education

Department of Education
REPUBLIC OF SOUTH AFRICA

SOIL SCIENCE

COURSE MATERIAL

Agricultural Research Council

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This material is developed for the Department of Education, for the training of subject advisors and teachers on Soil Science.

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BASIC SOIL PROPERTIES

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BASIC SOIL CONCEPTS

Why is soil important?

- Soil is the source of all plant growth (agricultural and non-agricultural)
- Soil contains much of the nutrients and beneficial organisms on the Earth
- Soil is the base for all human activity and construction
- Soil is a vital source and filter of our water supply.

What is soil? Soil consists of a variable amount of:

- Organic material
- Mineral components
- Water
- Air and pore spaces

How is soil formed? By a combination of the following factors, over varying lengths of time:

- **Parent Material** (rocks and other geological materials), as well as wind deposits and riverine deposits, which are affected by gravity as well as wind/water flow.
- **Climate** (mainly rain and heat, but also wind and ice/frost). Warm, wet conditions will produce faster and deeper weathering than cool, dry conditions
- **Topography** (slope steepness, aspect, and position)
- **Organisms** (soil fauna and microfauna), often too small to see with the eye.
- **Time** – the time for soil to form varies from a few hundred years to many thousands of years, but whether a soil is "recent" or "ancient", it can very quickly and very permanently be destroyed by human influence or negligence!

SOIL PROPERTIES

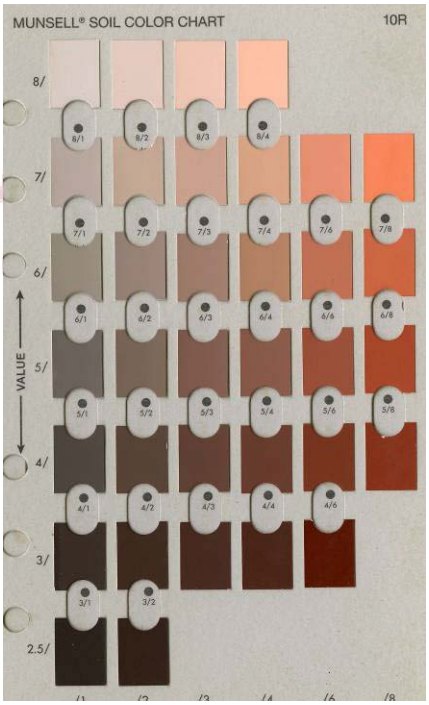
The various soil properties, which are always recorded/observed separately for each horizon (layer) in the soil, can be grouped as follows:

- **Morphological** (signs of wetness, soil structure, soil colour)
- **Physical** (texture, water retention, soil depth, consistence)
- **Chemical** (organic matter, CEC, pH, bases, acidity)

Soil colour gives a good indication of the drainage of a soil, and is measured by using the Munsell Soil Colour Chart. This notation records a combination of:

- **Hue** (base colour scheme) – each on a separate page
- **Value** (lightness/darkness) – vertical scale per page
- **Chroma** (intensity/contrast) – horizontal scale per page

So that any soil horizon will have a definite colour, both in the dry state and in the wet state. The colour of any significant mottles within a horizon should also be recorded.



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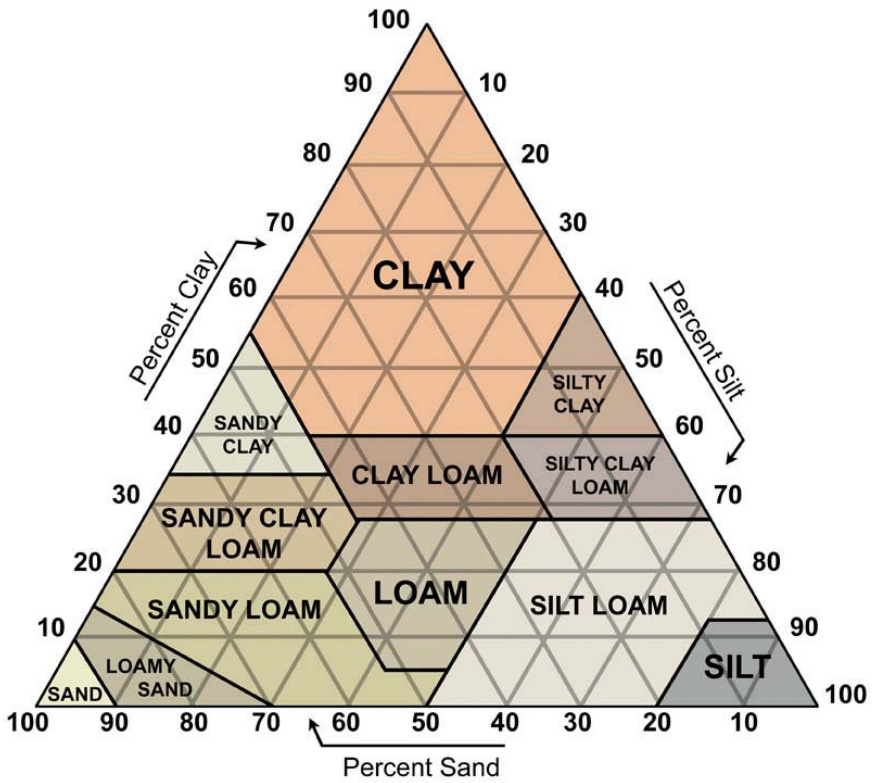

Soil texture triangle (http://www.soilsensor.com/images/soiltriangle_large.jpg)

Soil texture is the relative proportion of different sizes of particles that comprise it, and is a combination of **sand** (feels gritty, 0.5-2.0 mm), **silt** feels floury, 0.002-0.05 mm) and **clay** (feels sticky (<0.002 mm).

The texture is grouped into various classes, as shown in the standard texture triangle, so that the total of all the fractions will always add up to 100%.

The most favourable soil is neither too sandy (which will be less fertile and drain rapidly) nor too clayey (which will be heavy to work and tend to be impermeable), but somewhere in between.

Like any material, soil texture can be felt, and a good assessment can be made of the soil texture as follows:

Moisten the soil and rub into a ball. Then try to roll the ball into a sausage shape.
Sand – ball cracks, falls apart
Loamy Sand – cracks when a sausage is made
Sandy Loam – can be rolled into a sausage, but not bent
Sandy Clay Loam – sausage can be bent, eventually cracks
Clay – sausage forms a ring without cracking/breaking

The ability of a soil to **absorb and retain water** can be likened to a sponge, whereby the soil can be saturated by rain, then the water drains away, is then used by the plants and evaporates, before being too difficult to extract, when the plants will die.

Soil depth refers to the amount of soil above a limiting layer, and can be expressed either as the **total depth** (to a rock or non-soil layer), or **effective depth** (to the uppermost layer that is limiting for water or roots), or **specific effective depth** (in certain cases, for a specific crop root system).

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Soil rooting depth may be affected by: an impermeable layer (often cemented), compaction (a high bulk density), a dense clay subsoil, water saturation (poor aeration), soil acidity or salinity or stoniness (either a layer or total rock content. Compaction often affects root distribution unevenly, but usually detrimentally.

Soil depth will vary in suitability in different climatic regions, with less soil being required in cooler, moister areas, due to more water being available, as well as deeper weathering of the subsoil.

Soil consistency refers to the hardness/softness of the soil, and is closely related to how easily a soil may be worked. It is not always directly related to texture, and many problematic hard-setting soils may be quite sandy.

Soil structure (not to be confused with texture) refers to how the various structural units of the soil are put together, almost "how the soil is built". Structure varies from **apedal** (structureless), through **weak** and **moderate** to **strong**, where almost the whole soil will consist of blocks, with almost no loose crumbs or small particles. The structure units may be **blocky** (fairly round), **prismatic** (vertical columns) or occasionally **platy** (horizontal sheets).

Soil wetness is usually evidenced by grey soil colours and red, yellow and black mottling, and is usually found lower down in the profile. It often occurs seasonally (in summer), so a soil may be very dry, but show strong signs of wetness in the colour variegation, as shown in this photo.

The various **soil chemical properties** will be covered in a separate section of the course.

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*PDF version downloadable from www.soils.org.za

SOIL CLASSIFICATION AND MAPPING

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SOIL MAPPING PROCESS

Soil surveys started in South Africa in the 1920's, concentrating on irrigation areas. Major surveys in KwaZulu-Natal were carried out in the 1960's and the national Land Type Survey, at 1:250 000 scale, commenced in 1972.

The first edition of the South African Soil Classification, the Binomial System ("red book") was published in 1977, while the expanded second edition, the Taxonomic System ("blue book"), appeared in 1991, following the collection of much new information during the Land Type Survey.

There are **several steps** in the soil mapping process, which must be carried out in the correct order;

Preparation – this involves obtaining base maps, basic climate and geological information, creating a GPS grid, and other organisation before the fieldwork commences

Description – all available points are visited and excavated, and all relevant soil characteristics (texture, structure, colour, mottling, coarse fragments, lime, drainage, roots etc) for all soil horizons at each point are noted.

Classification – apply the diagnostic criteria, and classify each soil

Mapping – establish the spatial distribution of each homogeneous soil mapping unit.

Sampling – If necessary, collect representative samples from each map unit for analysis

Interpretation – use the soil map and analytical information to assess and interpret each map unit for the desired purpose.

Soil Classification is done for several reasons:

- Allocate **names**, each linked to a concept that can be universally applied and understood in many areas
- Uniform **standards** (use same methodology) so that the integrity of the classification is assured.
- Improve **knowledge transfer** (eg interpretation) per soil form, to optimise the application of the classification system

Most scientific concepts involve classification, e.g. animals, chemical elements etc

The first step is to describe and identify each of the **master horizons** that occur in the soil profile, working from the surface downwards. These will comprise two or more of:

O – dominated by organic material
A – surface (topsoil) horizon
E – leached, bleached ("eluvial")
B – subsurface horizon (rooting zone)
G – subsoil with signs of wetness ("gleyed")
C – underlying, altered material
R – rock (hard or weathered)

Transitional horizons (A/B, B/C etc) may also occur.

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Next, each of the master horizons is allocated to a specific **diagnostic horizon**, using the criteria as set out in the Classification System. The diagnostic horizons are:

Topsoil

O – O horizon
A – humic, vertic, melanic, orthic

Subsoil

E – E horizon
B – red apedal, yellow-brown apedal, red structured, soft plinthic, hard plinthic, pedocutanic, neocutanic, prismacutanic, lithocutanic, neocarbonate, podzol, regic sand, stratified alluvium, placic pan, dorbank,
G – G horizon
C – saprolite, soft carbonate, hard carbonate, unspecified (signs of wetness or not), man-made
R – rock

This process will provide a sequence of horizons that will comprise a specific **soil form.**

In order to sub-divide the soil form into a more specific **soil family**, certain properties that are relevant to the soil form must be determined. These properties include the presence, absence or degree of development of:

Fibrous/humified organic material; Thin/thick humic; Dark/light A horizon; Bleached orthic; Grey/Yellow E; Dystrophic/Mesotrophic/Eutrophic; Luvic/non-Luvic B; Continuous black cutans; Subangular/angular structure; Ortstein hardening; Hard/soft lithocutanic; Signs of wetness; Calcareousness; Podzol below yellow-brown B; Friable/firm C; Material beneath Organic O.

To summarise the classification process:

Classification into Soil Form
(determined by arrangement of diagnostic horizons in soil profile):
E.G.
Orthic A/Yellow-brown apedal B = **CLOVELLY**
Orthic A/Yellow-brown apedal B/soft plinthic B = **AVALON**
Orthic A/Yellow-brown apedal B/hard plinthic B = **GLENCOE**

73 possible combinations recognized (previously 41)

Classification into Soil Family
(determined by specific properties at that landscape position):

E.G. for the **CLOVELLY** form
Luvic characteristics, dystrophic = ***Brereton*** Family (1200)
Non-luvic characteristics, eutrophic = ***Setlagole*** Family (3100) etc etc

Soil Mapping involves the field investigation of the spatial distribution of the various soils in a specified survey area. It may be done on a free style basis, or on a regular grid, usually by GPS. The scale of the survey (level of detail) will vary according to the purpose of the survey, and will usually be carried out by a soil auger, but occasionally using excavated soil pits (or other available observations).

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Each map unit gets a symbol to identify it, and these are explained in a comprehensive soil legend table, usually contained in a survey report document.

As part of the mapping process, **soil samples** will be collected for analysis. This should be done on a logical basis, by first identifying the specific map units, then collecting enough topsoil and subsoil samples from each one to properly characterize that map unit for the purpose of the survey.

The **Soil Survey Report** will contain all the supporting information for the survey, normally:

- Terms of Reference (why was the survey done)
- Site Details (where was it carried out)
- Methodology (how was it done)
- Soils (Legend, Analyses etc)
- Relevant Interpretations (must be relevant to terms of reference)
- References (to show scientific integrity)
- Map(s)

Soil Interpretations based on the soil survey, are the most important aspect of the process, otherwise the report and map will not be properly utilised. Several types of interpretations may be included, such as:

"Positive" eg crop suitability
"Negative" eg erosion hazard
"Specific" eg peaches
"General" eg topsoil clay %

The interpretations may be **soil-based**, eg suitability of each map unit, or **land use-based**, eg suitability for growing peaches for the nearby canning factory.

SAMPLING

It is often necessary to sample the soil when not part of a survey, usually to determine the soil conditions from season to season, or at various times in the season.

Because the scale of the agricultural enterprise will vary greatly (from small-scale "backyard" plots up to large-scale commercial enterprises), specialized advice is often necessary, but the basic principles remain the same.

First, determine when to sample (before planting, before harvest etc).

Then, allow time for all the steps in the process:

- collecting the samples
- receiving the soil analysis results
- obtaining specific recommendations, if necessary
- applying the fertilizer
- for the fertilizer to start working in soil

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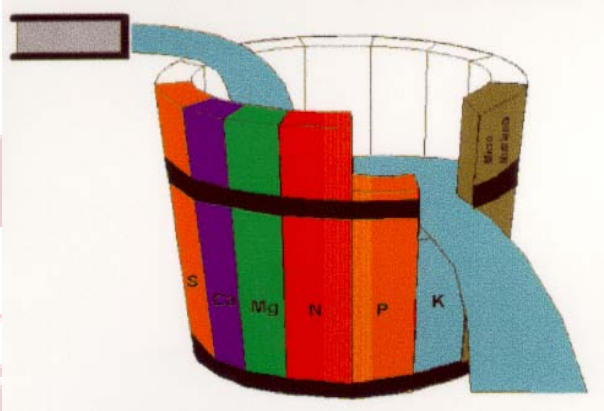
When should testing be carried out? This will vary with soil and crop conditions, but generally, a field being cultivated for the first time should always be sampled. For previously cultivated fields, the pH may only need to be checked every two to four years, while nitrogen should be checked each year and other elements may need checking each year, or possibly less frequently.
When sampling the topsoil, make sure that the soil is not contaminated by any other soil materials, and sample the top 200 mm (approximately the depth of the spade), placing a sample of approximately 2 kg in a clean bag.

Remember that the soil sample represents the growing environment (whether it be a field, a camp or a block), so proper sampling will give good results, while bad sampling will give bad results and be a waste of money!!

A sample may be collected at a specific point, but often, **only if the soil in a field is uniform**, several sub-samples may be collected, mixed and then bagged. It is very important to **label each sample bag**, and to refer the label number to a farm/field plan.

The analysis required will depend on many factors, but the aim is to obtain all relevant information for the specific crop, as well as to be able to make all necessary fertiliser recommendations. Usually, N, P, K, Ca are analysed and occasionally elements such as S, Al and Mg.



FERTILIZING

- The aim of fertilization is to ensure that each plant food required is supplied to the level needed by the plant
- Each plant food contributes to determining growth and yield
- Lowest element level will determine growth performance (limiting factor)

Microelements

Certain elements occur at lower levels, but can be just as vital for plant growth, so it is important to determine if there is a deficiency. These elements include Zn, B, Mb, Fe and Cu.

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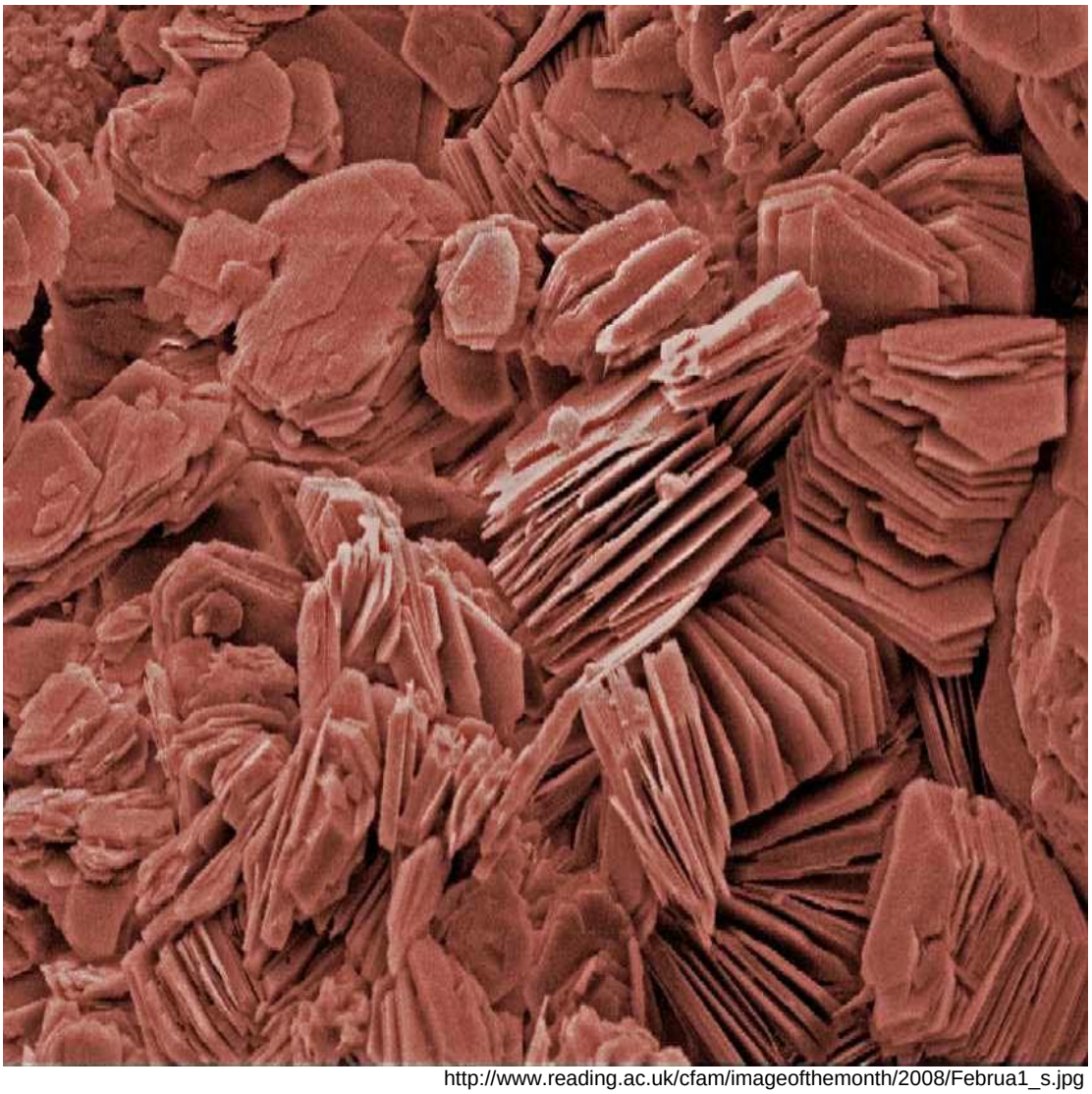
SOIL MINERALOGY



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INTRODUCTION: THE CLAY FRACTION OF SOILS

The inorganic fraction of soils is composed of rock fragments and minerals of varying size and composition. Their minerals are sometimes distinguished into *primary* and or *secondary* minerals depending on their state of weathering. Primary minerals are by definition rock forming minerals that are present in soils chemically unchanged, whereas secondary minerals are minerals formed by weathering of primary minerals.

On the basis of size, three major fractions are usually recognized: (1) the coarse fraction, called sand, the fine fraction called silt and the very fine fraction referred to as clay. The clay fraction of soils comprises particles that are less than 0.2 µm. Materials coarser than sand, like rocks and gravel, may also be present in soils, but they are usually not considered soil constituents. However, they may form sand, silt and clay upon weathering.

Silicate Mineral Groups

Despite the variability in composition, soils are predominantly made up of silicates and oxides minerals. Six types of soil silicates are usually recognized on the basis of the arrangement of the SiO_4 tetrahedra in their structure:

Cyclosilicates – closed rings of tetrahedra.

Inosilicates – single or double chains of tetrahedra.

Nesosilicates – separate silica tetrahedra.

Phyllosilicates – sheets of tetrahedra.

Sorosilicates – linked tetrahedra.

Tectosilicates – framework of tetrahedra.

The sand and a major part of the silt fraction belong to the cyclo-, ino-, neso-, soro-, or tectosilicates. They consist of primary minerals and make up the skeleton of the soil. Since they are coarse in size, they have low specific surface area and do not exhibit colloidal properties (such as cation exchange capacity). Even so, they play an important role in soil texture and soil permeability. Many of the sand and silt minerals are also important in the formation of clays. Most of the clays are phyllosilicates. They have a high surface area, because of their small size compared to sand and silt, and therefore are chemically active. Many of the minerals in clays are crystalline in structure, whereas others may poorly exhibit crystals or are structurally disordered (Tan, 1998).

Phyllosilicate Mineral Structures

Silicates are built around a silica tetrahedron, in which each oxygen atom receives one valency from the silicon atom (Fig. 1). To satisfy its divalent requirement, the oxygen atoms can be linked to other cations or to a silicon atom of an adjacent silica tetrahedron (Fig.2).

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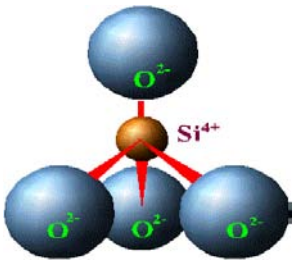

Fig. 1: Tetrahedron structure.

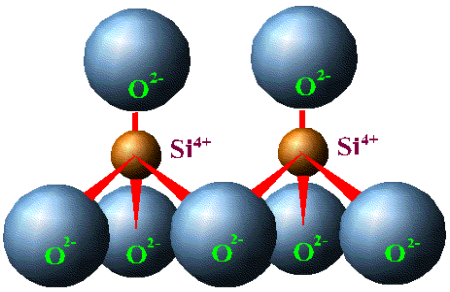

Fig.2: Linkage of tetrahedra.

Silicate clay minerals are characterized by a sheet structure. The sheets are developed by the linkage of three oxygens in each tetrahedron with adjacent tetrahedral units and they can extend indefinitely in a two dimensional direction parallel to the plane of this page (Fig. 2). In such a network of silica tetrahedra, one oxygen in each tetrahedron remains electrically unbalanced. To satisfy the divalent requirement, the latter is linked to Al in octahedral coordination (Fig. 3).

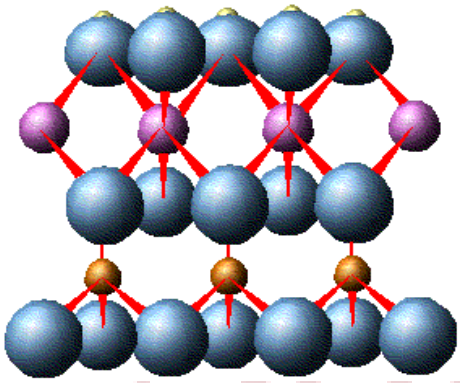

Fig. 3: A 1:1 mineral structure.

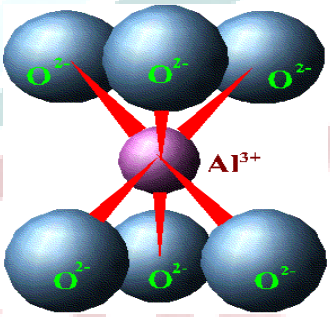

Fig. 4: Octahedron structure.

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In an octahedron (Fig. 4), six oxygen atoms are bonded around an Al ion in six fold coordination. The octahedra are linked together by sharing their six vertices/oxygens. The central cation may be either Al^{3+}, Fe^{2+} or Mg^{2+}. If the central cation is Al^{3+}, then the mineral is classified dioctahedral. If it's Mg^{2+} or Fe^{2+}, the mineral is categorized trioctahedral. The packing of silica tetrahedron and aluminum octahedron sheets on top of each other forms a layered clay structure (Fig. 5 & 6). Clay mineral structures may be classified as either 1:1 (1 octahedral sheet linked to 1 tetrahedral sheet, e.g. kaolinite), 1:2 (2 octahedral sheets sandwiching 1 tetrahedral sheet, e.g. smectite) or 2:1:1 (a 2:1 mineral weakly bonded to a brucite sheet, e.g. chlorite) (Fig. 3, 5 & 6). The bonds between the layers can be relatively strong, as in kaolinite, or can be relatively weak, as in smectite.

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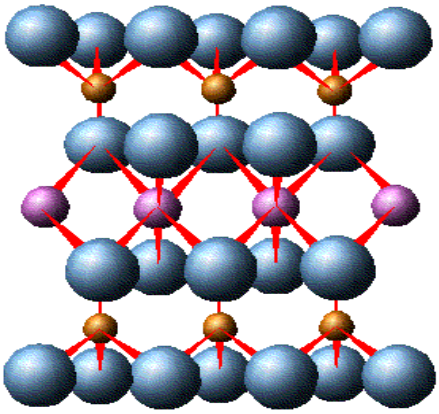

Fig. 5: A 2:1 mineral structure.

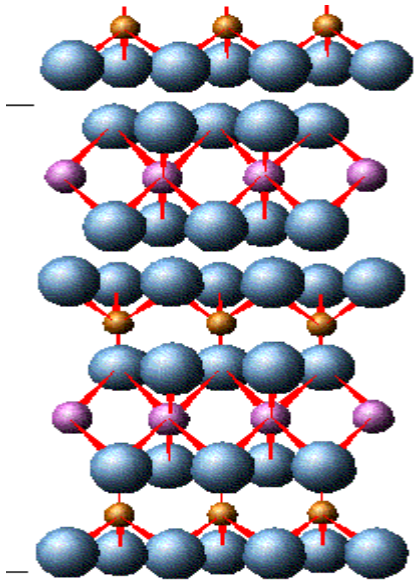

Fig. 6: A 2:1:1 mineral structure.

Kaolinite (1:1 Clay Mineral)

Kaolinite is one of the dominant minerals found in kaolin deposits. It is a 1:1 dioctahedral mineral (Fig. 7) with platy pseudo-hexagonal particles forming laths or vermicular books with irregular edges. The basic unit of kaolinite is made of a tetrahedral sheet of silica (SiO_2) and an octahedral sheet of gibbsite [$Al(OH)_3$] and both bonded by shared O atoms. Kaolinite units are held by hydrogen bonds. The layer stacking of kaolinite is controlled by repulsion between highly charged Si and Al cations which tend to avoid superposition (Dixon, 1989).
The chemical formula for kaolinite is $Al_2Si_2O_5(OH)_4$. Charges within the structural formula units are balanced, and there is very little substitution within the lattice structure. The regular stacking and close spacing of layers creates strong H bonds between successive layers (Tan, 1998).

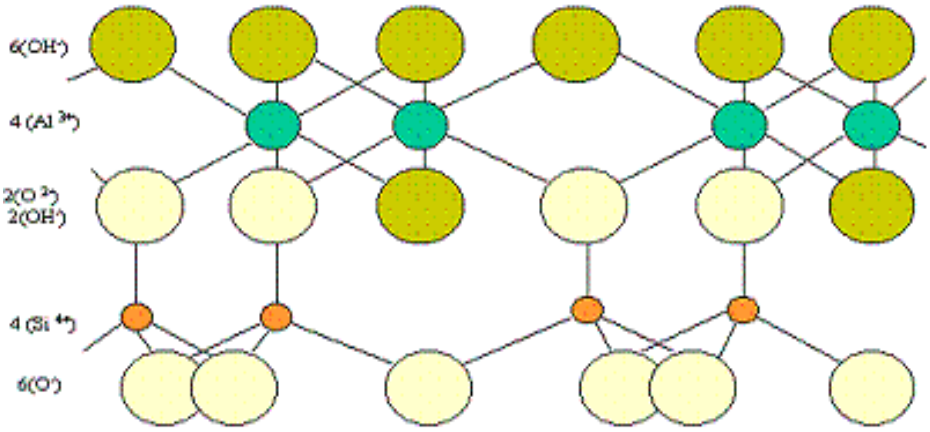

Fig. 7: Chemical Structure Representation of Kaolinite (University of Wisconsin-Madison, 1999)

Smectite (2:1 Clay Mineral)

Smectites are formed predominantly from the alteration of volcanic ash or transformed from feldspars and micas. Low energy environment under temperate climatic conditions (low relief, low permeability, low temperature and low rainfall) are necessary for deposition and formation. They are capable of shrinking and swelling depending on the moisture content.

Smectites are made up of mainly 2:1 structural type clay minerals (Fig. 8). Their basal spacing is influenced by exchangeable cations, relative humidity, association with organic molecules and heat treatment (Wilson, 1987). Smectites are composed of units made of two silica tetrahedral sheets with a central alumina octahedral sheet. Their composition and lattice structure usually differ because of substitution of Al with Fe and/or Mg in the octahedral sheet of the crystal lattice. Smectites derive about half of their negative charge from the octahedral sheet and half from the tetrahedral sheet. The chemical formula of Na-montmorillonite is $Na_{0.3}(Al,Mg)Si_4O_{10}(OH)_2.xH_2O$.

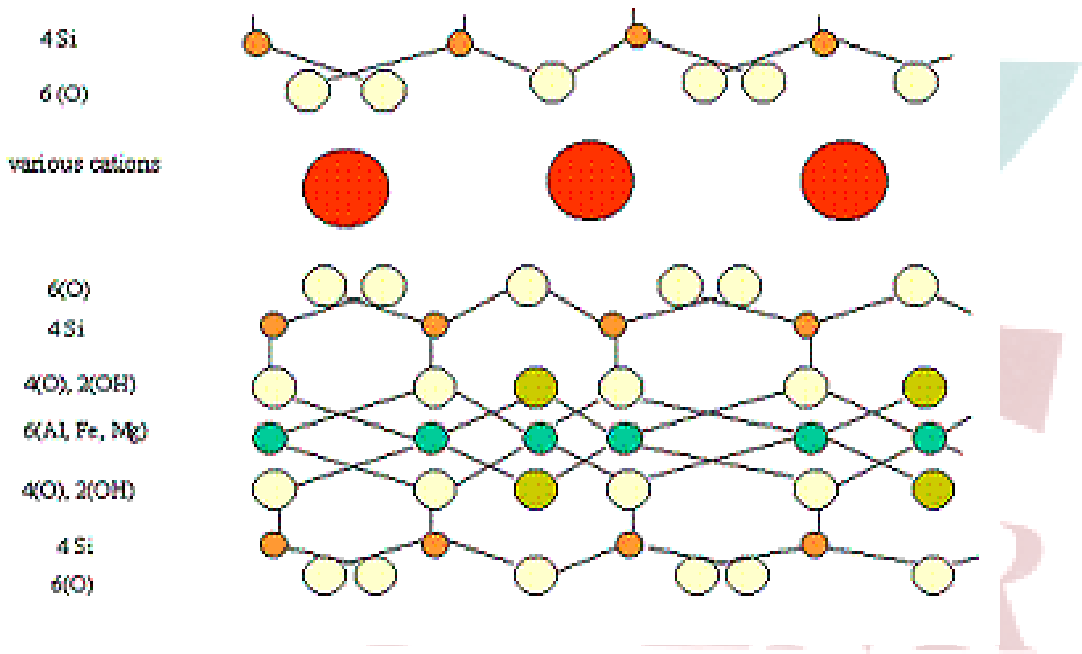

Fig. 8: Chemical Structure Representation of Smectite (University of Wisconsin-Madison, 1999)

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Mica (2:1 Clay Mineral)

Mica is a 2:1 clay mineral (Fig. 9) and can either be classified as a dioctahedral or trioctahedral. Biotite, illite and muscovite form members of the hydromicas group. The hydromicas occur in low to medium grade metamorphic and igneous rocks. Their layer charges result from isomorphous substitution taking place in the octahedral sheet of the unit cell. Potassium ions occur between the unit layers where they fit into hexagonal distribution along the surface of the O layer. This arrangement gives mica a slightly stronger chemical bond between layers than smectites and also increases the space between the layers.
The chemical formula of illite and muscovite are $K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)$. Al^{3+} and Si^{4+} substitution reactions with micas are less as compared to smectites (Murray an Keller, 1993).

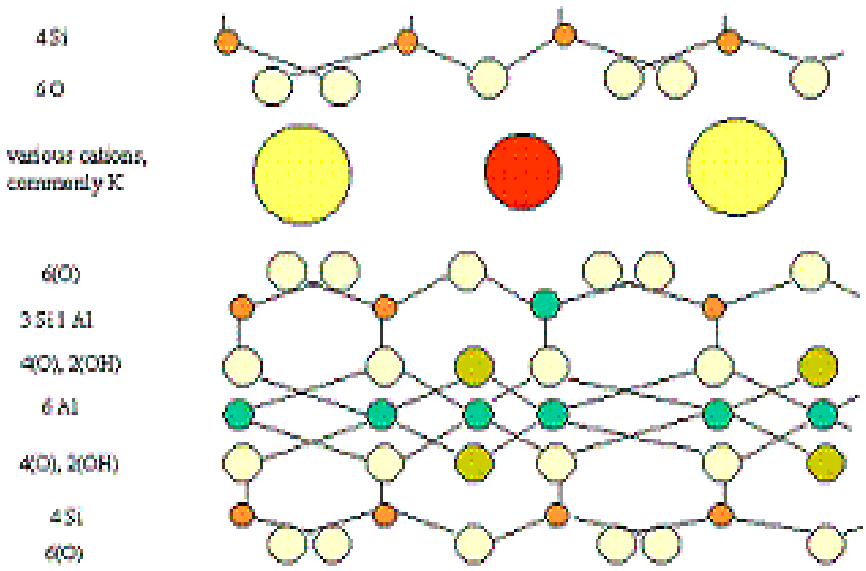

Fig. 9: Chemical Structure Representation of Mica (University of Wisconsin-Madison, 1999)

THE IDENTIFICATION OF CLAY MINERALS

Different instrumentation and techniques are used for the characterization of clay minerals, but focus will be on X-ray diffraction (XRD) since it is a popular technique for clay mineral analysis.

The XRD method can be used for qualitative as well as quantitative analysis. However, this method is not applicable to analysis of amorphous or no crystalline materials. The basis for the use of x-rays in the investigation of soil clays is the systematic arrangement of atoms or ions in crystal planes. Each mineral species is characterized by a specific atomic arrangement, creating characteristic atomic planes that can diffract (reflect) x-rays (Fig. 10). In most crystals, the atomic spacing, or crystal planes, has almost the same dimension as the wavelength of x-rays. The diffraction of x-rays by atomic planes produces characteristic patterns when recorded. This diffraction pattern is used as a fingerprint in the identification of mineral species (Klute, 1986; Tan, 1998).

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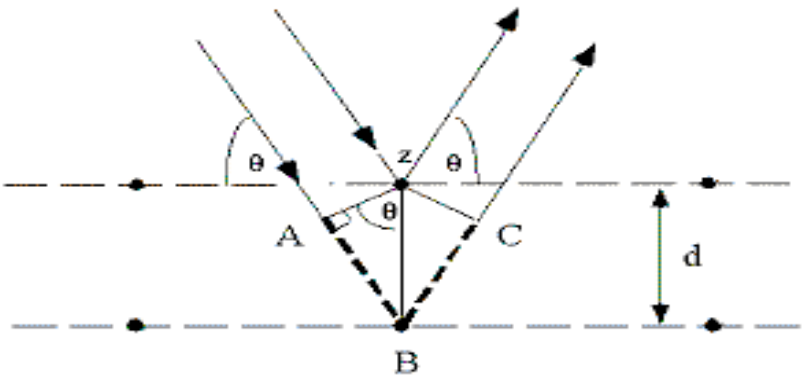

Fig.10: Diffraction from crystal planes (Mineral Physics Institute, 2007).

ISOMORPHOUS SUBSTITUTION

Soil clays carry an electronegative charge, which gives rise to cation exchange reactions. This charge is the result of one or more of several different reactions. One of the reactions that act as a major source for the origin of negative charge, especially in the 2:1 clays, is isomorphous substitution. In this reaction, part of the silicon in the tetrahedral layer is subject to replacement by ions of similar size, usually Al^{3+}. In the same manner, part of the Al in the octahedral sheet may be replaced by Mg^{2+}, without disturbing the crystal structure. Such a process of replacement is called isomorphous substitution. The resulting negative charge is called the net negative (or positive) charge of clay particles inherent in the crystal lattice of the particle, and that is not affected by pH changes or by ion exchange reactions (Tan, 1998).

THE ORIGIN AND FORMATION OF CLAY MINERALS

The clay mineral suite of a soil is governed by three principal processes, which may occur at different points in the geochemical cycle and include weathering or soil formation at the earth's surface. These processes are: (a) inheritance whereby, for soils, clay minerals are inherited from parent rock or sediment; (b) transformation where one mineral weathers into a different mineral (mica to smectite, for example) but the essential silicate structure is preserved to a large extent, with major changes mainly in the interlayer region of the structure; and (c) neoformation, where the clay mineral precipitates from gels or out of soil solutions (Wilson, 1999).

Rock weathering during pedogenesis is essentially a rock-water interaction and the dominant process of clay mineral formation at the earth's surface. The chemical composition of the parent material plays a major role in the type of clay minerals produced and their sequential transformation products. Climate, directly via temperature, rainfall and indirectly via vegetation, strongly influences soil clay mineralogy and bulk chemical composition (Curtis, 1990).

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SOIL COLLOIDAL PROPERTIES & CHEMISTRY

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CATION EXCHANGE CAPACITY AND CATION EXCHANGE

Origin of Charges on Soil Particles (after Sumner and Miller, 1996)

The origin of cation exchange capacity (CEC) lies in the negative charges carried, by soil particles, usually clay, organic matter and sesquioxides. Basically these charges fall into two distinct categories, being either permanent charge, resulting from isomorphous substitution within the mineral lattice, or a variable or pH dependent charge, dependent on soil solution pH conditions and salt composition.

The negative charges on soil particles are neutralized by an excess of cations and a deficit of anions (negative adsorption or anion repulsion). This essentially means that the major part of the negative charge attracts cations for neutralization and the remainder is involved in repelling anions. Thus CEC should be defined as

$$CEC = M^{x+}{}_{Excess} + A^{x-}{}_{Deficit}$$

where M^{x+} and A^{x-} are the cations and anions in the system, expressed on a charge basis (i.e., $cmol_{charge}\ kg^{-1}$ soil for cations and anions respectively). Fortunately the magnitude of the anion deficit is quite small and in many cases and is often ignored. In addition, all soils contain salts in the soil solution in equilibrium with the exchange sites. During the determination of CEC, these salts are extracted together with the exchangeable cations and can result in errors. Thus exchangeable cations ($M^{x+}{}_{Excess}$) in the system would be equal to the total cations extracted less the soil solution cations (Equal to the product of the soil solution concentration cations and the moisture content). In systems low in salt (Areas of high rainfall, most acid soils, many sandy soils), this correction is very small and often can be neglected.

Cation Exchange

The negative charge of the soil clay colloids are balanced by a range of cations. The commonly determined cations are the monovalent cations; H^+, Na^+ and K^+ and the divalent cations Mg^{2+} and Ca^{2+}. Transition metal cations may also be present as exchangeable ions, or as various oxides and hydroxides within the soil. Micronutrient cations of Fe and Mn would also occupy exchange sites within the soil. Cation exchange plays an important part in the supply potential of plant nutrients in soil fertility evaluations. It is equally important in stability of soils, in the assessment of saline and sodic soils, and in the evaluation of irrigation land.

The exchangeable cations are in equilibrium with those considered to be in the soil solution. Plant roots will take up these plant nutrients into the plant tissue. A simple model for this uptake is through the soil solution (Figure 1).

Measurement of Exchangeable Cations: Ammonium Acetate serves as an extractant for exchangeable and water soluble cations. The extractant may be 1M NH4Ac, pH 7 (Non-Affiliated Soil Analysis Working Group, 1990) (or on occasions 0.2 M NH4Cl).

[Principle: Soil (10g) is placed in a centrifuge tube, 50ml NH_4Ac extractant added, the tube shaken, and the supernatant solution collected. The solution is analyses for Na and K by flame photometry, and Ca and Mg by atomic absorption. The NH_4 saturated soil may now be used for CEC determination, as described below.]

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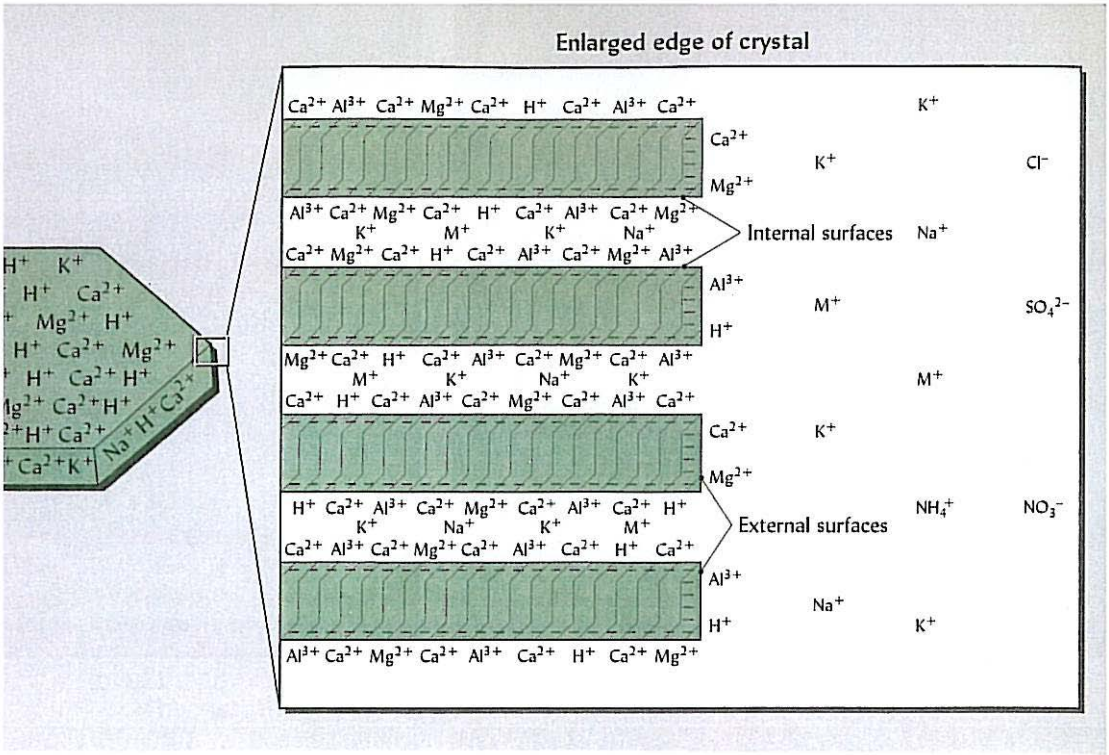

Figure 1. A diagrammatic view of the exchangeable and soil solution cations (after Brady and Weil 1999).

CEC Measurement: Although this statement of CEC appears simple, accurate measurement of CEC is dependent of several factors including concentration of cations in the external soil solution and soil solution pH. The practical use for which the CEC is required will determine the best method of measurement. Typically, the exchangeable cations will be replaced with a suitable cation (NH_4 or Li) to saturate all exchange sites, washing with ethanol to remove excess NH_4 or Li and then extraction again (usually with K) to remove the NH_4 or Li from all the exchanges sites.

For routine measurement of acid soils a "Field pH CEC" could be required, using an unbuffered low electrolyte extractant (0.5 M LiCl) (Non Affiliated Soil Analysis Working Group 1990) or on occasions (0.2M NH_4Cl). Commonly, CEC may be estimated for soil fertility requirements from the sum of the extractable cations as

$$CEC_{estimated} = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} + H^{+} + Al^{3+}$$

Historically, CEC measurement using a 1M NH4 Acetate, buffered to pH7, has been used for comparison of soil properties and for Soil Classification purposes. These CEC measurements are still reported in much literature despite giving errors in pH dependent charge soils.

SOIL PH AND SOIL ACIDITY

(after Thomas, 1996)

Soil pH is probably the single most informative measurement that can be made to determine soil characteristics. At a single glance, pH tells much more about a soil than merely indicating whether it is acidic or basic. For example, availability of essential nutrients and toxicity of other elements can be estimated because of their known relationship with pH. The development of the glass electrode brought the determination of pH very rapidly to its present importance and convenience. Soil laboratories are now equipped with accurate pH meters for routine measurement applications. Small, handheld portable pH meters are now available

making use of micro-circuitry and plastic technology to give pH meters and electrodes suitable for accurate field applications.

Definition of pH

The concept of pH was derived from the ion product of water, which dissociates very slightly.

$$H_20 \leftrightarrow H^+ + OH^- \qquad [1]$$
$$K_w = [H][OH] = 1 \times 10^{-14}$$

at 25°C temperature where H^+ and OH^- in brackets are activities. When $[H^+]$ and $[OH^-]$ are equal, each has an activity of $(10^{-14})^{1/2}$ or (10^{-7}). pH was defined by Sorensen (1909) as the negative logarithm to base 10 of the hydrogen ion concentration, but is now defined in terms of hydrogen ion activity.

$$pH = 1/ \log [H^+] \quad \text{or } pH = -\log [H^+] \qquad [2]$$

Thus, the pH of pure water would be -log of 1×10^{-7} or 7. As defined, any solution with a pH below seven is considered acidic, and one with a pH greater than seven is defined as basic.

Because only dissociated hydrogen ions affect pH, the type of acid that is present is important in interpreting pH values. Acids are roughly divided into strong and weak based on their degree of dissociation. Strong acids are almost completely dissociated (e.g., hydrochloric acid) while weak acids are slightly dissociated (e.g., acetic acid). In the case of weak acids, the total amount of acid in solution can be calculated from the pH and the dissociation constant.

Significance of Soil pH Values

Soil pH can aid in determining major soil characteristics. Although not accurate to determine the lime requirement, pH can be used to make a rough estimate of lime requirement and the relative availability of both P and many of the minor elements (Zn, Cu, B, Mn, Fe, and Mo, for example). In a more specific way, particular pH values in water can be used to predict the dominant cations on soil solution at the time of soil sampling and analysis. These characteristic pH values are described below.

Presence of Free Acids: Generally, very low soil pH values of two to three indicate the presence of free mineral acid, usually H_2S0_4. These low pH values (pH 2-3) can only be achieved with a continuing source of H^+. The usual source of this acid is pyrite minerals which, upon oxidation, form the H_2S0_4. Locations for these acid sulphate soils are is mine spoils, with an excess of pyrite, and recently drained marine sediments, marshes and estuaries. At pH values greater than 4 the H^+ ions on the exchange complex result in the dissolution of the clay minerals and the release of Al^{3+} to the soil solution. This exchangeable Al^{3+} ion is generally toxic to many crop plants and persists in the soil solution to $pH_{(water)}$ values of about 5.4. H+ ions are dominant at pH values greater than 5.4.

In the acid sulphate soils (pH3-4) the presence of free acid indicates three serious problems: (i) most plants will not grow, or become stunted by toxic levels of Aluminium. (ii) Very low soil acidity presents greater problems. The soil minerals are slowly (or rapidly) dissolved and (iii) there will be a very high cost of ameliorating soil acidity using lime for land restoration. Typical lime requirements for mine spoil rehabilitation could be several times that for agricultural crop land to establish a suitable cover crop. The cost of mine soil rehabilitation to alleviate compaction and soil acidity can be very high in relation to its agricultural value. However, this rehabilitation must necessarily be performed.

Presence of free Al^{3+}: At pH values of four to five, the presence of exchangeable, Al^{3+} will be encountered in mineral soils. The Al^{3+} ion is toxic to plant roots and severely limits crop plant growth. Maize is sensitive to exchangeable Al while certain grasses are less sensitive. In commercial agriculture this cost most offset against improved yields. Lime requirements of 1 to about 10 tons per hectare may be recommended. The lime requirement is often based on

the soil test acid saturation value. Acid saturation expresses the proportion of extractable acidity (Al + H) in relation to the total cation exchange capacity.

Presence of Hydroxy-Aluminum: At a pH of 5.4 and above, exchangeable Al^{3+} is no longer present. Instead, Al chemistry is dominated by a complex mixture of hydroxy-Al ions, many of them highly polymerized and virtually essentially non-exchangeable. The smaller particles may also have a high net positive charge and contribute to pH- dependent charge in soils. In many soils, the major part of the "buffering" region involved in practical liming is controlled by the hydroxy-Al ions adsorbed on both clay minerals and on organic matter. These hydroxy-Al compounds can be well buffered, restricting changes in soil pH upon addition of lime materials. Sandy soils with their low clay content and cation exchange capacity will then not exhibit this buffering to changes in soil acidity.

Presence of Calcium Carbonate: At the other end of the scale, pH is free $CaCO_3$, in the soil. Carbonates are visible as nodules or powder lime and can be easily detected as effervescence when dilute acid solution is poured on the soil or nodules. Although the effect of the partial pressure of CO_2 on pH of calcareous soils is strong, normally soils with pH values of 7.6 to 8.3 are found to be calcareous. Excess $CaCO_3$, in the soil indicates that no money need be spent on lime, that soil acidity will not be a problem. Minor elements such as Zn and Fe become limited to plant growth. In certain landscapes carbonates may be present in the lower mid-slope and bottomland positions and will require differing agricultural amelioration.

Presence of Sodium Carbonate: When pH values increase towards nine, $CaCO_3$, no longer controls the system. When Na_2CO_3 becomes dominant, Na^+ dominates the exchange complex, and soil health is seriously impaired. Clay dispersion following rain storms takes place, organic matter is dissolved, with high water tables and excess soil salinity often associated with these soils. These soils become unproductive and loose chemical and physical stability.

Factors that affect soil pH measurement

Soil to solution ratio: The ratio of water to soil suspension has an effect of increasing pH as the ratio increases. The increased dilution of the soil solution is not linear as buffering from the soil colloids, and hydrolysis of Al and basic cations takes place. In South Africa, soil pH measurements use a standardized soil to solution ratio of 1:5 (Non-Affiliated Soil Analysis Working Group,1980). This provides comparable pH measurements between soils and laboratories.

Salt Content: A major factor influencing pH of soils is the salt content of the soil solution. These salts may be a natural part of the soil, or they may be added in the form of fertilizers. In any event, the usual tendency of the salts is to lower the pH value of the soil progressively as the salt concentration increases. In acid soils the effect apparently is due to both displacement of Al^{3+} from the exchange complex and to increased hydrolysis of various kinds of Al species. In calcareous soils, an effect of about the same magnitude also is observed. In addition to pH measurements in water, pH measurements in 1 Molar KCl and 0.1 Molar $CaCl_2$ are commonly reported from SA soil laboratories.

Suspension Effect: The reduction in pH occurs when the electrodes are placed in the soil suspension rather than the supernatant solution above the suspension. The suspension may arise from the mobility's of K^+ and Cl^- of the calomel electrode used to measure pH.

ALUMINIUM

(after Bertsch and Bloom, 1996)

Aluminium is among the more important and commonly analyzed constituents in natural waters, soils, sediments, geological materials, and plant tissues, both because it is an ubiquitous element in soil and geological systems and because, when present in elevated

concentrations, Al can be a powerful toxicant to plants and aquatic organisms. Minerals containing significant quantities of Al are the aluminosilicates which include the feldspars, micas, kaolin, smectites and most other phyllosilicate minerals. Aluminium also is a primary component of other non-silicate minerals that occur in soils and geological materials, including such minerals as gibbsite [$Al(OH)_3$].

Chemically active soil Al can have a variety of forms that are controlled primarily by the pH and the mineralogical composition of the system. Al can be bound to negatively charged clay surfaces by electrostatic forces and thus can be freely exchangeable with other cations such as Ca^{2+}, Mg^{2+}, or K^+. It can be bound in organic matter and released on oxidation of that organic matter, or it can also be present as complex non-crystalline hydroxides and oxides with variable charge. In strongly acidic soils (pH < 4.0), $Al^{3+}(6H_2O)$ ions are the predominant exchangeable species. As the pH is increased, a range of hydroxy-Al complexes may form. Hydroxyl ions (OH^- ions) progressively neutralize the positive charge.

$Al^{3+} + H_2O = Al(OH)^{2+} + H^+$	$pK_a1 = 5.0$	[3]
$Al(OH)^{2+} + H_2O = Al(OH)_2^{+} + H^+$	$pK_a2 = 5.1$	[4]
$Al(OH)_2^{+} + H_2O = Al(OH)_3^{0} + H^+$	$pK_a3 = 6.7$	[5]
$Al(OH)_3^{0} + H_2O = Al(OH)_4^{-} + H^+$	$pKa4 = 6.2$	[6]

[Additional Note: The General Form $Al(H_2O)_{6-n}(OH)_n^{(3-n)+}$) with increasing replacement of OH^- to the simple Al^{3+} ion. However, complex hydroxy species (as opposed to the mononuclear ions noted above) are also considered to be present in soil solution. These complex ions contribute to pH dependent charge of many highly weathered soils.]

If the pH is raised high enough, Al precipitates as the $Al(OH_3)$, either as crystalline gibbsite ($Al(OH)_3$) or as a poorly ordered (X-Ray amorphous) analogue. At pH > 8, the amphoteric nature of Al is expressed with the formation of the aluminate ion $Al(OH)_4^-$.

Soil Acidity, Exchangeable and Extractable Aluminium

The measurement of extractable aluminium (usually described as exchangeable aluminium as the soil solution Al cation concentration is considered negligibly small) has significance in soil fertility as well as in soil chemistry, mineralogy. Much Al research has been directed to the influence of soil acidity and aluminium on crop production. This research has been directed at the effect of soil acidity on plant nutrient uptake, root development, and ultimately plant growth. Also included in this research is estimation of lime requirement to neutralize soil acidity.

Traditionally, there have been two primary uses for exchangeable Al values. The first is the formulation of lime requirements for acid soils based on some measure of exchangeable or extractable Al, or exchangeable or extractable acidity (Al + H) (Reeve & Sumner, 1970; Farina et al., 1980; Sumner 2002). Firstly, these methods are based on establishing plant response to additions of lime. Second, because of its importance as a predominant cation in acid soils, exchangeable Al (and H) is a critical in establishing effective cation exchange capacity (cation balance in soils).

Determination of Aluminium in soils and minerals

Total Al: A perchlorate - hydrofluoric acid mixture ($HClO_4$,-HF) can be used for total dissolution of soil minerals. The perchlorate mixture is potentially explosive such that care must be exercised (Thomas, 1996). The Al can be determined by ICP (Inductively Coupled Plasma), Atomic Absorption (AA) or spectro-photometric methods.

Extractable / Exchangeable Al: The extractant 1M KCl is used both for the determination of extractable Al, the calculation of effective CEC and acid saturation. The unbuffered salt, such as 1M KCl, replaces exchangeable H + Al. Exchangeable acidity (H + Al) is determined by titration with NaOH. Then adding excess NaF releases the OH from $Al(OH)_3$ that can be back titrated with acid to determine the exchangeable Al (Non-Affiliated Soil analysis Working Group, 1990).

Acid saturation percentage (AC) is expressed as (in units of cmol(+)/kg; old unit me/100g soil):

$$AS = [Al] + [H] * 100 / CEC \qquad [7]$$

Cation Exchange Capacity (CEC) can be determined directly or estimated by summing extractable cations (Ca, Mg, K, Na, H, Al = T). Lime requirement for a given crop is then the number of moles of lime required to reduce acid saturation to the desired threshold value, often called the Permissible Acid Saturation (PAS).

The lime requirement (LR to achieve a specific acid saturation is (in kg lime per hectare to depth of 200mm):

$$LR = (AS – 0.1\ T) \times \text{Lime Correction Factor} \qquad [8]$$

A Lime correction Factor of 6 000 is reported in Fertilizer Society of South Africa (2003) and is dependent on the effective neutralization of the brand of lime under field conditions. Other estimates of lime requirement are based on pH and the ratio of exchangeable acidity to exchangeable Ca + Mg (FSSA, 2003).

Certain vegetable crops have a low tolerance to acidity, maize has a low-intermediate tolerance, and grass crops a higher tolerance to acidity. Estimates of soil bulk density and purity of lime are incorporated into the lime requirement formula (Fertilizer Society of South Africa, 2003).

SOIL PHOSPHORUS

(after Sharpley, 2000)

Soil phosphorus (P) exists in inorganic (P_i) and organic (P_o) forms (Figure 2). Inorganic P forms are associated with amorphous and crystalline sesquioxides (largely oxides of Iron and Manganese), and calcareous compounds (Figure. 2). Organic P forms include relatively labile phospholipids and folic acids and more resistant humic acids. These forms of phosphorus are generalised in Figure 2. They may not all be as constant or discrete entities, but exist as transformations occurring continuously between the various forms in response to the external environmental conditions. These generalized forms of soil P have been recognised through dissolution of the soil P by different extractants of differing acidity or alkalinity that “selectively” dissolve the different forms of soil P.

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Topsoil P content is usually greater than that in subsoil due to the sorption of added P and greater biological activity and accumulation of organic material at the surface. However, soil P content varies with parent material, extent of pedogenesis, soil texture, and management factors, such as rate and type of P applied (rock phosphate, single or double supers and fertilizer mixtures) and soil cultivation. These factors also influence the relative amounts of inorganic and organic P. Generally, Calcium-phosphates decreases with increasing soil weathering, whereas amorphous Al and Fe-phosphates and organic forms of phosphate tend to increase. This follows weathering of primary phosphate minerals, and with increased weathering follows increases in the clay fraction and of the Fe and Al oxides constituents in soils.

Phosphorus additions are usually needed to maintain adequate available P for plant uptake. The level of these additions varies with both soil and plant type. Once applied, P is either taken up by the crop, becomes weakly (physical) or strongly (chemical) adsorbed onto Al, Fe and Ca surfaces, or incorporated into organic P. As the inorganic P generally supplies most of the P taken up by crops in productive agricultural soils, more research has been focused on the availability of inorganic P availability, over organic P sources.

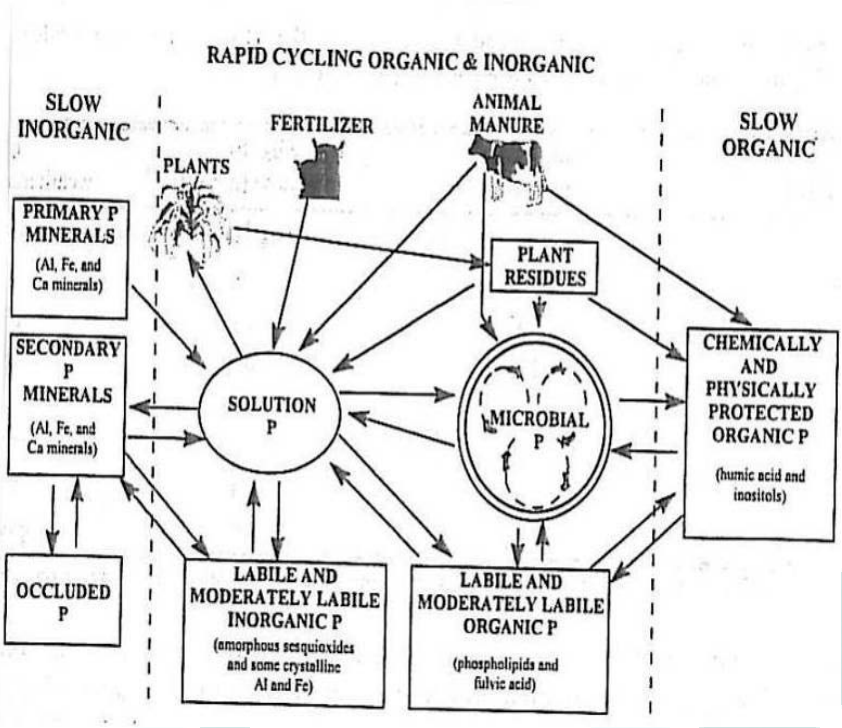

Figure 2. Components and forms of phosphorus in soil (after Sharpley, 2000).

Overall, soil pH is an important soil property controlling inorganic P forms, although Al, Fe, Mn, and Ca contents determine the amounts of these forms. In acid soils, amorphous and hydrous oxides of Al, Fe, and Mn dominate P sorption processes, while Ca compounds dominate P sorption and precipitation reactions in alkaline soils. As a result, P availability is greatest at soil pH values between 6 and 7. Immobilisation of inorganic P by these processes renders a portion of the added P unavailable for plant uptake. Even though inorganic P has generally been considered the major source of plant-available P in soils, the mineralization of labile organic P has also been shown to be important P source.

ELECTRICAL DOUBLE LAYER AND CLAY DISPERSION

(after Sumner M.E. University of Georgia, USA)

Introduction

The phenomena of flocculation and dispersion (de-flocculation) are very important in determining the physical behaviour of the colloidal fraction (clays and organic matter), and have a major bearing on soil physical properties. Soil crusting, being the breakdown of soil aggregates under the impact of rain-drops, the dispersion and movement of clays, especially in sodium rich soils, and the evidence of gully erosion are examples of colloidal dispersion.

Attractive and repulsive forces and Brownian motion play an important part in the stability of colloids. It is necessary to understand the shape and charge distribution of colloids before describing the Electrical Double Layer, responsible for the attractive and repulsive forces. Both permanent and variable charge soil particles play a role in colloid stability.

Smectite minerals

This group comprises 2:1 swelling clay minerals such as montmorillonite, with repeating structure of aluminium-oxygen-hydroxyl-octahedra between two silicon-oxygen tetrahedral layers. These minerals carry a permanent negative charge arising from isomorphous

substitution of lower valency cations (Mg for Al) for Silicon in the octahedral layer, with few substitutions in the tetrahedral layer. This is largely permanent charge and is much larger than the possible variable charge that can develop on the crystal edges of individual atomic sheets. As the surface layer of each sheet is composed of oxygen atoms, and because the sites of the isomorphous substitution are in the central octahedral layer, there is little affinity for opposing surfaces. This gives rise of a plane of cleavage allowing single clay platelets to separate from one another when solution conditions are favourable. Thus in smectite clays dispersion can take place in favourable conditions

Mica minerals

This group comprises 2:1 non-swelling clay minerals such as biotite, muscovite and illite with the same basic crystal structure as smectites, but also with isomorphous substitution of Silicon in the in the Silicon–Oxygen tetrahedral layer. The more frequent substitution results in potassium (K) lodged in the spaces between the oxygen tetrahedral. The unit layers become stacked and cemented together by the interlayer K ions. The pH dependent variable charge on the edges of clay platelets is larger than in smectites. It is thought that micas may play a greater role in clay dispersion that may arise from this variable edge charge.

Vermiculite minerals

Soil vermiculites have essentially the same structure as micaceous minerals except that the interlayer is devoid of potassium (K) ions. The individual sheets can separate giving a greater specific surface and charge than mica, but lower than smectite. The spaces between the sheets may be filled with Aluminium or Magnesium Hydroxide sheet giving Interstratified (layered) Minerals common in highly weathered soils.

Kaolinite minerals

This group consists of a single silicon-oxygen tetrahedral layer attached to a single aluminium-oxygen-hydroxyl layer. The extent of isomorphous substitutions is limited, with both permanent and variable charge at the edges of clay plates. The crystal edges usually have negative charge in acid soils and positive charge in alkaline soils. Kaolinite is a dominant mineral in many soils, that the mineral consequently has important implications for soil stability. The charge characteristics and non-swelling character often imparts aggregate stability to soils.

Oxides minerals

The group comprises oxides, hydroxides of aluminium, iron and manganese which occur in soils as discreet particles and coatings on clay surfaces. Examples are the minerals, goethite (Fe), hematite (Fe) and gibbsite (Al). Isomorphous substitution leading to permanent charge is limited, while in acid soils the oxides are positively charged and in alkaline soils they become negatively charged. The oxides minerals are considered to contribute to aggregate stability.

Amorphous Minerals

These alumino-silicates lack fixed crystalline structure, and have variable but negative charge in acid soils. Amorphous alumino-silicates are present in the clay fractions of highly weathered acid soils of the escarpment areas of South Africa.

Organic Matter

Humic materials in soils are finely divided and have high surface area and negative charge arising from –COOH and –OH groups.

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Electrical Double Layer

Consider an idealized clay platelet with negative charge distributed over the surface. The negative charge of this colloid is balanced by a cloud of positively charged counter ions whose concentration decreases with increasing distance form the clay surface (Figure 3). Electrostatic repulsion of negative ions results in a deficit of negative ions in the vicinity of the clay platelet until at increasing distance from the clay surface an equilibrium solution is reached. The double layer then consists of the surface charge and the surrounding cloud of ions distributed at distributions from the surface (Figure3).

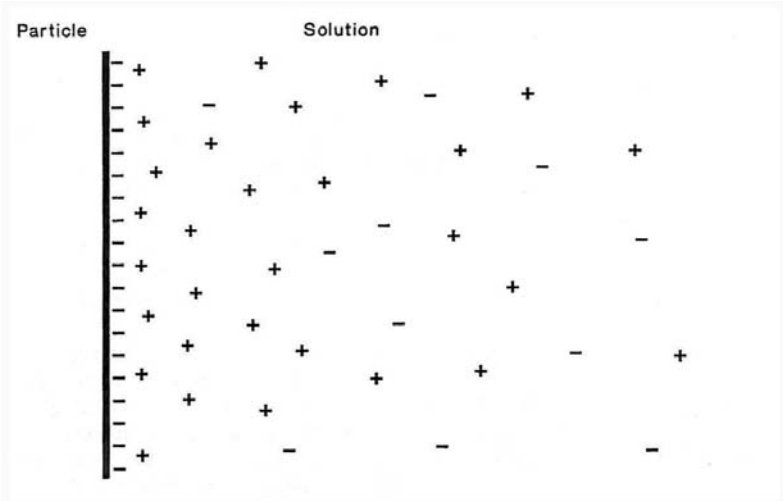

Figure 3. Schematic distribution of charges in the diffuse electrical double layer according to the theory of Gouy-Chapman (after van Olphen, 1963).

Gouy-Chapman Double Layer Theory has been proposed to predict this system when conditions in the equilibrium solution are changed in soils. This occurs when rain water with low electrolyte concentration infiltrates the system, or when salts are added to the system through mineral weathering or additions of saline irrigation water. The chemistry of soil clays deviates from the ideal nature of the assumptions proposed in the theory, that it does not entirely describe the system. However, the Gouy-Chapman Theory is useful in understanding the forces responsible for flocculation and dispersion functioning in the electrical double layer of clay colloids.

The development of the theory is mathematically complex. However, readers should not be disturbed by the mathematical formulation, rather to understand the broad relationship between colloid charge, electrolyte concentration of the equilibrium solution, valency of the counter ions and electrical potential at the clay colloid surface. The relationship between the charge at the colloid surface and the equilibrium concentration of the soil solution is approximated by the equation

$$\sigma = (2\varepsilon nkT / \pi)^{1/2} \sinh (ze\psi_0 / 2kT)$$

σ = charge on the colloid surface	Constants
and	
e = electronic charge (1, 2. 3 ...)	ε = dielectric constant of the solvent (water)
n = electrolyte concentration	k = Boltzmann constant
z = valency of counter ions	T = Temperature
ψ_0= electrical potential at the colloid surface	sinh = mathematical function

This complex equation (please do not remember it) reduces to a simpler equation with constants K_1 and K_2, the surface electrical potential (that we will consider also as a constant):

$$\sigma = K_1(n)^{1/2} \sinh (K_2 z\psi_0)$$

where the charge at the colloid surface (σ) is proportional to the valency (z) and concentration of the ions in the soil solution (n).

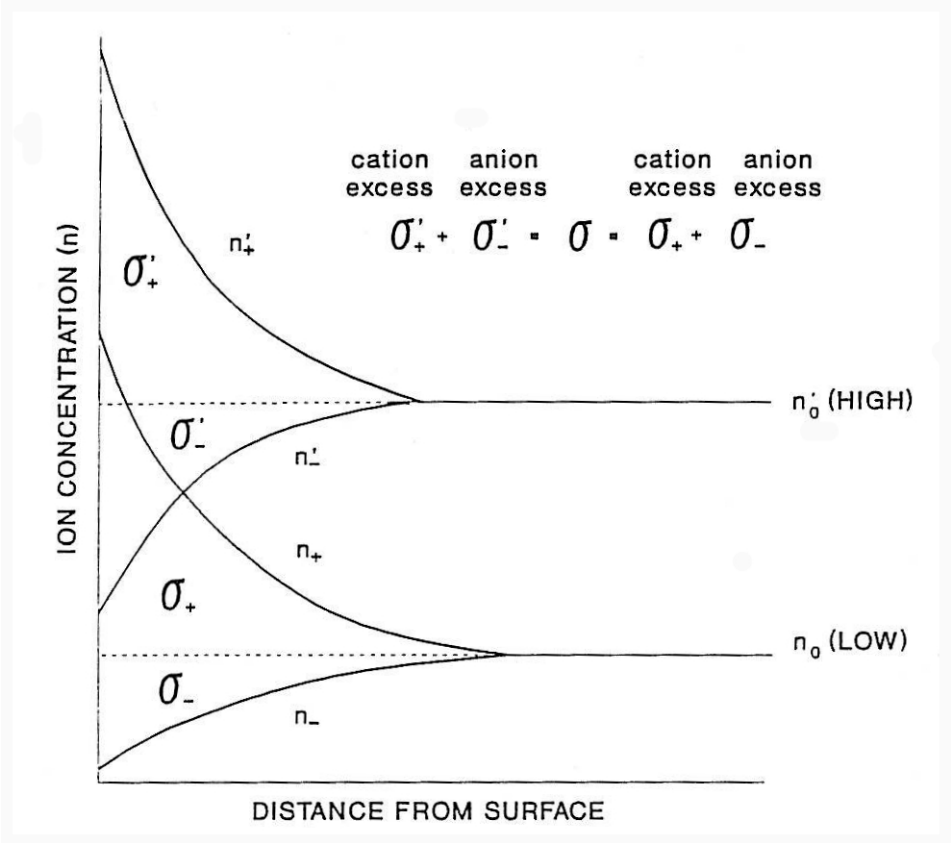

Figure 4. Distribution of counter ions {($\sigma^{+)}$ - the curve above the horizontal lines (n)} for high electrolyte concentration (n HIGH) and low electrolyte concentration (n LOW) for a permanent charged surface (after van Olphen, 1963).

The "thickness" of the Electrical Double Layer of cations is proportional to the electrolyte concentration and the valency of the balancing ions. This is illustrated schematically in Figure 4 with the decreased distance from the colloid surface for a higher over a lower electrolyte concentration. Similar extended and compressed distances for the Double Layer can be calculated for lower and higher valency cations. Similar relationships can be developed for minerals with variable charge.

Particle Repulsion and Attraction

The classical approach to colloidal stability is based on opposing forces of attraction (van der /Waals Forces) and repulsion (Double Layer Repulsion). The attractive forces between atoms and molecules are known as van der Waals forces. Since these attractive forces are additive over atoms and molecules, the total attractive force can become large and decays less rapidly with distance for large molecules as is the case with soil clays. In the case of low electrolyte concentration, the repulsive energy dominates the attractive energy resulting in net repulsion of particles (Figure 5). Such a system would be dispersed and colloidally stable. In the case of a medium counter ion concentration, or valency, more collisions between particles would be successful with resultant greater attraction forces (figure 5). The system would be less stable and slow flocculation would take place. In the case of high concentration, or counter ion valency, the attractive energy dominates at all particle separations (Figure 5). This results in most collisions being successfully attractive. Rapid flocculation takes place. This can be schematically illustrated in Figure 5 where the repulsive forces for low, medium and high electrolyte concentrations are illustrated against the attractive van der Waals forces.

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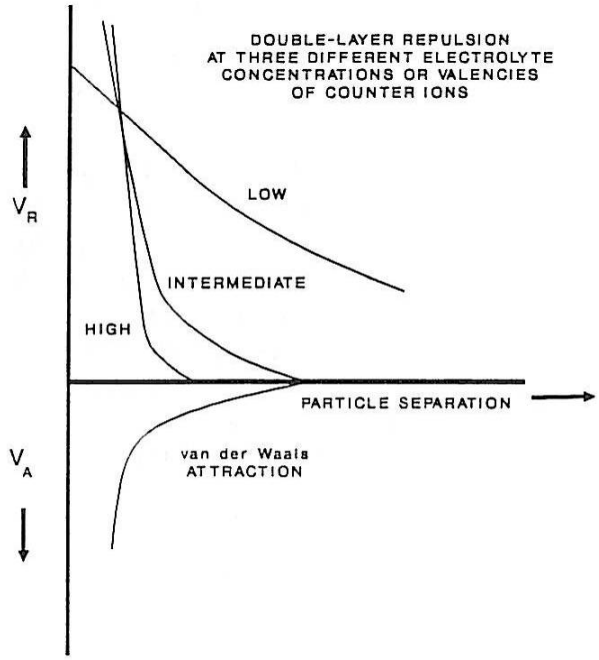

Figure 5. Schematic representation of the variation in repulsive at three (3) electrolyte concentrations, and the attractive forces between colloidal particles of like charge from the particle surface (after van Olphen, 1963).

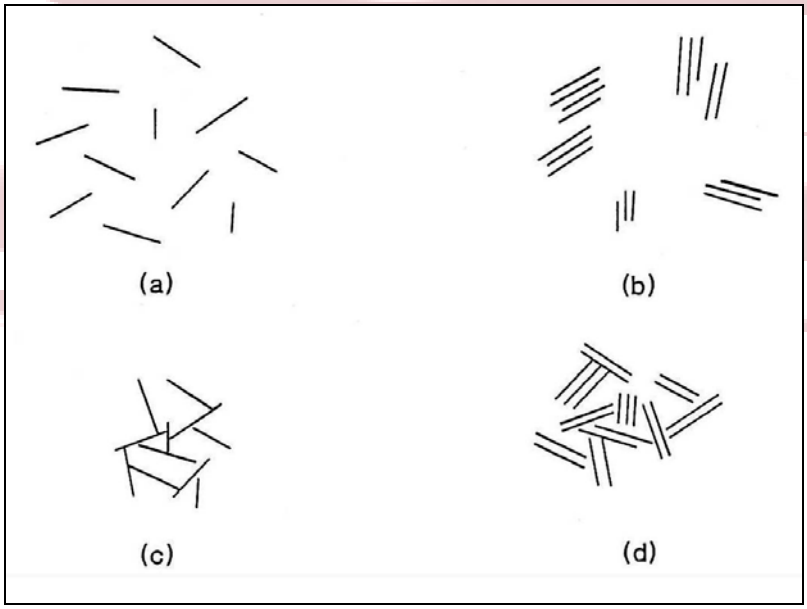

Figure 6. Schematic representation of modes of flocculation, (a) Dispersed, (b) Face to face flocculation, (c) Edge to face flocculation, (d) Face to face and edge to face flocculation.

Applications

Topsoils are likely to have their soil particles covered with organic matter with physical binding of soil particles, as well as net attraction of soil colloids. In acid soils, positive charges of the edges of certain clay minerals and of sesquioxides can be positively charged, resulting in a

stable card-house edge to face flocculation (Figure 6c). As electrolyte concentration increases, face to face flocculation may be present (Figure 6b). If this system contained largely sodium ions, and the system were to become diluted (through infiltration of rain water, or addition of good quality irrigation water) the smectite minerals could become dispersed (Figure 6a), and result in the blocking of soil pores with poor hydraulic conductivity.

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INTRODUCTION TO

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COMPOSITION OF SOIL

Soil is a combination of materials. Soils are composed of mineral matter and organic matter and contain pore spaces filled with air or water and soluble nutrients. The relative volumes of each of the three states of matter present in a soil can be illustrated by a diagram such as Figure 1. Usually the solid matter in the A horizon occupies roughly half of the volume, the remainder is pore space. The pore space is divided between air and water in proportions that vary with the wetness or dryness of the soil. In general, the larger pores contain air unless the soil is completely waterlogged, and the smallest pores contain water unless the soil is thoroughly dried.

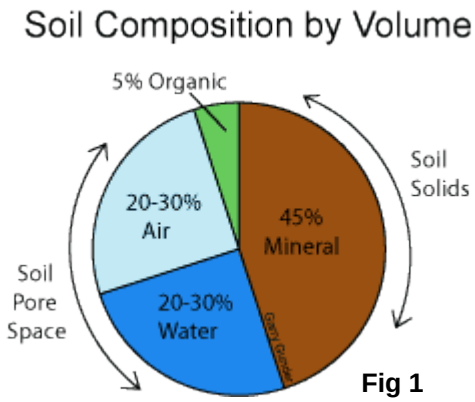

Fig 1

The solid matter consists mostly of soil minerals but usually include a small organic portion such as that shown in the figure. Although, organic matter comprises only a small fraction of the total mass of most mineral soils, this dynamic soil component exerts a dominant influence on many soil physical, chemical, and biological properties.

THE DEFINITION OF SOIL ORGANIC MATTER

In the broadest context, organic matter may be referred to as the total complement of organic substances present in soil, including (1) living organisms of various sizes, (2) organic residues in various stages of decomposition, and (3) dark coloured humus consisting of non-humic and humic substances.

Organic materials of plant and animal origin incorporated into the soil provide the parent material of soil organic matter. Plant and animal residues undergo extensive alteration in the soil before they become humus (the relatively stable portion of soil organic matter). Various types of microorganisms (viz, bacteria, fungi, actinomycetes etc.) attack the residues and decompose their constituents. The residues serve as a source of nutrients and energy for the life processes of the microorganisms. Readily decomposed organic compounds are utilized rapidly and would soon disappear if they were not replenished by fresh residues from time to time. The more resistant organic compounds are altered in nature by the microorganisms but persist for long periods as a part of the soil humus. There is great variability in the nature of the organic material added to the soil, yet there is a surprising similarity in the soil humus of different soils. Humus is relatively stable and has a major effect on various soil characteristics and processes that play a role in soil fertility.

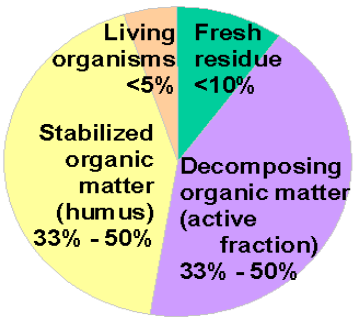

Figure 2. The relative proportions of soil organic matter fractions present in a typical A soil horizon.

AMOUNTS OF SOIL ORGANIC MATTER

The amount of organic matter present in a soil is normally expressed as a percentage of the oven-dry weight of the soil. This percentage may be determined by burning out the organic matter in a furnace or by the use of a chemical oxidizing agent such as hydrogen peroxide.

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Alternative procedures include determination of the amount of organic carbon or nitrogen present and multiplying by suitable factors.

For example;

Grassland A horizon:	% organic carbon x 1.72	= % organic matter
Most B horizons:	% organic carbon x 2.5	= % organic matter
Either of the above:	% nitrogen x 20	= % organic matter

Such calculations are sometimes useful, but they should be considered as approximations only.

The organic matter content of soils varies widely. South African soils have, in general, a low organic matter content if based on the organic carbon (C) content of virgin soils (Table 1).

Table 1. Percent organic carbon (C) content of South African soils.

Organic C	Percentage of RSA soils
< 0.5%	58%
0.5 to 2.0%	38%
>2.0%	4%

Only 4% of the soils contain more than 2% organic C, and 58% of the soils contain less than 0.5% organic C. The remaining 38% of soils contain between 0.5 and 2% organic C. In most soils 1% organic carbon is approximately equivalent to 1.72% organic matter.

FUNCTIONS OF SOIL ORGANIC MATTER IN SOIL

Although it usually occurs in small quantities, organic matter has a major effect on various soil characteristics and processes. These are physical, chemical and biological in nature and often have a direct and indirect effect on soil fertility.

Physical functions

- It enhances the crumb structure in soil, as it serves as a binding agent between the mineral particles and so promotes the forming of aggregates. The effect of this is a lower density or higher porosity that leads to better water infiltration, gas exchange and root development. Such aggregates are also more stable against water and wind erosion.

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Chemical functions

- The cation exchange capacity of humus (100 – 550 $cmol_c\ kg^{-1}$) is high in comparison with clay (2 – 180 $cmol_c\ kg^{-1}$), with the result that more cations (Ca, Mg, K and NH4) can be adsorbed.
- In slightly acid to alkaline soils organic matter can serve as a buffer and helps to keep the soil pH at acceptable levels (against changes in soil pH).
- It increases the availability of P for plant uptake by forming complexes with Fe and Al in acid and Ca in alkaline soils, competes for adsorption positions and displaces adsorbed P.
- It forms stable complexes with metals such as Cu, Fe, Mn and Zn. In the chelated form the plant nutrients are more soluble and thus available for uptake.
- It changes the biodegradability, activity and persistence of pesticides in the soil.

Biological functions

- It supplies metabolic energy for micro-organisms in the soil, with the result that the population and diversity of micro-organisms increase with an increase in organic matter.
- It is a major source of plant nutrients like N, P, and S that are released during decomposition. In the process small quantities of Cu, Fe, Mn and Zn are sometimes also released.

ORGANIC MATERIALS IN SOIL

As shown in Figure 3, soil contains living and dead organic materials of plant and animal origin ranging in size from submicroscopic particles to the largest tree roots.

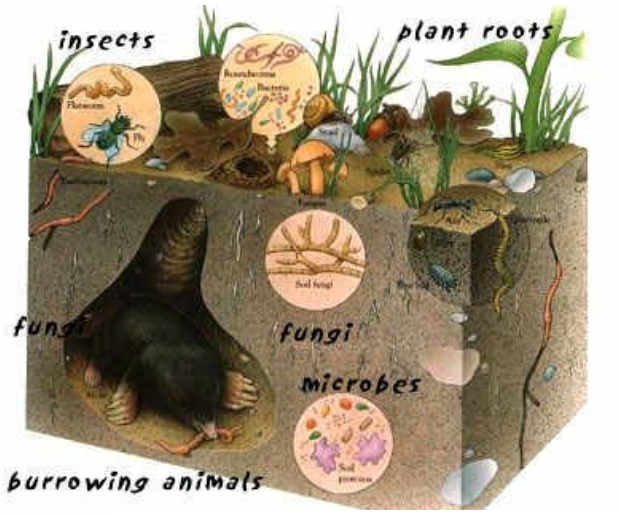

Figure 3. Organic materials in soil.

The following groups can be used to classify soil organic materials according to their mode of origin:

Living macroorganisms

These include plant roots, insects, earthworms, nematodes, crustaceans, snails, slugs, rodents, snakes. Living macroorganisms are usually not considered to be a part of the soil, rather, they constitute a soil forming factor that exerts a potent influence on the nature of the soil. Plant roots shift and move soil particles as they penetrate the soil and grow in size. This rearrengement changes the sizes and shapes of soil peds. Later when the roots die and decompose, a channel is left in the soil that serves as aeration pore space for a time. Roots and other plant parts growing below ground constitute most of the mass of living macro-organisms in most soils, but animal life should not be overlooked. Earthworms are one form of animal life that produce important effects on soil. A large population of earthworms ingests and excretes many tons of soil per acre in a year's time. They leave the soil material in a strongly aggregated granular condition that along with the channels they create, greatly increases permeability to air, water, and roots. Other animals (including moles, badgers, prairie dogs, meerkats, and certain burrowing insects) also mix the soil in which they live.

Living macro-organisms are active participants in decomposition processes in and out of the soil. Much coarse plant material is chewed up by ants and other insects before microbial decomposition takes place. The residues left by the macroorganisms include gummy materials that help glue soil particles together.

Identifiable remains of dead macro-organisms (plant and animal residues)

Remains of plant and animals are the input materials from which humus is formed. These materials are as variable as the plant and animal parts from which they come. The amount present in the soil varies from time to time according to the season of the year when plants mature and die or shed surplus parts.

In agricultural ecosystems, the residues that decompose in soil are generally derived from crop plants and consist primarily of leaf, stem, and root tissues that remain after harvest. Because of their location in the soil, roots are very susceptible to decay. Even during growth, roots supply exudates (secretions) and sloughed-off cell materials that serve as carbon substrates for the microbial population in the same manner as post-harvest root residues.
In natural ecosystems, the residues that undergo decomposition are derived primarily from natural grassland and forest vegetation. In the forest system, leaf litter and other plant debris fall to the soil surface and accumulate as layers in which decay occurs. In the natural grassland, the aboveground plant debris accumulates year after year on the soil surface. In addition, considerable below ground residue is deposited each year from root systems that die back periodically during periods of cold or drought induced dormancy.

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Living microbes

The microbial population of the soil includes members of both the plant and animal kingdoms. Organic matter added to the soil is decomposed sooner or later by various microorganisms (also known as microbes). The most important groups of microbes are bacteria, actinomycetes, fungi, algae, protozoa and nematodes.

Finely divided non-living organic materials

The finely divided non-living organic material (a largely amorphous/ill-defined and colloidal mixture of complex organic substances no longer identifiable as tissues) is relatively resistant to decomposition and forms major component of soil humus. Finely divided non-living organic materials tend to coat the mineral particles of the soil and are especially associated with clay.

CHEMICAL COMPOSITION OF HUMUS

Humus contains every element absorbed by growing plants but not in the same proportions as in plants. The principal elemental constituents are carbon, hydrogen, oxygen, and nitrogen, with lesser amounts of phosphorus, sulfur, and other elements. Decomposition gradually change the elemental composition of the soil humus.

Organic compounds in humus

Soil humus, the complex array of substances left after extensive chemical and biological breakdown of fresh plant residues, makes up 60 percent to 70 percent of the total organic carbon in soil. Because of its complexity humus is often divided into three components following extraction in NaOH: fulvic acid, humic acid and humin. Both fulvic acid and humic acid are soluble in dilute sodium hydroxide (NaOH) solutions, but humic acid is larger and will precipitate out (be insoluble) when the solution is made acidic (by adding HCl). The molecular weight of humic acid varies from 10 000 to 100 000 whilst that of fulvic acid ranges from 1000 to 3000. Humin is the portion of humus that is insoluble in dilute sodium hydroxide (NaOH).

In addition to fulvic acid, humic acid and humin, some other specific organic substances comprising soil organic matter are sugar amines, nucleic acids, lipids, and polysaccharides - the chains of sugar molecules that help to cement soil aggregates together. All of these substances are large, complex molecules or portions of intricate mixtures. They are residual materials from plant tissues and substances synthesized or degraded as microbes decompose organic materials.

Microbial activity

Organic matter contains 3-9% active microorganisms. These organisms include plant life, bacteria and actinomycetes, fungi, yeasts, algae, protozoa, and nematodes. Microbial activity is essential for the release of plant nutrients from dead plant materials. An active, thriving microbial population is a good indication of a fertile soil. Factors that influence microbial activity include energy supply, soil moisture, soil texture, soil temperature, soil pH. Soil environmental conditions that favour microorganism growth will favour fast decomposition rates.

ORGANIC MATTER DECOMPOSITION

The decomposing organisms excrete a variety of enzymes to begin breakdown of the organic materials. The decomposition rate is directly proportional to the numbers of microbes present. Microbes absorb the nutrients released during decomposition – particularly nitrogen and carbon compounds - and use them for growth and reproduction.

Carbon:Nitrogen (C:N) Ratio

The C:N ratio of organic materials such as composts, potting mixtures, animal manures, mulches etc. is a very old concept. It is the ratio of the percentage of carbon (C) in the material to the percentage of nitrogen (N), expressed on a dry matter basis. For example, a material with 65% C and 1.5% N will have a ratio of 43. The ratio has no units.

The ratio of carbon to nitrogen (C:N) in organic residues applied to soils is important for two reasons: (1) intense competition among microorganisms for available soil nitrogen occurs when residues having a high C:N ratio are added to soils, and (2) the C:N ratio in residues helps determine their rate of decay and the rate at which nitrogen is made available.

Influence of Carbon:Nitrogen (C:N) Ratio on decomposition

Decomposition releases nitrogen if the organic material has a sufficiently narrow C:N ratio. Plant residues with C:N ratios of 20:1 or narrower have sufficient nitrogen to supply the decomposing organisms and also to release nitrogen for plant use. Residues with C:N ratios of 20:1 to 30:1 supply sufficient nitrogen for decomposition but not enough to result in much release of nitrogen for plant use the first week after incorporation. Residues with C:N ratios wider than 30:1 decompose slowly because they lack sufficient nitrogen for the microorganisms to use for increasing their numbers, which causes microbes to use nitrogen already available in the soil. Thus, the incorporation of high C:N residues will deplete the soil's supply of soluble nitrogen, causing higher plants to suffer from nitrogen deficiency. The process of decay (decomposition) can be hastened by adding more nitrogen (usually from fertilizers) to supply microbial needs.

Carbon:Nitrogen (C:N) Ratio of organic materials and soils

The carbon content of typical plant dry matter is about 42%; that of soil organic matter ranges from 40 to 58%. In contrast, the nitrogen content of plant residues is much lower and varies widely (from <1 to >6%).

The C:N ratio of organic residues ranges from between 5:1 to 27:1 in soil microbes and seaweed (Table 2) to as high as 550:1 in some kinds of sawdust (Table 3). Most of the materials in Table 2 have C:N ratios below 20:1. Their decomposition therefore results in "surplus N" if they are applied to soil as mulches, organic fertilizers, or used in potting mixtures. In fact, they should be regarded more as organic fertilizers than mulches, especially those with very low C:N ratios. Poultry litter for example, are very high in N (5.5%) and have a C:N ratio of 7. The amount applied should therefore be carefully worked out, based on soil plant nutrient needs and expected speed of decomposition.

Table 2 Typical C:N ratios of dried organic materials which have "surplus N"

Organic material	C:N ratio
Seaweed (kelp)	27:1
Mill mud (filter press)	23:1
Grasses	22:1
Mixed weeds	19:1
Clovers	18:1
Soil organic matter (Humus)	10:1
Urine	15-19:1
Kraal manure	15:1
Lucerne hay	13:1
Peanut shells	12:1
Poultry litter	7-11:1
Pig manure	5:1
Microbe tissue	
Bacteria	5:1
Actinomycetes	6:1
Fungi	10:1

In Table 3, materials have C:N ratios of above 30. Therefore, when decomposing, they require extra N from the surrounding soil. Either this is borrowed or stolen from the soil, for example as in mulching, or it must be supplied as N fertilizer to make up the N deficit. Therefore, they can be used to reduce excess available N in soils, if this is a problem. Soils with high clay content and especially high organic matter content may fall in this category, leading to excessively vigorous trees, poor fruit set and poor fruit quality in avocados on such soils). In theory, the higher the C:N ratio the more such excess N will be "mopped" up by the

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applied mulch, which would have to be mixed with the soil for fastest and most effective response. In practice, uncomposted barks and sawdust may pose dangers to trees because of resins, volatiles etc., and they should first be composted. Also, thick layers of sawdust can seal off the soil surface to water.

Table 3 Typical C:N ratios of "N deficient" dried organic materials

Organic material	C:N ratio
Pinus radiata sawdust	550:1
Pinus radiata bark	500:1
Eucalypt sawdust	500:1
Eucalypt bark	250:1
Paper	170:1
Sugarcane trash	150:1
Bagasse	120:1
Composted P. radiata bark	100:1
Composted Eucalypt sawdust	100:1
Wheat or oats straw	100:1
Sugarcane tops	80-100:1
Mature leaves	60:1
Macadamia husks	40:1
Composted pine bark	30-40:1
Maize stalks	33:1
Peat	30:1

Decomposition of organic compounds in soils

When organic tissue is added to an aerobic soil, three general reactions take place:

1. carbon compounds are enzymatically oxidized to produce carbon dioxide, water, energy, and decomposer biomass
2. the essential nutrient elements, such as nitrogen, phospshorus, and sulfur, are released and/or immobilized by a series of specific reactions that are relatively unique for each element.
3. compounds very resistant to microbial action are formed, either through modification of compounds in the original tissue or by microbial synthesis.

If soil is not well aerated, less desirable products result. For example, in anaerobic conditions significant amounts of methane (CH_4), are produced. Also, some organic acids (R–COOH), various amine residues (R–NH_2), the toxic gases hydrogen sulfide (H_2S), dimethyl sulfide, and ethylene ($H_2C = CH_2$), plus the resistant humus residues are produced.

Rate of decomposition

Organic compounds may be listed in terms of ease of decomposition as follows:

1. Sugars, starches, and simple proteins — rapid decomposition
2. Crude proteins
3. Hemicellulose
4. Cellulose
5. Fats, waxes etc.
6. Lignins and phenolic compounds — Very slow decomposition

DISTRIBUTION OF SOIL ORGANIC MATTER IN SOIL

Organic matter is added to the soil throughout the root zone, but the concentration is normally greatest near the surface and declines with depth. Aboveground parts that fall on the soil

may decompose on the surface or become mixed with depth. Grass roots add more organic matter to the upper layers than to lower layers because root density declines with depth. Many roots die annually, so a large percentage of the organic matter produced by grass roots becomes soil organic matter each year.

Soil parent material

The organic matter content of soil is influenced by parent material thickness, texture, and mineral content. The nutrient supplying capacity the soil inherits from its parent material helps determine the kind of vegetation and influences the amount of growth produced on the soil. Thin soils resulting from parent materials formed from hard rock produce less plant growth and contain less organic matter than deeper soils.

Sandy soils store less water and are therefore likely to produce less plant growth than soils with more clay. Moreover, unfertilized sandy soils are inherently likely to be less fertile than the soils with more clay, and this too, leads to less plant growth and consequently less organic matter.

Other things being equal, the parent materials that provide a more adequate supply of mineral nutrients generally produce more plant growth and therefore more organic matter.

Topography

Soils on steep slopes have more runoff and make less water available to plants. Not only is the organic matter content less because of the reduced plant growth, but also some of the organic matter produced is lost by erosion from the steep slopes, particularly from the convex upper parts of the slopes. The result is a relatively shallow soil with a reduced percentage of organic matter and a much reduced total organic content.

Effect of vegetation

Various types of grasses, bushes, and other plants produce different kinds and amounts of soil organic matter. Changes in vegetation alter the pattern of organic matter accumulation within the soil.

Much of the organic matter of forest soils is derived from leaf fall. Tree roots are less important sources of organic matter than grass roots because much of the tree root system lives for many years. The annual turnover of organic matter from dying tree roots is therefore smaller than from grass roots.

Effect of climate

The organic matter contents of grassland soils of drier climates have less plant growth and hence less organic matter is turned over to the soil.

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MANAGING SOIL ORGANIC MATTER IN SOIL

Organic matter plays an important role in soil fertility. Consequently, every endeavour should be made to maintain the organic matter of soil under crop cultivation and to increase it to an acceptable level where it has decreased. The following general principles should be considered in managing organic matter.

- Favourable conditions for vigorous plant growth must be created in order to ensure the maximum quantity of plant residues. The plant residues can be supplemented with other residues such as cattle manure, chicken manure, sewage sludge or compost.
- Plant residues must be added to the soil on an ongoing basis. For this reason, fallow periods with no plant cover must be reduced to a minimum.
- Because of the relationship between C and N in organic matter, sufficient N must be applied. The inclusion of a legume crop in the crop rotation system is essential, as well as the judicious use of nitrogen containing fertilizers.
- Soil tillage accelerates the decomposition of organic matter and for this reason it must be kept to an absolute minimum. No-till or conservation tillage, where the crop residues are kept on or near the soil surface, must be considered instead of conventional tillage, where the crop residues are incorporated into the soil.
- In cases where the organic matter of a soil has declined markedly, a perennial grass crop should be included in the crop rotation. The establishment of a legume together with the grass is the ideal.

- No attempt must be made to increase the organic matter content of the soil to a level higher than that dictated by the soil-plant-climate system. In a sandy soil in a warmer area 1,5% organic matter may be adequate, though this may not be the case with a clayey soil in a cooler area.

Factors affecting the balance between gains and losses of organic matter in soils

As indicated in the table below, the level to which organic matter accumulates in soils is determined by the balance of gains and losses of organic carbon.

Table 4. Factors affecting the balance between gains and losses of organic matter in soils

Factors promoting gains	Factors promoting losses
Green manures or cover crops	Soil erosion
Conservation tillage	Intensive tillage
Return of plant residues	Whole plant removal
Low temperatures and shading	High temperatures and exposure to sun
Controlled grazing	Overgrazing
High soil moisture	Low soil moisture
Surface mulches	Burning of plant residues
High plant productivity	Low plant producitvity
High plant root:shoot ratio	Low plant root:shoot ratio
Appropriate nitrogen levels	Excessive mineral nitrogen
Application of compost and manures	Application of only inorganic fertilizers/materials

DECOMPOSITION OF ORGANIC RESIDUES AND GLOBAL WARMING

When soil is tilled or worked, it is aerated and much of the organic matter decomposes with the accompanying release into the atmosphere of carbon as carbon dioxide or methane. An issue of major concern is the possible effect of accelerated organic matter decomposition, the burning of fossil fuels, and other contributors to the increase of carbon dioxide in the atmosphere. The action of carbon dioxide and other greenhouse gases in trapping infrared radiation is called the greenhouse effect. It may measurably increase the overall average temperature of the Earth, which could have disastrous global consequences.

Because the potential consequences of global warming in terms of loss of snow cover, sea level rise, change in weather patterns, etc are so great, it is a major societal concern. Much effort and expense are currently being directed at reducing the human-caused contributions to global warming.

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SOIL MICROBIOLOGY

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INTRODUCTION

Understanding soil microbiology is essential when studying agricultural and environmental sciences. Many processes start with soil organisms. These organisms give life to soil, it makes soil breath, it assist is soil formation, it eats and dies and releases nutrients, it absorbs energy and releases heat. Before the discovery of microorganisms, in 1675, it had been a mystery why grapes could be turned into wine, milk into cheese, or why food would spoil. In the past decades the microbiology has advanced tremendously, but even so, only about 1% of all microbes on earth have been studied. This is not surprising when you consider that one teaspoon of soil contains over a billion microbes!

Definition of microbiology is as follows:
Soil microbiology: A sub-specialization of soil science concerned with soil-inhabiting microorganisms and their functions and activities.
Microorganism: A member of a heterogeneous assemblage of simple organisms, consisting of the protozoa, algae, fungi, slime molds and bacteria. They are either unicellular or, if multicellular, their tissues are relatively undifferentiated.

IMPORTANCE AND FUNCTION OF MICROORGANISMS

- Microorganisms decompose organic matter.
- Microorganisms facilitates in humus formation in soil, thereby
  - increase cation exchange capacity of the soil.
  - maintain soil fertility and crop protection
  - increase soil aggregate stability
- Some microbes live in symbiosis with plants, contributing to moisture and nutrient uptake, such as legume-*Rhizobuim* a bacterial symbioses with higher plants, and mycorrhiza, a fungal symbioses with higher plants.
- Facilitates in soil formation through lichens, a symbiosis between algae and fungi, that biochemical weathers rock.
- Release gas, such as O_2, CO_2, N_2O and N_2 back into the atmosphere.
- Certain microbes can facilitate in N fixation
- Vital function in C, N, P, S etc cycles
- Part of ecosystems – provide food for higher organisms, either directly or indirectly
- Bioremediation: Some microorganisms have ability to decompose oil (biodegrading of petrochemical contamination) biodegrade waste (urban and municipal), and can remove toxic heavy metals from water
- Facilitates in producing agricultural products such as cheese, yoghurt and wine.
- Other agricultural application include: biofertilizer (Rhizobium, Azotobacter, Beijerinckia, Azospirillum, Cyanobacteria, etc.), biopesticides (viruses, bacteria, and fungi are being developed).
- Microorganisms can also be used in non-agricultural products, such as antibiotics, probiotics, vitamins, acids and alcohol.

SOIL ORGANISMS

Soil organisms include plants and animals from various communities, classes and sizes. It can be classified in different ways.

Kingdom	**Groups**
Monear	Bacteria and prokaryotic algae
Protista	Protozoans, algae and slime molds
Fungi	Lichens, molds and yeasts
Plantae	Higher plants
Animalia	Higher animals

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Organism	Food	Energy
Large eucaryotes		
Animal	*Solid organic*	*Oxidation of organics*
Plants	*CO_2 + ions*	*Light*
Small eucaryotes		
Protozoa	*Solid and dissolved organic*	*Oxidation of organics*
Algae	*CO_2 + ions*	*Light*
Fungi	*Dissolved organic*	*Oxidation of organics*
Procaryotes (bacteria)		
Phototrophic	*CO_2 + ions*	*Oxidation of organics*
Litotrophic	*CO_2 + ions*	*Oxidation of inorganics*
Heterotrophic	*dissolved organics*	*Light*

Group	Type / Organism	Size (mm)	Abundance (individual/m^2)
Macrofauna	Earth worm	15 - 85	2
	Insects	1 - 30	1×10^2
Mesofauna	Rotifers	0.20 – 1.00	5×10^2
	Nematodes	0.20 - 2.00	3×10^4
Microfauna	Protozoa	0.02 - 0.20	1×10^9

Eucaryotes: All living things which are individually visible to the naked eye are eucaryotes. However, a large number of eukaryotes are also microorganisms. Unlike bacteria and archaea, eukaryotes contain organelles such as the cell nucleus, and mitochondria in their cells.
Prokaryotes: The prokaryotes are a group of organisms that lack a cell nucleus, or any other membrane-bound organelles. They differ from the eukaryotes, which have a cell nucleus. They are the most ancient and successful form of life, and nearly 3 billion years old. Two distinct groups of prokayotes are Archaea and Bacteria.
Protozoa: microorganisms classified as unicellular eukaryotes
Macrofauna (in terms of soil organisms) accelerate organic matter decomposition, mix and aerate the soil. Larger organisms, such as lice and fly larvae grind and macerate organic matter, increasing the surface area. Other organisms such as earth worms and dung beetles bury organic matter, thus incorporating and mixing it successfully into the soil.
Mesofauna are on average smaller than macrofauna, yet not small enough to be considered microscopic. The most representative and ecologically important organisms in this group are the nematode (also called roundworms, threadworms and hairworms). Nematodes are important plant pathogens.
Microfauna: protozoa and archezoa are the simplest animals and the most abundant invertebrates. Protozoa affect the structure and function of microbial communities.
Algae are eukaryotes (have a cell nucleus), photosynthetic and aquatic, and play a role in soil only where there is available water and light. It could contribute to the formation of organic carbon compounds and formation of soil structure.
Fungi are different from bacteria in that they are larger, eukaryotic and filamentous. Well-aerated environments with lots of organic matter favour the growth of moist soil fungi. Fungi decompose organic matter, allowing other microorganisms to consume it.
Actinomycetes are prokaryotic and most are saprophytes, growing by decomposing OM. They compose 10-50% of the soil microbial population. Actinomycetes are the greatest known natural source of antibiotics.
Heterotrophic organisms almost always obtain carbon from breakdown of organic material and energy from oxidation of carbon in organic compounds.
Autotrophic organisms obtain their carbon from CO_2 or carbonate minerals and their energy from light or from inorganic oxidation reactions.

SYMBIOSIS

Most of the interactions between species involve food:

- competing for the same food supply
- eating (predation)
- avoiding being eaten (avoiding predation)

In symbiosis, at least one member of the pair benefits from the relationship. The other member may be

- injured = **parasitism**
- relatively unaffected (= **commensalism**)
- may also benefit (= **mutualism**)

Two of the best examples of mutualism in agriculture are mycorrhiza and symbiotic N fixation.

Mycorrhiza

Mycorrhizae are fungi that infect plant roots, sometimes in obligatory symbiotic relationships. It occurs on most terrestrial plants and benefit plant by improving uptake of nutrients (especially P and Zn) and water. Vesicular arbuscular mycorrhyza (VAM) infect most agricultural crops Mycorrhizae contribute to the overall P nutrition of plants by four main mechanisms: they solubilise mineral P by producing organic acids and CO_2 production during respiration. ; they expand the volume of soil from which P is adsorbed because they extend the root surface, mycorrhiza is more effective in P uptake at low P levels compared to roots, and some mycorrhiza may release P that mineralize organic P in soil.

Legume-Rhizobium

Symbiosis of bacteria (collectively know as rhizobia) and higher plants (particular legume plants) are responsible for a large part of plant available N. Rhizobia persist in soil as saprophytic heterotrophs when they are not infecting their host. Upon infecting the host, N_2-fixing nodules are formed on the roots.

Lichens

Symbiosis between an algae and a fungi is called a lichen. Lichens begin the biochemical weathering of rocks that leads to soil formation.

ADDING ORGANIC MATTER TO SOIL

Carbon

Organic matter (OM) is a carbon and energy source for heterotrophic microorganisms. When OM is incorporated into the soil, microbial activity instantly increases and there is an immediate drop in O_2 and an increase in CO_2 concentration. Initially a fast growing colony of microorganisms consume easily degradable component in the OM, and are eventually replaced by slower growing microorganisms subsisting on resistant compounds. This process of OM breakdown and nutrient release is called mineralization. **Mineralization can be defined as the transformation of an element from an organic to an inorganic state as a result of microbial action**.

Certain components of organic material is easier to digest, such as sugars or starches, while cellulose, hemicellulose and lignin are not as easily digestible by microbes, and takes longer to decompose. The older a plant gets, the higher the content of cellulose, hemicellulose and lignin gets, while the proportion of sugars, protein and oils decrease.

After decomposition of plant material by microorganisms, soil organic matter (SOM) remains and consist of decomposing residues, by-products formed by decomposition, microorganisms and resistant soil humic material. The C in SOM comes from carbohydrates, which are primarily microbial origin.

Nitrogen

N is a macronutrient and needed in large concentrations for successful crop production. Microbial degradation of OM is central to the fate of N in soil.

<u>N fixation</u>: The ability to fix N_2 is restricted to prokaryotic soil microorganisms, of which the *Rhizobium* species within this group are the most important N_2 fixers in agriculture. Rhizobia

are bacteria that infect roots of plants of the legume family, forming N-fixing nodules. The bacteria becomes embedded in the vacuole, and enclosed by a membrane. This develops into a bacteroid, which contains nitrogenase, the enzyme that brings about the assimilation of molecular N_2. The tissue is extended to produce nodules on the roots of legumes. This process is accountable for 65% of the N currently required for agriculture.

N mineralization: decomposition of organic N compounds to release inorganic N. Mineralization takes place in three steps, namely aminization, ammonification and nitrification. The first two steps are carried out by heterotophic microorganisms, while the third one is carried out by autotrophic bacteria

Ammonification: NH_3 is quickly transformed by microorganisms into ammonium ions (NH_4^+).

Nitrification is the microbial oxidation (by *Nitrosomonas, Nitrosolobus, Nitrobacter* etc) of NH_4^+ and organic N into NO_2^- and NO_3^-. Nitrification is an acidifying process in soil.

Immobilization or assimilation: inorganic soil N is converted to organic forms through biological activity. Immobilization of N occurs with addition of organic matter with a high C/N ratio. N is then unavailable for plant uptake, until the microbial cells decompose or mineralize.

Denitrification is the process by which nitrogenous oxides, particularly NO_3^- NO_2 are used as terminal electron acceptors in the absence of O_2 and are reduced to dinitrogen gases during respiratory metabolism.

Nitrogen forms

Dinitrogen (N_2): Gas consist 78% of atmosphere, it is inert molecules with strong tipple bonds. It is also a product of denitrification and the only place in the N cycle where N_2 is returned to the atmosphere.

Ammonia (NH_3): Gas under normal conditions, and does not accumulate in soil. It is mostly an intermediate product from organic N to NH_4^+.

Ammonium (NH_4^+): (Plant nutrient) These ions are the product of heterotropic organisms after breakdown of OM.

Nitrite (NO_2^-): Normally very low levels in soil, since it is only an intermediate product during nitrifcation, but can accumulate when the pH is high, and oxidation of NO_2^- to NO_3^- is limited.

Nitrate (NO_3^-): (Plant nutrient) Very mobile since it is water soluble and negatively charged, it can not be absorbed onto negatively charged clay minerals. It could therefore easily be leached from the soil with percolating water. It is also responsible for groundwater contamination, and eutrophication of water courses.

Nitric oxide (NO): Gas resulting from denitrifcation process.

Nitrous oxide (N_2O): Gas resulting from denitrifcation process. N_2O is a trace gas, but one of the most significant greenhouse gases associated with agricultural soils, especially under fertilized and irrigated land (up to 60% of N_2O from agric soils).

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$$\text{Organic N} \rightarrow NH_3 \rightarrow NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

mineralization / ammonification — nitrification — denitrification

Phosphorus

P is the second inorganic nutrient needed by plants and microorganisms. The amount of organic P in the soil can vary between 20-80% of total P, and is dependant on a number of factors such as climate, vegetation, soil texture, land use pattern, fertilizer practises, drainage and irrigation. Organic P can change over time and space. During the initial phase of pedogenesis, most P in rocks is present as apatite, which is gradually dissolved due to chemical and biological processes. This P is utilized by microbes and plants, and only later becomes available as organic P in the soil. Topsoil P content is usually greater than subsoil P, due to sorption of added P from organic matter.

Microbial cycling of P involves transforming P between inorganic and organic pools and insoluble and soluble forms. Microorganisms have a major role in solubilisation, immobilization and mineralization.

ENVIRONMENTAL FACTORS

Temperature:

Optimal temperature for most microorganisms is 20-30ºC, and optimal temperature for mineralization is 40-60ºC. Too cool temperatures reduce activities, and too hot (> 80 ºC) may kill microorganisms. Cold periods retard plant growth and OM decomposition (could result in OM build up in soils) while warm temperature in crease plant production but also promote faster mineralization (depletion of OM).

Water:

Microbes need water to grow and microbial activity nearly stops when the soil is completely dry. Optimum water content for mineralization is 50-75% field capacity[1]. The more water a soil has, the cooler it is, and the cooler the soil is, the lower the metabolic activity of microorganisms. Low microbial activity reduces C loss through respiration (CO_2); soil N increases as soil water increase. Saturated soils, however, result in limited oxygen supply, and anaerobic conditions favours denitrification and methane production

Oxygen:

Microorganisms can be grouped according to their oxygen requirements. Some microbes are obligate aerobes, and require O_2 for growth. Other microbes are flexible and to some microbes O_2 might even be toxic. O_2 is used as an electron acceptor for microbial metabolic activity. When the soil is saturated, the macro-pores are filled with water and the soil is sealed off from the atmosphere. Free O_2 in these soils is severely limited and is rapidly consumed within a few hours by microbes. The saturated soil is practically devoid of molecular O_2. As long as O_2 is available it acts as the preferred electron acceptor followed by NO_3, Mn oxides, Fe (hydr)oxides, SO_4 and finally CO_2.

pH

Optimum pH is near neutral for most microorganisms, with an ideal pH of 6.5 – 7.2. Nitrification is rapid in neutral to alkaline soils, and at pH < 6 nitrification is very low. At high pH, NH_4^+ accumulates in the soil.

Vegetation:

Type, age and the C/N ratio of OM will determine the quality of the food source and the availability of the nutrients. Different ecosystems have different amounts of soil organic matter (SOM), partly because of different temperature and decomposition rates. Different types of OM result in different mineralization and SOM. There is more soil N under permanent grass vegetation than under forest soil, due to the dense rhizosphere in grassland soils that promotes humus formation.

MICROORGANISMS AND AGRICULTURE

Conservation agriculture

Conservation agriculture (CA) aims to achieve sustainable and profitable agriculture. Agriculture benefits from CA mainly by the increase of SOM and all the subsequent advantages such as increased infiltration, aggregate stability, better water holding capacity, that is associated with a higher SOM content. Environmental benefits include the reduction of erosion, improved water quality, biodiversity increase, carbon sequestration and conserves natural ecosystems. CA make use of soil biological activity and cropping systems to reduce the excessive disturbance of the soil and to maintain the crop residues on the soil surface in order to minimize damage to the environment and provide organic matter and nutrients. To

[1] Field capacity is the percentage of water remaining in the soil 2-3 days after having been thoroughly wetted and after free drainage is negligible.

achieve an increase in crop production, while conserving the environment, CA adopted three basic principles, **minimal soil disturbance**, **permanents soil cover** and **crop rotation**.
Minimal or no-till advances: In general microbial populations and activity in no tillage soils are greater than in conventional tillage soils, due to higher moisture and OM content in no till soils. Tillage reduces the moisture content of the soil, increase oxidation and result in faster decomposition of OM. Soil compaction as a result of cultivation has a negative effect on microbial activity.
Soil cover: soil cover can reduce soil temperatures, improve water infiltration, reduce evaporation, conserve soil moisture, thereby creating a better environment for microbes. It also provides organic material that can be incorporated into the soil. Increased soil water content, helps maintain soil erosion, improves soil aggregation, biological activity and soil biodiversity, and increases soil carbon sequestration.
Crop rotation and intercropping: Crop rotation and intercropping can be used to maintain soil fertility, N fixation, bio-control and efficient use of soil profile. This practice could reduce requirements for pesticides and herbicides, control off-site pollution and enhance biodiversity. Crop rotations and associations can be in the form of crop sequences, relay cropping, and mixed crops.

Management and cultivation

Microorganisms are effective only when they are presented with suitable and optimum conditions for metabolizing their substrates, including available water, oxygen (depending on whether the microorganisms are obligate aerobes or facultative anaerobes), pH and temperature of their environment. Optimal soil conditions would result in optimal microbial functioning and subsequent nutrient availability.

Over -irrigation and water logged soils can cause N losses from the soil, through NO_3^- leaching (removal of nitrate from the soil profile) or denitrification (gaseous loss of NO_3^- in the form of N_2O through microbial activity). Nitrate leaching could cause groundwater contamination and eutrophication of water courses. Denitrification could lead to increased global warming. In both processes the loss of NO_3^- could have a negative effect on crop production, since NO_3^- is needed in large concentrations for plants to grow. Other factors that must be considered for healthy, beneficial microbial populations include erosion control, limited use of chemical fertilizer and pesticides, management of OM, reduced tillage and traffic control to minimize compaction.

Composting

Composting is a microbial process in which noxious organic waste is converted into stable humus-like substances. Composting is initiated by mesophilic chemoheterotrophs. As they respire, the temperature in the compost pile increases. The heat is produced by aerobic oxidation of the waste. If the temperature rises above 80ºC, it becomes too hot and kills the microorganisms responsible for composting. However, high temperatures are more effective at killing pathogens and weeds in the compost. Optimal composting is dependant on type and composition of organic waste, availability of microorganisms, aeration, C, N, P ratios, temperature, moisture content, temperature, pH and time.

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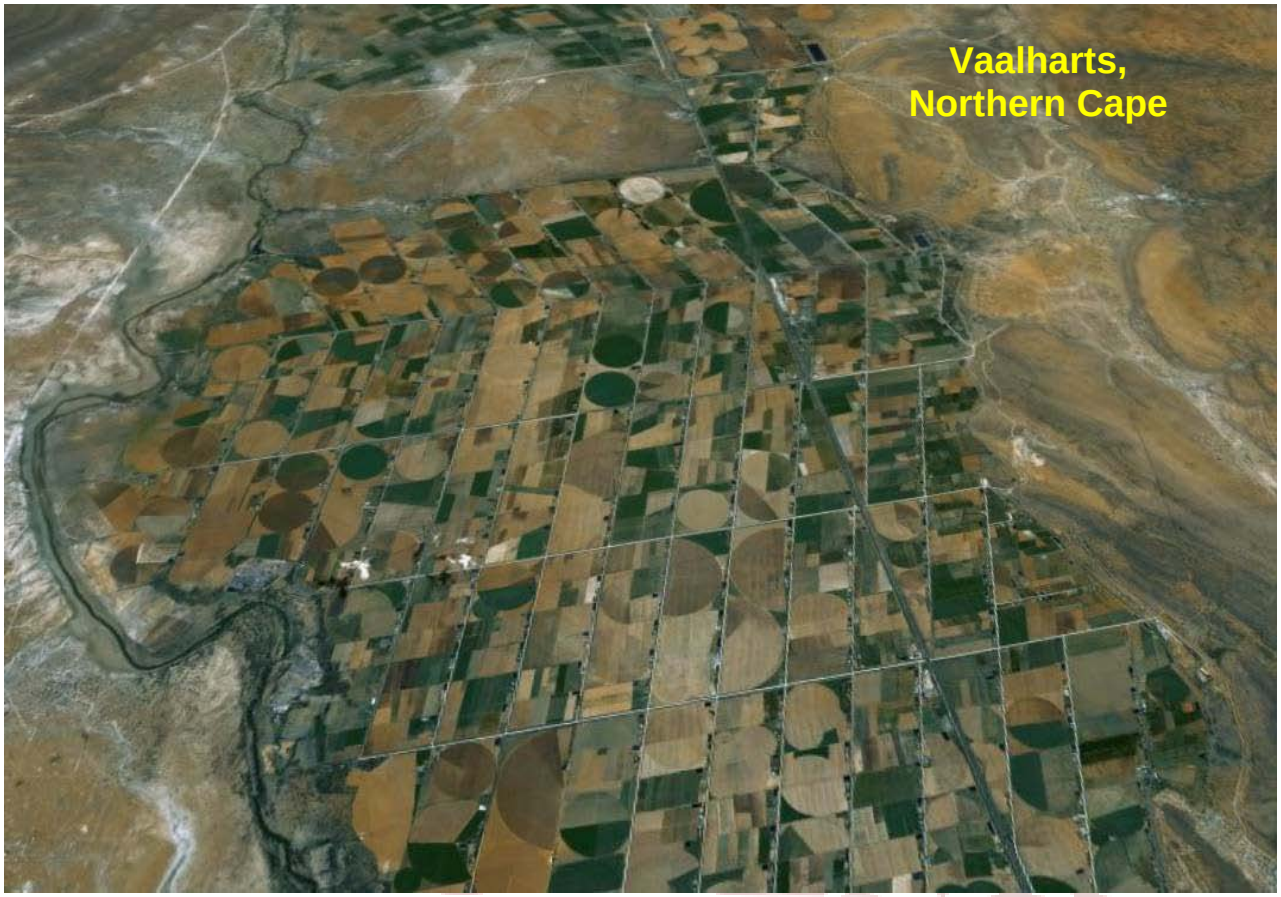
IRRIGATION



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1

INTRODUCTION TO IRRIGATION

Irrigation involves several broad aspects:

Supply of additional water to rainfall – this can either be as a supplementary source (e.g. at critical times in the growth cycle) or as a virtual replacement (more or less constantly throughout the growth cycle). This must also be assessed as a risk over the long-term

Water requirement – the amount required for a crop within a growing season must be balanced against the amount available from the irrigation source.

Crop parameters – the requirements and tolerance (e.g. to salts) of the crop must be compared with the irrigation water quality, as well as the soil characteristics, again taking possible long-term effects into account

Irrigation system design – this is usually costly, so a full economic study needs to be done for the input costs and output costs of the planned crop.

South Africa is on the whole a semi-arid country, with a great variation in rainfall, both from year to year and within any particular growing season. This makes irrigation both an attractive option as well as a significant challenge.

SOURCES OF IRRIGATION WATER:

Surface Water – this involves extracting water from surface bodies, such as perennial rivers or reservoirs, either on a large scale (such as a controlled irrigation scheme) or on a small scale (such as a small earth dam on a farm).
Ground Water – this involves the extraction of water from underground sources, usually by pumping from an aquifer, but occasionally using a natural spring. The scale may also vary.

Saline Soils – sufficient soluble salts to adversely affect plant growth*, low Na content:
EC >400 mS^{-1}, ESP <15

Sodic Soils – soils with low salt content but enough sodium to cause deflocculation (dispersion): **ESP >15**, EC <400 mS^{-1}

Saline-Sodic Soils – high salt content and high sodium levels: **EC >400 mS^{-1} *and* ESP >15**

* This usually involves the collapse of the cells of the plant, a process known as plasmolysis.

Irrigation Suitability: uses a five-class system, combining slope aspects, soil depth, texture, structure and drainage.

Class 1 – Soil is irrigable with no preconditions or limitations
Class 2 – Soil is irrigable with minor limitations
Class 3 – Soil has significant limitations and is only irrigable in special circumstances, or if small areas are surrounded by larger areas of better soil
Class 4 – Soil has severe limitations and should not be irrigated
Class 5 - Soil has very severe limitations and irrigation would lead to significant degradation

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CASE STUDY: MULTI DISCIPLINARY CO-OPERATION IN IRRIGATION PLANNING

C. Malan
Netafim SA, P O Box 129, Kraaifontein, 7570

This presentation aims at illustrating the most important considerations involved in planning an irrigation development for crop production. “Maiximum yield is attained through uniformity”, “quality is produced in the field”, “quality is the only way to ensure competitiveness in the international market”. These remarks are often heard and are used to describe the main criterium for success in irrigated agriculture which boils down to quantity and quality. The emphasis between quantity and quality varies from crop to crop but both are influenced by aspects such as climate, terrain, soil, rootstock, cultivar, water requirement, irrigation, optimal ripeness and various cultural manipulations.
All these aspects must be considered and analyzed through multi disciplinary co-operation between the producer, crop specialist, soil scientist, meteorologist, irrigation specialist, fertilizer specialist and irrigation engineer in order to plan a development consisting of production units with uniform quantitive and qualitive potential. A well designed irrigation system must accommodate these variations to allow control over moisture and nutrient levels according to the requirements of the irrigator, plant and soil.

Thee development planning in this presentation was adapted from a previous presentation that was the result of multi disciplinary co-operation where a specialist from each scientific field involved in vineyard development planning were asked to plan a farm according to the latest know-how existing in the wine industry. Most new vineyard developments are these days planned according to these principles. The same principles are applicable to the planning of irrigation systems for virtually all crops.

A good irrigation system able to meet the production requirements of the producer, is the end result of proper planning and requires the inputs of various specialists.

Land suitability assessment for vine production based on the principles of the terroir concept.

Critical decisions need to be taken by the wine producer throughout the life span of a vineyard, but none as critical as those taken during the planning phase. Some of these decisions have to do with finding the right terrain and soil for a specific cultivar, deciding on the most appropriate rootstock, soil preparation, drainage system, soil amelioration, row width, and irrigation design. To support this decision-making, the division for Resource Utilisation at Elsenburg now renders a service, custom-made for the biggest challenge facing the wine industry, namely the production of quality wine.
Wine quality can be achieved through various manipulations, but the effect of the soil, topography and climate will always be notable in the wine character. This phenomenon is what the French call *TERROIR*. Recent scientific and technological developments have lead to a more systematic quantification of environmental factors contributing to wine character.

Based on this, a three-tiered service is offered to assist the planning phase of vineyard development:

1. An analysis of topographic and climatological properties, such as slope, aspect, solar radiation, temperature, rainfall and evapotranspiration.
2. Detailed soil mapping at a scale of 1:7 500 or larger.
3. The option of a digital spatial database of the entire production environment and incorporation into a Geographic Information System (GIS).

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The terroir-analysis

This component of the service entails a detailed description and analysis of the topography on a scale that makes it possible to identify most suitable terrain units from as small as 1 hectare in size (typically a grid of 30 m x 30 m). Being a GIS-based analysis, maps compiled of the study area depict slope steepness, aspect (i.e. north, south, east, west, etc.) and terrain form (i.e. crest, midslope, footslope and valley floor).

From the digital elevation model (DEM) a calculation of an important variable, namely the solar radiation is made and mapped. In addition to this, an analysis is made of the long-term climatological features of the area, through an interpolation of data captured at nearby weather stations.

Soil mapping

Soil mapping is done after the description of soil profile pits on a grid of 50 m x 50 m to 75 m x 75 m, depending on the complexity of the soil pattern. At the end of the survey, representative profiles of each of the soil types identified are sampled. These samples are submitted to the laboratory for chemical and physical (water holding capacity and particle size) analysis.

A report is compiled, consisting of a general description of the soils of each soil type mapped, the soil codes of all profiles occurring inside each soil compartment and a discussion of the physical properties of the soils and possible ways in which physical limitations (e.g. wetness, shallow effective soil depth) can be removed or ameliorated. The water holding capacity of the different soil horizons as well as the total water-holding capacity up to a specific depth is provided. The levels of the macro- and micro- plant nutrients are discussed and amount of lime, phosphate and potassium required before establishment is recommended. A production potential rating is also given.

All analytical results as well as tables summarizing the soil information, chemical ameliorant requirements and mechanical soil manipulation required are supplied as appendices to the report. The soil map with a short soil legend accompanies the report. This map can be supplied at any scale and in digital format.

Digital Spatial Data Base

This component of the service is offered as an option for clients requiring the versatility and capability of a GIS-based information system of the entire production environment and history. It normally requires an intensive initial input to digitise all relevant spatial information, either from aerial photographs or scale true maps or by performing some GPS surveys. Once operational though, this system provides multiple benefits with minimal input to everybody involved in the production chain, from the vineyard manager, and viticulturist all the way to the wine maker and financial manager.

The system can best be described as computerised maps of the entire production area, including soil and climate maps, electronically linked to all the production statistics of each vineyard. The span of this part of the service is entirely client dependent and is custom-made to suit the needs of each individual.

Viticultural inputs (Crop specialist)

I. Viticulturist will visit the site to familiarise him/herself with the terrain, soils, topography, slopes, etc.
II. After acquiring the terroir analyses, soil maps and GIS maps, a meeting will be set-up with the owner/winemaker/managers to discuss and plan the following:
   - Cultivars according to available terroir and market requirements

- Product specification/ wine style/market aims
- Product quantities – litres/tonnes per cultivar or product
- Recovery calculations
- Required tonnes; average per ha
- Ripening periods

II. Meeting with owner/production manager, soil scientist, irrigation, designer and irrigation specialist to decide on most appropriate production units. The following will be discussed and taken into consideration: soil types, row orientation, and cultivars, water holding capacity classes, irrigation blocks, etc.

III. Report specifying:
- Products and quantities per cultivar
- Cultivar, rootstock, clones per production unit
- Long term production expectations per cultivar according to planting program

Water source analyses

Water source analyses according to suitability for:

- for crop production
- risk of emitter clogging
- irrigation system maintenance procedures

Water requirements and irrigation scheduling

Reports for water requirements on a monthly basis, total per annum and irrigation scheduling advice according to climate, soil type, expected rooting depth, irrigation system, yield potential, leaf canopy and type of trellising system for each soil type/production unit.

Nutrition

Fertilizer agronomist will do recommendations according to soil, water and crop. Consultation between different parties involved to determine intensive or extensive approach, water enrichment or dumping and fertilizer injection equipment to be used.

Irrigation equipment

Consultation is essential between producer, irrigation engineer, soil scientist, irrigation specialist and crop specialist to determine most appropriate irrigation method with specifications for emitter type, spacing and delivery. Decisions regarding filtration, automation, etc.

Irrigation engineer

System to be designed according to above inputs and specifications of various specialists.

A well-designed irrigation system is the end result of proper planning with the inputs of various specialists and will be able to allow control over moisture and nutrient levels according to the requirements of the irrigator, plant and soil.

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SOIL SCIENCE:

Training of Subject Advisors for the Department of Education, May 2009

DETAILS OF PRESENTERS

Dr. Dave Turner (Pr. Sci.Nat.*)
Tel: 012 310 2597
Cell: 082 441 1676
E-mail: DTurner@arc.agric.za
Speciality field: Soil physics, pedology, soil survey and mapping, clay mineralogy.

Mr Garry Paterson (Pr. Sci.Nat.)
Tel: 012 310 2601
Cell: 083 556 2458
E-mail: Garry@arc.agric.za
Speciality field: Pedology, soil survey and mapping, irrigation.

Mr Ernst Jacobs (Pr. Sci. Nat.)
Tel: 012 310 2668
Cell: 082 320 0278
E-mail: Ernst@arc.agric.za
Speciality field: Pedology, soil survey and mapping, data base management.

Dr Goodman Jezile
Tel: 012 310 2545
Cell: 074 370 4903
E-mail: JezileG@arc.agric.za
Speciality field: Soil chemistry, organic matter, soil nitrogen, Conservation Agriculture (CA).

Ms Corrie Swanepoel (Pr. Sci. Nat.)
Tel: 012 310 2630
Cell: 076 618 0605
E-mail: SwanepoelC@arc.agric.za
Speciality field: Soil chemistry, soil organic matter, soil nitrogen, wetlands, CA.

Mr Faith Seabi
Tel: 012 310 2653
E-mail: SeabiF@arc.agric.za
Speciality field: Pedometrics, soil mineralogy

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Agricultural Research Council
600 Belvedere Street, Arcadia, 0001
Private Bag X79, Pretoria, 0001
Tel: 012 310 2500
Fax: 012 323 1157
www.arc.agric.za

* Registered as a professional scientist (Pr. Sci. Nat) at The South African Council for Natural Scientific Professions (SACNASP)

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