Assume that the soil organic matter has a C.E.C. of 100 me per 100 g; and recall that an organic matter content of  $0.01 \text{ kg kg}^{-1}$  corresponds with an organic carbon content of  $0.0055 \text{ kg kg}^{-1}$ .

Is the presence of organic matter in the surface soil of Kpuabu 1 important for the supply of nutrients to a crop? Explain your answer.

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### *Element toxicities*

Element toxicity occurs if elements have accumulated in the soil in quantities that are noxious to plants. However, toxic effects can also occur at low absolute element concentrations if the soil solution is dominated by one or only a few elements and, consequently, ion supply to the roots is grossly imbalanced.

Accumulation of high levels of salts in (surface) soils may occur in arid and semi-arid regions, where a distinct evaporation surplus is associated with a predominantly upward movement of soil solution and ions. When this soil moisture evaporates, soluble salts accumulate on top of the soil or in the rooted surface horizons and hamper root activity: the soil has become saline. The degree of soil salinity is established by measuring the electrical resistance of a water-saturated soil paste. The inverse value of electrical resistance is the electrical conductivity ( $EC_e$ , expressed in  $S \text{ cm}^{-1}$ , S standing for Siemens). Normal plant growth is inhibited at conductivity values in excess of  $16 \times 10^{-3}$

$\text{S cm}^{-1}$ , corresponding to a salt concentration in the soil of approximately  $0.01 \text{ kg kg}^{-1}$ . Salt damage becomes apparent already at much lower electrical conductivity values ( $\text{EC}_e \geq 4 \times 10^{-3} \text{ S cm}^{-1}$ ). Salt accumulation can be remedied by leaching of the soil with fresh water. The harmful effects of salts in the root zone gain prominence if the accumulated cations are dominated by sodium ('saline-alkali soils'). Salt accumulation outside arid or semi-arid regions is usually limited to low-lying coastal areas subject to saline seepage or to periodic inundation with saline or brackish water.

Element toxicity at low salt levels in the soil solution is widespread in acid ( $\text{pH} < 5$ ) soils in the humid tropics. Soil acidity, associated with high levels of hydrogen ions in the soil solution, hampers crop growth directly, but it is often more harmful because it results in the formation of toxic levels of aluminium and/or manganese in the soil. Accumulation of aluminium ions is particularly harmful: crop production is affected already at low levels of aluminium and is drastically reduced when aluminium occupies more than two-thirds of the exchange complex. Aluminium poisoning is most prominent on dry land; it rarely occurs where wetland rice is grown, with the exception of certain acidifying soils in coastal areas ('Acid Sulphate Soils'). Wet-

Table 56. Criteria for the recognition of some important constraining soil chemical conditions.

Poor parent material/ leaching of cations	$<7 \text{ me cations/100 g soil material in 1N ammonium acetate extractant at pH 7.0 (C.E.C. } <7 \text{ me/100 g)}$
N deficiency	Widespread agronomic evidence of nitrogen deficiency in principal crops. No quantitative soil definition
P deficiency associated immobilization	Top soil clay fraction dominated by allophane (X-ray amorphous), or $>20\%$ of clay fraction as Fe and Al oxides and $>30\%$ clay in topsoil, or $\text{pH} < 7.3$ , or fizzing of soil material with HCl (= presence of free $\text{CaCO}_3$ )
K deficiency	$<0.6 \text{ mg K per 100 g soil in top 50 cm.}$
Deficiency of other nutrients	Soil test values below critical levels for main crops
Al toxicity	$>67\%$ Al saturation of C.E.C. in top 50 cm or $\text{pH} < 5.0$
Mn toxicity	$<100 \text{ ppm acid extractable Mn in top 50 cm.}$
Fe toxicity	$>300 \text{ ppm ferrous iron in topsoil.}$
Salinity	$\text{EC}_e > 4 \times 10^{-3} \text{ mS cm}^{-1}$ in top 50 cm.
Alkalinity	$>15\%$ Na-saturation of C.E.C. in top 50 cm.
Acid sulphate soil conditions	pH drops to values $< 3.5$ upon drying of soil material.

Source: Buol et al., 1974; Sanchez and Cochrane, 1980.

land rice is known to suffer from excess organic acids or hydrogen sulphide but such damage is comparatively rare. More common is damage to wetland rice by toxic levels of ferrous iron. The mechanism of iron accumulation in intermittently wet soils has been outlined in Subsection 5.3.1. Iron poisoning occurs when rice on flooded land is exposed to a soil pH lower than 6.5 and a dissolved iron content in excess of 300 ppm (Moormann & van Breemen, 1978). In soils with low nutrient levels, especially P and K, an iron content as low as 30 ppm may even be toxic. Table 56 summarizes indicative criteria for the most common chemical soil disorders.

### *Popular misconceptions in soil chemical analysis*

Although chemical soil analysis is a practice of long standing, it suffers from a number of persistent imperfections that complicate the interpretation of analysis results. Those shortcomings, which pertain to the routinely collected soil chemical data discussed in this subsection will be mentioned here:

- Soil chemical data are traditionally expressed on a weight basis, e.g. as percentage, ppm or me per 100 g. Such data give no information on the quantities of nutrients (in  $\text{kg ha}^{-1}$ ) present in the rooted soil volume. It is therefore essential that bulk density values (which vary by a factor of almost two, viz. between  $0.85$  and  $1.55 \text{ g cm}^{-3}$ , in mineral soils) are specified with the element concentrations. Unfortunately, this is rarely the case. An extreme example may demonstrate the possible implications of this omission. Peat soils are generally considered high in nitrogen with a typical nitrogen concentration between  $0.01$  and  $0.02 \text{ kg kg}^{-1}$ . However, a normal peat soil with a bulk density of  $0.20 \text{ g cm}^{-3}$  and a nitrogen concentration of  $0.02 \text{ kg kg}^{-1}$  has a total nitrogen content of  $4000 \text{ kg ha}^{-1}$  in its upper 10 cm layer, whereas a mineral surface horizon with a nitrogen concentration of only  $0.005 \text{ kg kg}^{-1}$ , but a bulk density of  $1.5 \text{ g cm}^{-3}$ , has a total nitrogen content of  $7500 \text{ kg ha}^{-1}$ . In spite of the seemingly high N concentration, nitrogen deficiency is quite common on peat soils. For that reason analysis results should be presented on a weight – per – unit – volume basis. (Driesen, 1978).
- The stoniness of a soil must be specified if critical element levels (Table 56), defined to indicate deficiencies or toxicities of elements, are to be useful. This is rarely done in routine soil analysis.
- Cation – exchange capacity is traditionally determined by measuring the ammonium retention of an aliquot of soil in a neutral ammonium acetate solution (buffered to pH 7.0). However, the surface charge of organic matter and of some clay minerals (notably kaolinite, chlorite and allophane, see Table 55) is strongly pH dependent. As field pH is normally lower than 7, the actual exchange capacity of tropical soils is often lower than suggested by chemical analysis data. Only C.E.C. data determined at field pH would allow a meaningful comparison of soils with regard to exchange capacity and base status.

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**Exercise 74**

Deeper than 25 cm below soil surface, Profile Kpuabu 1 (Table 52) has a gravel content of more than  $0.7 \text{ kg kg}^{-1}$ . What does this information imply with regard to this soil's nutrient status?

Profile P9 (Table 51) contains less than  $0.02 \text{ kg kg}^{-1}$  of gravel throughout. How does its real capacity to retain cations compare with that of profile Kpuabu 1?

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