European Commission

SOIL ATLAS OF AFRICA

A collaborative initiative of the European Union, the African Union and the Food and Agriculture Organization of the United Nations to support and encourage the sustainable use of soil resources in Africa and the Global Soil Partnership for Food Security.

Joint Research Centre

World Soil Information

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Cover

The striking map on the cover depicts the diversity of soil types across Africa according to the World Reference Base for Soil Resources classification and correlation scheme.

The central, more humid part of the continent is dominated by deeply weathered, acidic soils with high levels of iron oxides and lacking in essential plant nutrients (brown-orange are Ferralsols, often associated with Acrisols, light orange). In drier conditions, weathering processes are less intense which, together with inputs of wind-blown dust, give rise to soils with increased clay content and slightly higher pH (Lixisols appear as pale pink areas). In West Africa large areas are characterised by soils with surface layers hardened by iron and clay compounds, often leading to an inversion of the landscape (Plinthosols are shown by the dark brown colour).

The desert regions in the north and the south are dominated by soils that are lime-rich (bright yellow: Calcisols), shallow (grey: Leptosols), weakly developed (pale rose: Regosols), sandy (brownish yellow: Arenosols) and gypsum-rich (pale yellow: Gypsisols). In the dry part of southern Africa, soils with a significant accumulation of silica and an associated 'hardpan' can be found (pinkish grey: Durisols).

The dark purple colour on the map, notable in Sudan and Ethiopia, indicate soils containing high levels of swelling and shrinking clays (Vertisols) whereas the bright red colours depict associated with volcanic deposits (Andosols), especially evident along the African Rift Valley. This is also where most of Africa's most fertile soils are found (dark rose: Nitisols). In the Mediterranean region the pale brown and light green colours indicate soils that have developed under permanent grasslands (respectively, Kastanozems and Phaeozems).

Soils that are have been strongly influenced by water are found throughout the map and indicate wet conditions caused by high groundwater levels (dark blue: Gleysols), stagnant water (dark orange: Planosols) or sediments associated with Africa's river systems, deltas or mangroves (bright blue: Fluvisols). Saline and sodium-rich soils (purple: Solonchaks; light purple: Solonetz) are mainly associated with ephemeral lakes in arid climates and coastal plains.

Soils that are young in age and weakly developed (orange: Cambisols) or rich in organic matter (dark grey: Histosols) are scattered throughout the map. Soils such as Luvisols (dark pink), Podzols (green) and Umbrisols (dark green) can be locally important. In urbanized areas and near large mines, highly disturbed soils (Technosols) may occur. However, they are too small to be visible given the small scale of this map.

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http://en.wikipedia.org/wiki/Digital_Chart_of_the_World

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Soil Data

The soil maps presented in this atlas are derived from several projects covering the African continent. They include:

- The Harmonized World Soil Database
- The Soil Geographical Database of Eurasia (scale 1:1 000 000)
- The FAO-UNESCO 1:5 000 000 Soil map of the World

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  http://www.iiasa.ac.at/

- Van Liedekerke, M., Panagos, P., Daroussin, J., Jones, R., Jones, A. & Montanarella, L., 2004. The European Soil Database Version 2.0. Distributed by the European Commission Joint Research Centre, Ispra, Italy

  http://eusoils.jrc.ec.europa.eu/

- FAO - UNESCO, 1974. Soil Map of the World, 1:5.000.000

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The EU supports the efforts by the Secretary General of the United Nations and his Personal Envoy to find a just, lasting and mutually acceptable political solution which will allow the self-determination of the people of the Western Sahara as provided for in the resolutions of the United Nations.

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Finally, every effort has been made to recognise all contributors and trace all copyright holders. The Editorial Board offer their sincerest apologies for any unintentional omissions and offer their appreciation for all contributions. The JRC would be pleased to amend or add any missing acknowledgment in future editions or online versions of the atlas.

† Regrettably, Peter Bullock, an enthusiastic supporter of the atlas project and an experienced authority on the soils of Africa, passed away during the early stages of this publication, to which he willingly gave much valuable material and direction. An active researcher and an excellent scientist, his enthusiastic contributions are sorely missed.

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Soil, along with water, is arguably the most precious resource on the planet. In addition to the widely recognised agricultural benefits, soil also provides a myriad of life-critical environmental services that are fundamental to the well-being of all creatures on the planet. This picture from the Ubari Desert of Libya shows an oasis in the lee of a large dune complex in a sand desert. Oases are isolated areas of vegetation in arid areas surrounding a water source, normally a spring or a well to an underground aquifer. The combination of water, organic matter from plant remains, animal manure and the soil provides the necessary conditions for vegetation to survive and flourish in an otherwise hostile environment. If properly managed, oases soils can support a large variety of plants and crops. The surface of soils in oases are often raised due to the addition of organic matter and irrigation water containing substantial amounts of sediments. (TS)

In contrast to the desert landscape from Libya, this photograph shows a lush, verdant environment on volcanic deposits along the Rift Valley in Tanzania. It is clear that the soil characteristics here will be very different to those in the desert. Throughout Africa, rural populations depend on soil functions to provide food for their families, fodder for animals, fuel for cooking, crops for markets – activities that are fundamental to the economies of most African countries – and even the walls of their homes. Plants such as tea, coffee, cocoa, oil palm, cotton, sugar cane, bananas, oranges and olives are often referred to as 'cash crops' because of their high economic value. Mono-culture (i.e. the continued cultivation of a single crop) will in time lead to a reduction in soil fertility and the onset of land degradation issues such as erosion. Recent interest in the development of biofuels as an alternative source of energy is putting many soils in Africa under increased pressure. (VL)

Preface

The sustainable management of natural resources in Africa is a formidable challenge, crucial for the survival of over one billion people. Africa has the capacity to feed itself, and its soil has maintained its fertility over millennia. Throughout the continent, many areas now suffer from land degradation from inappropriate cultivation practices which are often driven by a desire for quick economic return, but ignore the capacity of the soil to support them, exacerbated by a high level of rural poverty.

Understanding the evolution of soils and associated vegetation patterns in relation to their use by society is fundamental if we wish to assess fully the impacts of processes driving change in Africa. This applies equally to climate change, population growth and food security, which are key challenges that EU policies seek to address through numerous initiatives.

The evidence for soil degradation and environmental change is apparent in many parts of Africa. By building on existing cooperation with researchers from Africa, EU Member States and international organisations, the European Commission's in house science service, the Joint Research Centre (JRC), brings together people from diverse national and political backgrounds to address this relevant issue, and communicate science to the wider society.

This innovative "Soil Atlas of Africa" aims to raise public awareness on the importance and the key role of soil in Africa as a non-renewable resource essential to human existence. In doing so, it supports the development of protective measures to safeguard soils for current and future generations.

The atlas compiles existing information on different soil types in easily understandable maps that cover the entire African continent. While it is intended primarily for the educational sectors and policy makers, the atlas aims to bridge the gap between soil science and society at large.

We believe that this impressive publication will become a widely-used reference and marks an important step towards a better understanding of the role of soil in the sustainable development of Africa.

Máire Geoghegan-Quinn

EU Commissioner
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Andris Piebalgs

EU Commissioner
Development

In its role as the only Commission service performing direct research in support of European policies, the Joint Research Centre (JRC) has undertaken the task to collect and compile a dataset about soils worldwide. This "Soil Atlas of Africa" is a significant step forward in this effort.

Resulting from a fruitful partnership of leading African and European scientific experts in soil research, the issue complements a series of other atlases developed in recent years: Soil Atlas of Europe, Soil Atlas of the Northern Circumpolar Region, European Atlas of Soil Biodiversity, and the forthcoming Soil Atlas of Latin America and the Caribbean.

One of the main outcomes of JRC's long term engagement in soil research concerns the acknowledgement of the strategic importance of soils for all nations, especially in face of the current global economic, social and environmental challenges. All these aspects are included in the atlas in clear and accessible language, completely illustrated with diagrams and many maps. I am pleased to endorse this atlas, which demonstrates that a wealth of scientific information can be disclosed in a very interesting way.

Dominique Ristori

Director-General
European Commission DG Joint Research Centre

Foreword

Although it is all around us, soil is often the most overlooked natural resource. We know that, depending on the region, it can take one hundred to one thousand years to form just one centimetre of soil. And yet, degradation and erosion can lead to the loss of that precious soil in few minutes.

Recognizing that soils are the foundation of agriculture and food production, and thus one of the main pillars of food security, FAO has played a lead role over the years in developing tools and providing technical and policy support for soils and land resources information and sustainable management in Africa.

The Soil Fertility Initiative with the World Bank in the '90s raised attention of countries in Sub-Saharan Africa to the need for integrated soil policy for sustainable agriculture. However, soils have not been a priority area in the decision making agenda for many years. Why is this? It seems that soil is a "hidden resource" and few decision-makers are really aware of its key role in the provision of ecosystem goods and services.

Strategies to address sustainable management of soils and the preservation of this resource for future generations need to be scientifically sound and based on the most current data. For its part, the FAO, together with the African Union and the European Commission, will continue to promote awareness raising events, soils data and information, research projects to fill knowledge gaps and address real problems on the ground, technical support and capacity development in particular to mentor young soil scientists and the integration of soil related issues into policy decisions for agricultural development and food security Agenda in Africa.

This striking, informative and timely document perfectly supports the ideals of the FAO led Global Soil Partnership. I hope that you will find this Atlas both enlightening and useful as a scientific reference and as general source of information about the immense variety of African soils and their vital functions.

Prof. José Graziano da Silva

Director-General
United Nations Food and Agriculture Organisation

Key messages

To ensure the sustainable use of soil resources, the people of Africa should strive to:

- assess the current state of soils and associated pressures across their territories;
- assess the impacts of current policies and land use practices on soil quality in areas such as agriculture, waste, urban development or mining, and to adopt preventative measures to ensure the sustainable use of soil and maintenance of soil functions and services;
- develop action programmes to deal with the main issues of local concern, including strategies for the remediation of degraded and contaminated land;
- develop systems for the collection of harmonised soil information and long-term monitoring of trends in soil functions and characteristics;
- support the networking of soil scientists and land use experts from across Africa in order to improve information exchange and develop a more comprehensive knowledge-base to underpin sustainable soil use policy development and practices;
- develop awareness raising strategies to highlight the importance of soil to everyday life and thus promote the good management of soil for future generations.

Preamble

Healthy, fertile soils underpin food security, social cohesion and the economies of most African countries. Unfortunately, soil tends only to reach public consciousness when it fails – often with catastrophic consequences as seen by the famine episodes of the Sahel in the 1980s and more recently in Niger and the Horn of Africa. While large parts of the continent are hot and arid, in reality, Africa has some of the most fertile soils on the planet. However, conflicting or competing demands on the use of the land is putting increasing pressures on what remains.

This atlas, the result of collaboration between African and European scientists outlines the specific challenges facing soil resources across Africa. By highlighting the factors that control specific ecological, agricultural and economic services, the atlas highlights the need for a coherent and holistic approach to the management of soil across the continent.

I hope you enjoy this beautiful book.

Tumusiime Rhoda Peace

AU Commissioner
Rural Economy and Agriculture

Message from the Africa Soil Science Society

If asked to consider the question of what they know about soil in Africa, the vast majority of people have no idea how to answer. For many, the first thoughts that spring to mind are scenes of dusty, infertile land, accompanied by images of people suffering from drought and famine. Further reflection may bring to mind images of hot and humid rainforests with dense, lush vegetation growing on bright red tropical soils. In reality, soils on the African continent can be productive, are highly diverse and, in many cases unique. Healthy soils underpin so many vital services. Of these, one could argue that food production is the most critical as it is basic to human survival. Yet where would we be without the myriad of other soil functions – a rooting medium for plants (hence the main source of food, fibre and fuel on the planet), water storage, the preservation of our cultural heritage, and so on.

Averting soil degradation in Africa is a major challenge. Across the continent, annual soil losses are estimated to be in the order of hundreds of millions of tonnes. The population explosion, rapid urban expansion, increased pressure on existing agricultural areas, and the short-term financial gains made through overstocking, mono-cropping and the ploughing of marginal lands unsuitable for cultivation are all drivers of land degradation. Such practices encourage the exploitation of the land without due regard to the long-term consequences.

When erosion by wind or water removes the nutrient-rich topsoil, cultivation becomes increasingly difficult. When this occurs in areas where people are too poor to replace the loss with fertiliser, soil fertility slowly declines and yields fall, driving farmers deeper into poverty. If left unattended, the result can be catastrophic, not just for the land but also for the populations that depend on the soil for their wellbeing and livelihood. For these reasons, understanding the importance of the proper and sustainable management of soil should be a crucial goal for society as a whole. Political and economic changes are needed to address soil use and management throughout Africa. The Soil Atlas of Africa represents a consolidated effort to raise awareness about the value of this key resource. Finally, this Atlas would certainly not have been produced without the scientific heritage that was left by the many European soil scientists who travelled to Africa.

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Introduction

A general perception of tropical Africa is probably one of lush rainforests growing on red soils (as shown by this striking profile from Tanzania). Most soils in the tropics are actually deeply weathered (which indicates that they are very old), highly acidic and largely devoid of essential nutrients (such as phosphorus, potassium, calcium and magnesium) which have been leached out over time. They contain high levels of iron oxides which give rise to their distinctive reddish or yellowish colour. Natural ecosystems have evolved to survive in such poor soils by maintaining a fragile nutrient cycle that exploits a unique relationship between the rapid decay of litter, the roots of plants and a type of fungus called mycorrhiza. Clearing the forest destroys this balance, causing the soil to become infertile within a few years. (EM)

Soils underpin the classical landscapes of Africa which, in turn, reflect the principle soil forming factors of parent material, climate, topography, vegetation (itself driven by the chemical and physical properties of the soil), time and the influence of human beings. The photograph shows giraffes (*Giraffa camelopardalis*) grazing on Acacia trees (also known as thorntrees) on the Rift Valley floor in east Africa. Acacias can tolerate many soil condition, even dry, well-drained, lime-free soils. Once established, vegetation provides organic matter to the soil and, in some cases, shade for other plants to flourish, especially in dry or hot climates. Where soil moisture is low or lacking, the roots of plants such as Acacias can extend for up to 30 m below the surface. As a member of the pea family, most Acacia trees are able to take nitrogen from the air and store it in the soil. (EM)

Scope of the atlas

Soil, a material composed of minerals, organic material, air and water, performs a number of key environmental, social and economic services that are vital to life. Supplying water and nutrients to plants, at the same time soil protects water supplies by storing, buffering and transforming pollutants. Soil is also an incredible habitat that provides raw materials, preserves our history and reduces the risk of floods. Without soil, the planet as we know it would not function.

However, the importance of soil and the multitude of environmental services that depend on soil properties are not widely understood by society at large. A part of the problem is that with an increasingly urban society, many people have lost contact with the processes that produce food. Most people expect to find food on the shelves of supermarkets and have limited or even no appreciation of the roles played by soil. Concepts such as nutrient cycling and organic matter management, that are critical to soil fertility and food production, are a mystery to most. To compound matters, there is very little dialogue between the soil science community and the general public. The majority of soil-related print material is geared towards university level or scientific journals - normally beyond the reach and understanding of the general public. This results in a lack of material to help interested stakeholders appreciate the value of soil and guide them in preserving this precious resource.

As a consequence, soil as a topic tends not to feature in the minds of the public or politicians. However, some groups are becoming increasingly aware of a greater need to inform and educate the general public, policy makers, land managers and other scientists of the importance and global significance of soil. This is particularly true of the soils in Africa where the dramatic consequences of the failure to use soil sustainably have led to desertification, famine, civil unrest and human suffering, often on astonishingly large scales.

It is in these contexts that the European Commission's Joint Research Centre initiated a project to bring together experts from Europe and Africa to produce the **first** ever **SOIL ATLAS OF AFRICA**. The main goal of the project was to produce a publication, aimed at the general public, decision makers, politicians, teachers and even scientists in other disciplines, that raises awareness of the significance of soil to human existence in Africa.

Soil is the interface between the hydrosphere, atmosphere, lithosphere and organisms inhabiting it. Consequently, the structure and other characteristics of soil are the products of age-old processes. As the regulator of biogeochemical and energy cycles, soil is extremely sensitive to the effects of climate change and to human activities. Such changes can have dramatic consequences on one of the key services provided by soil – the provision of food, fibre and fuel. This striking photograph of Mt. Kilimanjaro, Africa's highest mountain, shows the several aspects of soil. In the foreground, the soil is being used for agriculture under a plantation farming system. This aspect provides for the production of food and underpins the economy of many African countries. In the middle ground, the soil supports semi-natural vegetation and a host of ecological services such as biodiversity and nutrient cycling. In the background, the receding glaciers are a clear indication of a changing climatic conditions, which in turn, will affect the surrounding soils. (WS)

The atlas attempts to show and explain in a simple and clear manner the reasons for the varying patterns of soil across Africa as well as the need to conserve and manage this increasingly threatened natural resource through sustainable use. At its heart is a series of annotated maps that show, for the very first time, the diversity of soil characteristics across the African continent in a manner that is comprehensible to the layperson.

The atlas explains in a non-technical manner how soils are formed, the key factors that shape soil characteristics and why these vary across the African continent. Special attention is given to the pressures on the soil of Africa through illustrated examples.

Furthermore, the atlas supports the goals of the European Union's Thematic Strategy for Soil Protection [1,1a] and the Sustainable Use of Natural Resources [2]. The atlas is a practical example of the aims of the joint Africa-EU Strategic Partnership, especially in the context of sustainable environmental development [3] while being a major contribution of the EU to the United Nations Food and Agriculture Organization's Global Soil Partnership initiative [4].

After reading this atlas, we hope that the content helps you to understand better how the product of the complex interactions between climate, the landscape, the geological substrate, vegetation, living organisms, human influences and time leads to the creation of the valuable resource we call soil.

The preservation of organic matter is a precondition for a soil to undertake many of its key environmental services, especially that of supporting agriculture. In this photograph from North Africa, the dark colour of the soil indicates a high level of organic matter, usually as a result of a permanent cover of grass and a climate where the soil is moist for most of the year. Such soils are valued for their agricultural productivity, in particular cereals, such as wheat and barley, or vegetables. However, the characteristics that make the soil favourable for agriculture should be managed by timely cultivation and careful use of irrigation, if required. In Africa, such soils are limited in their extent. In the humid tropics, most soils are highly leached and low in organic matter. Traditional shifting cultivation practices, where land was abandoned after a few years of cultivation, allowed organic matter levels in soils to recover during sufficiently long fallow periods. However, modern sedentary farming methods on such soils require constant fertilisation and specific management practices to achieve satisfactory yields. (GT)

Red is the dominant colour of soils in tropical Africa. While soil colour can vary dramatically throughout the continent, the long-term weathering of iron-rich sediments, especially in the tropics, does produce striking red and yellow colourations of the soil. This picture shows villagers looking at a red, fertile soil that has developed from the nutrient-rich weathering products of basaltic rocks found on the southern slopes of Mount Kilimanjaro in Tanzania. (EM)

Key facts about soil

- A sample of mineral soil consists of (by mass) minerals (up to 95%), water (15-35%), air (15-35%) and organic matter (5%). In arid regions, the amount of water and organic matter will be much less.
- Some soils in Africa can be very old – often reflecting dramatic changes in climate and vegetation.
- Many soils in Africa are red in colour indicating high levels of iron or aluminium oxides.
- More than half of the African land surface is characterised by sandy soils (22%), shallow stony soils (17%) and young, weakly developed soils (11%).
- Unlike other continents, the area of peat soils is very small in Africa.
- In some temperate ecosystems, 5 tonnes of living organisms (or the equivalent of one elephant) can be found in one hectare of soil – most of which still needs to be studied.
- Soil reduces the risk of floods and protects underground water supplies. Soil organic matter can store more than ten times its weight of water.
- The soils of Africa store about 200 Gt of organic carbon - about 2.5 times the amount contained in the plant communities of the continent.
- One of the most important functions of soil is the recycling of nitrogen, phosphorus, carbon and other nutrients. The harvesting of crops from cultivated soils breaks the nutrient cycle, which then requires additional inputs. In many parts of Africa, soils are losing nutrients at a very high rate, much greater than the levels of fertiliser inputs.
- Soils under tropical rainforests are not naturally fertile but depend instead on the high and constant supply of organic matter from natural vegetation. Breaking this cycle (i.e. through deforestation) quickly reduces the productivity of the soil.
- The largest earthworm ever found was discovered in 1967 in Williamstown, South Africa and measured 6.7 metres in length.
- 98% of all calories consumed in African comes from the soil.
- Soil degradation (e.g. erosion, chemical and physical damage) affects about 65% of African farmlands.

The role and importance of soil

Soil is the vital natural habitat that regulates our environment and responds to the pressures imposed upon it. Ignored by the majority of us, soil carries out a number of key tasks that are essential to our well-being:

A lush meadow in South Africa growing on a clay–rich soil that typically develops in depressions or basins that are periodically wet. One of the main services provided by soil is in the provision of food, feed for animals, fibre for clothing and wood for fuel or construction. However, soil depletion and degradation are major issues which can lead to hunger and poverty in many parts of Sub–Saharan Africa. Since the 1970s, food production has not kept pace with population growth in Africa, which is now in excess of 1 billion people. Increased pressure on the land, a decline in soil fertility, and an acceleration of desertification in many places means that the soil is unable to meet expectations. Strategies for improving soil fertility include the use of compost, crop residues, animal manure, biomass, chipped wood, hedgerow intercropping (alley farming) and cover crops. In addition, natural grasslands such as this are an important store of carbon. (EM)

Soil is the medium that enables us to grow our food, natural fibre and timber and supports wildlife habitats

One of the most widely recognised functions of soil is as the material in which plants grow. In turn, many of these plants are used by people directly as food (i.e. crops) or medicines, as feed for animals or for fibre (e.g. for fuel or construction). Food security is a key issue in Africa. While many areas have naturally productive soils, many African farmers traditionally maintained soil fertility by practising shifting cultivation or applying mineral fertilisers on their fields. However, economic and social conditions in recent years have seen a decline in both traditional shifting agriculture systems and access to subsidised agro-chemicals. Additionally, many soils in Africa have severe limitations for growing crops because they are too shallow, too wet, too dry or lacking in nutrients. Extreme climate zones mean that biological activity and the availability of essential nutrients in the soil vary significantly. In hot, dry regions, the most productive agricultural soils are to be found along the major river valleys or around wells or oases.

Soil is a natural filter and regulator of water flow

One of the key functions of soil is to act as a natural purification system. Over time, soil has the ability to filter, absorb and transform substances. Chemical compounds that are deposited on or in the soil, together with excess agro-chemicals, can be trapped, thus preventing them from reaching clean water supplies. Additionally, contaminates can be degraded or otherwise made unavailable to plants and animals through a range of biogeochemical processes. However, high levels of toxins or severe soil degradation can disrupt these processes leading to a loss of this function.

Soil is also a key regulator of water flow. Soil can absorb much of the rain that falls on it, but the amount varies according to texture, structure, organic matter content and vegetation cover. Well structured loamy soil under grass or woodland acts like a sponge and can absorb as much as 40% of its volume as water. Soil also acts like a tap, turning water flow on and off by storing and releasing water for plants when needed. Urban planners now realise that the sealing of soil by materials such as concrete and asphalt, together with compaction of the subsoil, is a significant factor in exacerbating the risk of floods from heavy rainfall. Any reduction in the capacity of soil to absorb water will lead to increased overland flow, the rapid transfer of rainfall to river channels, flooding and erosion.

Soil and water

Infiltration is the physical process involving the movement of water through the soil surface, essentially the boundary between the atmosphere and the ground. The ability of water to enter the soil is related to its porosity (the amount of space within the soil) and permeability (the ability of liquids to flow through the soil). In turn, these factors are governed by the texture and structure of the soil, the initial soil moisture content, soil composition and the swelling of clay minerals that can cause cracks in the soil to close. Water that has infiltrated the soil can later be released through evapotranspiration or subsurface flow.

Percolation is the movement of water though the soil by gravity and capillary forces. Water that is in contact with air in the soil is called vadose water. Where the voids (pores) in the soil are full of water, this saturated zone is called groundwater. Groundwater can move in both vertical and horizontal directions. The boundary that separates the vadose and the saturation zones is called the water table.

A spring is a feature in the landscape where the water table reaches the surface. Groundwater discharges from the soil form the base flow of streams and rivers. This is especially important for maintaining a minimum level of water in channels during dry periods.

Lake Ubari, a brackish oasis in the Libyan desert (Erg Awbari) which, despite the saline water and encroaching dunes, supports extensive groves of palm trees. In recent years, the water table has dropped markedly in some of the lakes. Lake Mandara, once one of the biggest, is now almost dry. The drop in water level has been attributed to water diversion schemes. (BN)

Soil protects our buried heritage of archaeological and historic remains from damage and depletion

Much of the evidence of human heritage remains buried within the soil, awaiting discovery and study by archaeologists and palaeoecologists (scientists that study past environments and ecosystems). The degree of preservation of such remains depends very much on the local soil characteristics and conditions.

Soils with extreme characteristics (e.g very acid, very alkaline or waterlogged with low levels of oxygen) have very little microbial activity and provide an ideal environment for preserving organic remains. Any disturbance of these environments, such as by drainage or ploughing, changes these conditions and leads to the rapid decay and loss of the material. Archaeologists use these historical artefacts and the layers in which they are preserved to reconstruct the communities that produced them and the environments in which they lived. But to do this, the soil layers must remain undisturbed.

The occurrence of fossil soils (paleosols) and rock art across the Sahara provide clear evidence of dramatic fluctuations in climatic and environmental conditions. This carving of a cow comes from the Wadi Methkhandoush in Libya, a region that was once rich in lakes and rivers where such animals roamed the land (see also page 142). (TS)

Soil is the environmental engine room where dead plants, animal tissues and other organic matter remains are decomposed to recycle nutrients for the growth of new life

The decay of organic matter is driven by soil organisms, the total weight of which often equals or exceeds the above-ground biomass. A few hundred grammes of fertile soil can contain billions of bacteria, kilometres of fungal hyphae, tens of thousands of protozoa, thousands of nematodes, several hundred insects, arachnids and worms, and hundreds of metres of plant roots.

The biota turns the soil into a biological engine. Living creatures are involved in most of the key soil functions, driving fundamental nutrient cycling processes, regulating plant communities, degrading pollutants and helping to stabilise soil structure. Soil organisms also represent a crucially important biotechnological resource, with many species of bacteria and actinomycetes providing sources of antibiotics.

Soil provides the foundation upon which we construct our buildings, roads and other infrastructures

In addition to providing the support for the vast majority of human infrastructure, soil provides a range of raw materials such as clay, sands, minerals and peat. Clay is used for making bricks for construction, pottery items (e.g. earthenware) and was an early writing medium (clay tablets).

Daub is a building material that has been used for at least 6 000 years for making the walls of buildings. A woven lattice of wooden strips is daubed with a sticky material usually made from wet soil, clay, sand, animal dung and straw. It is still an important construction material in many parts of Africa and the technique is becoming popular again as a low-impact, sustainable building technique.

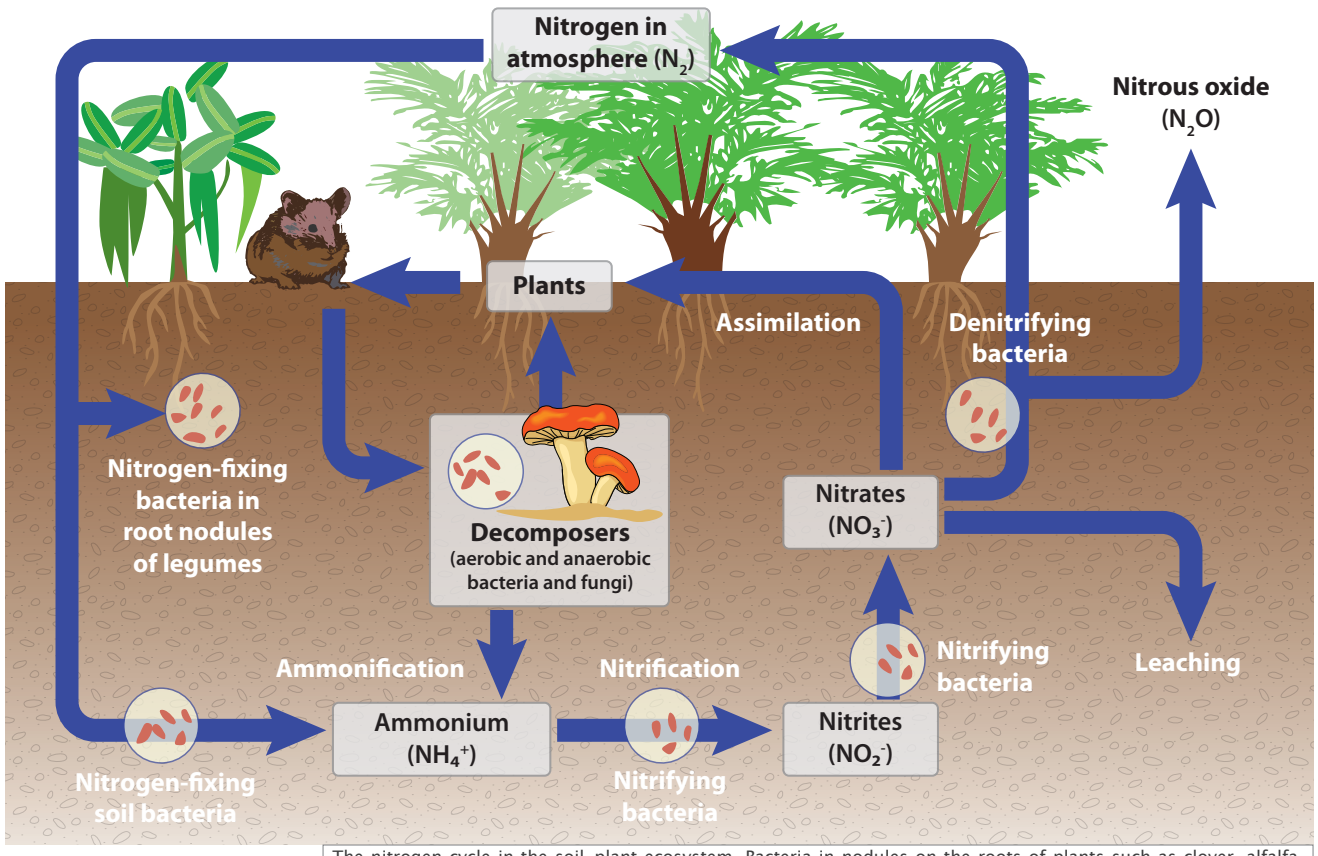
Mud bricks, made of a mixture of clay, silt, sand and water mixed with a binding material such as rice husks or straw, are a common building material in countries such as Niger and Mali. Dried in the sun for 25 days, these bricks have a lifetime of some 30 years.

Due to its impermeable properties, clay is used as a barrier to stop water seeping away which is why many ponds, canals and landfill sites are lined with clay.

Sand and gravel deposits, laid down by rivers, are heavily used in the construction industry as aggregates in concrete making, while sand is the principal ingredient in glass making and is used in sand-blasting to clean buildings and in sandbags to stop flooding. Like sand, gravel has countless uses. For example, in Africa, more roads have gravel surfaces than concrete or asphalt.

While peat can be added to soil by gardeners to improve structure and enhance soil moisture retention, in some parts of Africa, peat is a source of fuel. Increasingly, people are becoming aware of the environmental impact of peat exploitation and are looking for 'peat-friendly' alternatives.

The Great Mosque of Djenné in Mali, is the largest mud brick structure in the world. The structure is built from thousands of sun-baked mud bricks (called ferey) and a mud-based mortar coated with a mud plaster. Massive walls (between 40 – 60 cm thick) bear the weight of the tall structure and provide insulation from the sun's heat. During the day, the walls gradually warm up from the outside and cool down at night. The mosque's prayer hall can contain up to 3 000 people. The outside plaster is renewed every spring. (AG)



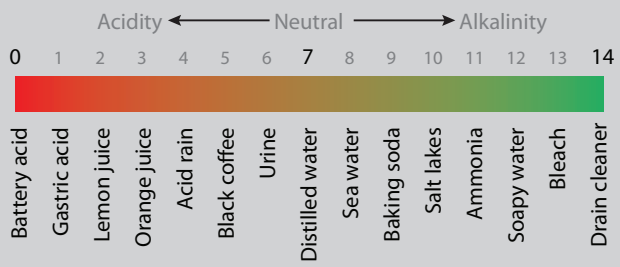
The nitrogen cycle in the soil–plant ecosystem. Bacteria in nodules on the roots of plants such as clover, alfalfa, and soybeans take nitrogen from the air and convert it into ammonium. This is then converted by other bacteria into nitrite ions and then into nitrate ions. Plants use the nitrate ions as a nutrients for growth. Other bacteria in the soil carry out a process known as denitrification which converts nitrates back to nitrogen gas. As well as being a greenhouse gas, nitrous oxide is also a mild anaesthetic known as 'laughing gas'. (LJ/EPA)

What is meant by heavy or light soil?

Soils are sometimes referred to as heavy or light. This is the ease with which they can be worked or tilled and depends on their texture (see box on page 12). Heavy soils contain greater proportions of clay or silt particles and retain much more moisture than soils with larger particles, such as sand. Consequently, they are heavier to dig into and turn over than light sandy soils.

What is pH?

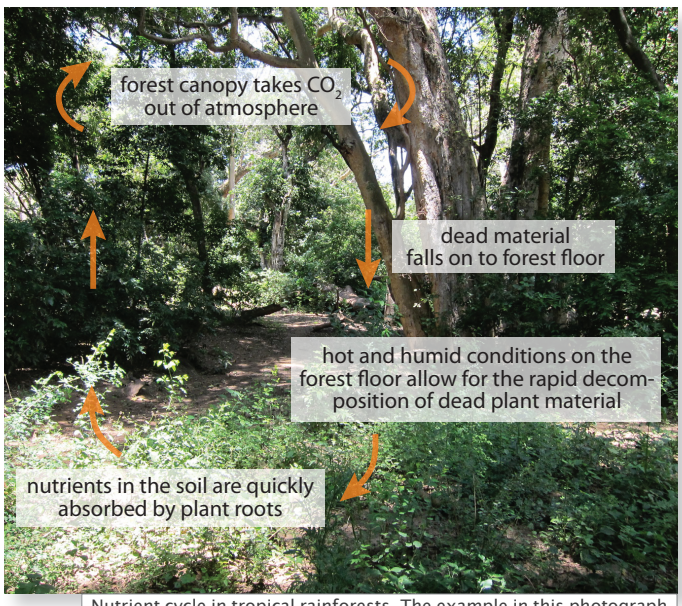
Soils are often described as being acid or alkaline or having a certain pH value. The pH scale (from 0 to 14) indicates the degree of acidity based on the concentration of hydrogen ions in a solution. Soils typically fall between pH4 to pH11, with a neutral soil having a pH of 7. Alkaline soils will have a pH greater than 7 while acid soils will have a pH below 7. The pH is usually measured by mixing a sample of soil with deionised water, KCl or $CaCl_2$.



Soil as a regulator of the biogeochemical cycles

Soil plays a crucial role in a number of life-sustaining natural biological and chemical cycles. Carbon, nitrogen (see above) and a range of essential nutrients are continuously recycled between the soil and plants, geological deposits, groundwater and the atmosphere. The intensity of these biogeochemical exchanges (fluxes) varies from place to place and is regulated by soil characteristics, land use and climate.

The graphic below demonstrates nutrient cycling in the rainforest. The hot, damp conditions on the forest floor allow for the rapid decomposition of dead plant material. This provides nutrients to the soil that are then easily absorbed by plant roots. However, as these nutrients are in high demand from the rainforest's lush vegetation, they do not remain in the soil for long. Therefore, more nutrients must be supplied. This rapid consumption means that nutrients in the soil are concentrated near the surface. If the forest vegetation is removed, the flow of nutrients from the vegetation to the soil is interrupted and the soils quickly lose their fertility so becoming vulnerable to erosion. The majority of cleared rainforest can only be used for agriculture if additional lime and fertiliser are added.



Nutrient cycle in tropical rainforests. The example in this photograph comes from near Arba Minch in South Ethiopia. (SD/JRC/LJ)

Trees growing in shallow and weakly developed soils in a semi-arid part of East Africa. Litter fall and the roots of the trees provide sufficient nutrients for other shrubs to flourish in their shade. In turn, soil organisms and larger mammals can survive. (EM)

Soil the vital role

The soil functions described on these pages are vital to life on Earth. However, not all soil types can carry them out to the same extent and some are far more susceptible to failure when stresses are placed on them. A clear understanding of the functional capability and potential of different soil types is thus vital for planning and managing the sustainable development of African resources.

What is soil?

The term 'soil' means different things to different people. To the vast majority living in cities and towns, soil is simply the 'dirt' or 'dust' to be cleaned from their hands or the vegetables that they buy to eat. However, to the gardener or farmer, soil is the uppermost 25 cm of ground that is cultivated and nurtured to produce crops. To the engineer, it is the 'overburden' or unwanted loose material at the ground surface that needs to be removed to provide a more stable foundation upon which to work. To the biologist, it is a fascinating habitat teeming with life. To the climate change modeller, it is both a storehouse and source of carbon and greenhouse gasses such as methane, carbon dioxide and nitrous oxide. To the hydrologist, soil is a buffer that stores rainfall, alleviating floods and providing drinking water as well as base flow for rivers.

In fact, soil is all of these things. Soil is the living, breathing skin of our planet. Soil is the result of the interactions between the atmosphere (as governed by climate), the biosphere (local vegetation, animal activities including those of man) and the geosphere (the rocks and sediments that form the upper few metres of the Earth's solid crust). Those of us who study soil have a definition for it. We say **'soil is any loose material at the surface of the Earth that is capable of supporting life'** and these life-supporting functions have been understood from the earliest of times.

> "Essentially, all life depends upon the soil ...
> There can be no life without soil and no soil
> without life; they have evolved together."
>
> Charles E. Kellogg (1938)

What is soil made of?

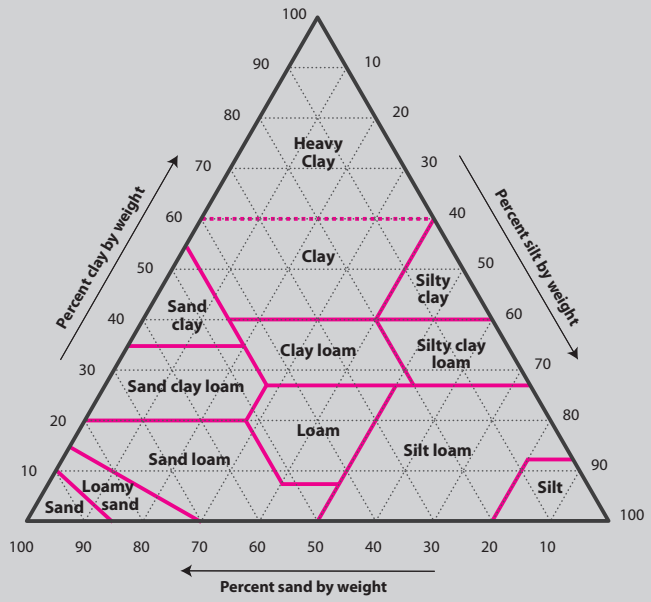
All of us have come into contact with soil at some time in our lives and most people are familiar with such terms as clay, silt, sand or peat. In reality, soil consists of a complex mixture of mineral and organic particles that represent the products of weathering and biochemical processes. Rocks are weathered into individual grains while the dead vegetation and organisms are transformed into soil organic matter.

When we handle soil, the fact that it usually stains and moistens our fingers, shows that it holds different amounts of water, organic compounds, minerals and chemicals.

Soil texture and structure

Texture describes the proportion of different sized mineral particles that are found in a soil. The main particle size classes are broadly clay (<0.002 mm), silt (0.02 – 0.63 mm) and sand (0.063 – 2.0 mm) [5]. Texture is measured by sieving or by feeling the grains by rubbing the soil between your fingers. Particle size classifications may vary in different countries. Furthermore, large sand particles can be described as coarse, medium and fine.

Structure refers to the natural arrangement of soil particles (also called aggregates) and the space between them. Soil structure thus has a major influence on the movement of water and air and root growth. Structure depends on factors such as the parent material, mineralogy, biological activity, environmental conditions, land management and the amount of clay and organic matter.



Soil texture triangle – soils can be categorized according to their texture following particle size analysis in a laboratory. Thus a soil with 40% sand, 40% silt and 20% clay fractions will be a loam. (FAO) [5]

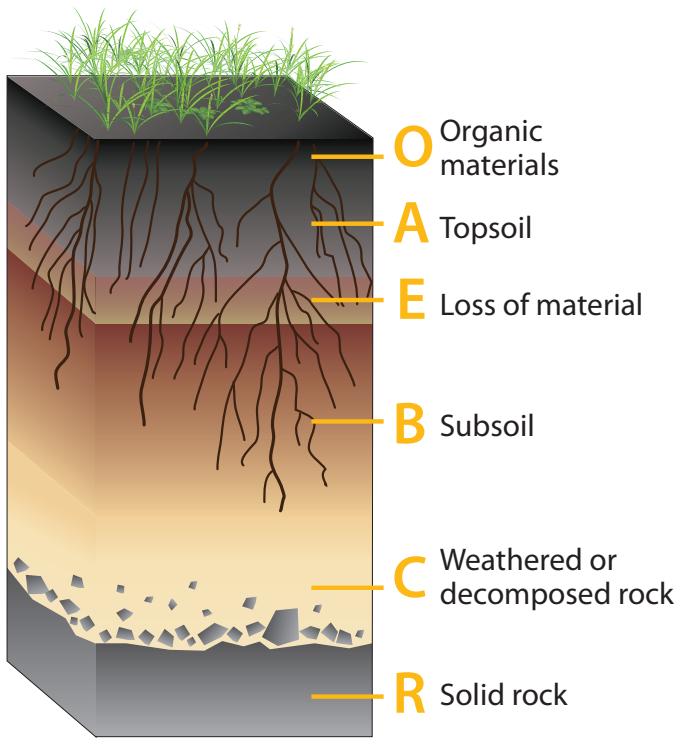
Unlike hard rock, pores and cracks in the soil contain 'soil air' with a higher concentration of carbon dioxide than exists in the Earth's atmosphere. The most important components that make up soil are the organisms, both plants and animals, that live (and die) within it.

The soil in profile

In most cases, if we dig a hole into the soil and look at the vertical section revealed, we will notice a number of different layers, roughly parallel to the surface. These layers are referred to as 'horizons' and are the result of a range of geological, chemical and biological processes that have acted upon the parent material over the lifetime of the soil. Relatively young soils, such as those on river sediments, sand dunes, or volcanic ash, may have indistinct or even no horizon formation. As age increases, horizons are generally more easily observed (there are exceptions such as in deeply weathered tropical or permafrost-affected soils).

Most soils usually exhibit three or four horizons (there can be more or less). Horizons are generally described by colour, texture, structure, organic matter and presence of carbonates. More detailed chemical characteristics can be measured in the laboratory. Some soils show a gradual change from one horizon to another while other soils may possess horizons that have markedly different characteristics to each other.

The identification and quantitative description of horizons are an important aspect of studying soils. Most soils conform to a similar general pattern of horizons and in soil science, major horizons are usually denoted by a capital letter as a means of shorthand and easy communication (typically followed by several alphanumerical characters to denote a characteristic feature). [5]



A hypothetical profile showing the main soil horizons and their relation to parent material, root development and soil-forming processes. The E horizon occurs in mineral soils when materials such as clay, iron and aluminium have been destroyed or flushed to deeper layers by percolating water. E horizons are usually lighter in colour (but not always) and have a coarser texture. Other possible horizon codes are L (sediments deposited in a body of water) and W (presence of water layers). (LJ)

Know Your A, B, C...

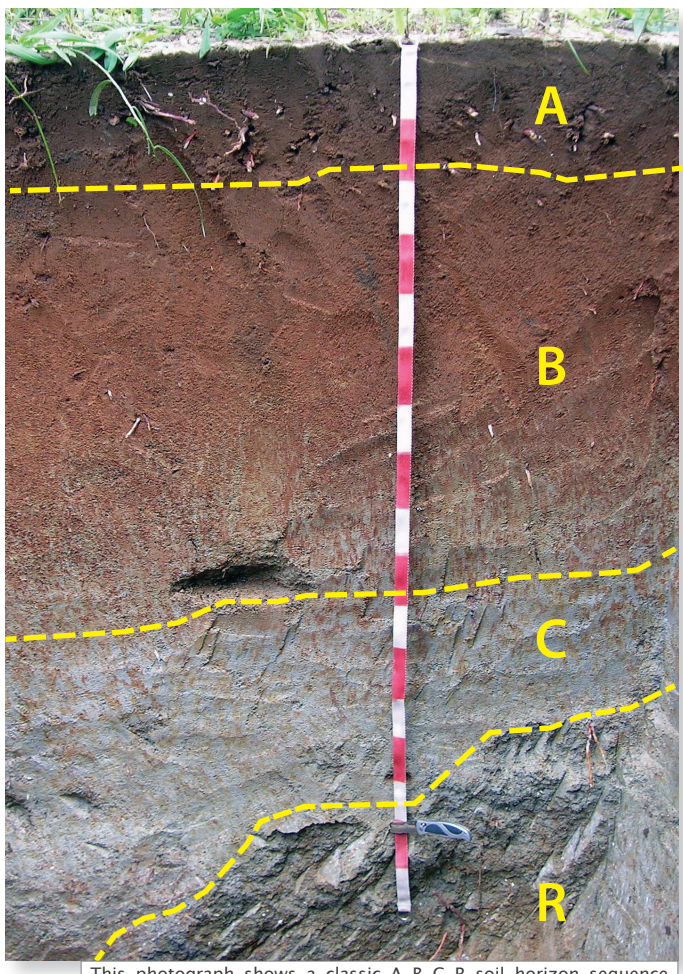
When a vertical section of the soil is examined, the uppermost thin layer normally contains the undecomposed or slightly decomposed remains of plants lying on the surface of the soil. This layer is called an organic horizon and is referred to by the letter 'O'. The O horizon is not saturated by water for prolonged periods and its mineral content is very low. Where the accumulations of organic material on the soil's surface are saturated by water for prolonged periods, this is referred to as an H horizon.

Organic matter in both the H and O horizons may be further divided into i) slightly decomposed - plant remains are visible to the naked eye; ii) an intermediate phase where decomposition is greater but plant remains are still visible; iii) completely decomposed organic layer on top of the mineral soil.

Beneath the O horizon, a dark horizon containing a mixture of organic and mineral material can be recognised which is referred to by the letter 'A'. The A horizon is the topsoil, which contains most of the organic material within the soil, hence its darker colour. It is the engine room of the soil where most of it's biological and chemical activities occur (e.g. biomass growth, dead litter and root decay and release of nutrients, formation of organic acids and their reactions with minerals, etc.). If the topsoil layer is removed by erosion or human activity, most of the soil's ecological potential goes with it. While the topsoil layer will regenerate over time, if left undisturbed, it may take hundreds of years for its full original potential to be restored.

Below the topsoil (O and A horizons) is the mineral subsoil containing one or more brighter coloured layers that are referred to by the letter 'B'. Apart from Podzols (see page 59), the B horizons contain much less organic material than topsoil (making them different in colour) but they are still exploited by plant roots and soil animals which use the water, air and nutrients stored in them. Brownish, yellow or reddish colours originate from iron oxides formed by weathering in the soil, whereas greyish tones result from chemical reaction in reducing conditions. Towards the base of the subsoil, the soil structure gradually becomes less apparent as the factors affecting its development decrease in influence.

Eventually, a layer is reached where the influence of soil-forming processes is less apparent. This layer is referred to by the letter 'C'. This horizon lies above hard bedrock or parent material. The characteristics are usually very different to the A and B horizons and may contain weathered blocks of the underlying geological substrate.



This photograph shows a classic A–B–C–R soil horizon sequence under arable cultivation in Tanzania.

The greyish, soft C horizon has weathered from the hard bedrock below (R), and provided the parent material for the development of the A and B horizons. The uppermost, dark A horizon (0 – 20 cm) indicates a higher level of organic matter. Below is a well structured, reddish B horizon (20 – 100 cm) with high amounts of iron oxides and clay, as a result of weathering and soil-forming processes.

Plant roots and burrows are clearly visible in both the A and B horizons. (EM/JRC/LJ)

The R horizon basically denotes the layer of hard bedrock underneath the soil. Soils formed in situ will exhibit strong similarities to this layer.

Where do the soils of Africa come from?

Soil-forming factors

As we can see from the pictures on this page, the appearance and characteristics of soils can vary considerably from place to place. The next few pages of the atlas will describe the main soil-forming factors and illustrate how they dictate the properties of a particular soil.

Vasily Vasil'evich Dokuchaev, commonly regarded as the father of pedology, was the first person to articulate that geographical variations in soil characteristics were related to climatic and topographic conditions as well as geological factors (parent material). His ideas were developed by a number of soil scientists, including Hans Jenny who, in 1941 [6], established a mathematical relationship that states that the observed properties of soil are the result of the interaction of many variables, the most important of which are:

Parent Material

Topography or position in the landscape

Climate

Living organisms, especially vegetation

Human activities

Time

Jenny expressed this relationship through a formula:

soil = f (climate, organisms, topography, parent material, time)

According to this formula, variations in parent material, climate or the age of the soil will result in specific soil characteristics.

For example, the weathering of solid bedrock through processes such as heating-cooling or freeze-thaw cycles (determined by topography and climate) produces a matrix of rock fragments (also known as regolith). Further, weathering leads to the production of finer structures containing crystalline minerals that have been liberated from the rock. These fine-texture materials provide the conditions for seeds to germinate and plants such as lichens and mosses to become established. The growth of vegetation is supported by the decomposition of minerals into simple molecules or compounds that act as plant nutrients. As plants become established, dead leaves will fall on the surface and decay to form thin organic layers, which in turn, support the next cycle of plant growth by returning the nutrients to the soil. Over time, the parent material becomes covered and buried by more and more organic matter allowing larger plants to grow. The slope or aspect of the site may determine growing conditions but also the drainage and inputs or removal of material. In this way, a soil will form with characteristics that reflect the interplay between the various factors.

A changing climate may reduce the weathering processes and thus halt the supply of parent material and the release of minerals. Alternatively, climate change may favour a more luxurious vegetation community, leading to the production of more plant matter, resulting in deeper organic layers. In both cases, the soil characteristics will be different from the initial example.

Many people argue that these basic soil-forming factors are not truly independent. Climate has an obvious bearing on living organisms while at the same time, the (micro)-climate at the surface of the soil may be very different to the general regional climate. This micro-climate may itself be controlled by topography which, in turn, is the result of the interaction between the underlying geology (in many cases the parent material) and the regional climate.

Nevertheless, the underlying principles of soil formation have been shown to be sound. An additional important factor that should not be ignored is the influence of human activities. Soil processes and characteristics can be significantly altered by the way that the land is used or managed. Drainage, the addition of fertilisers or the removal of natural vegetation are only a few examples of how soil characteristics can be changed artificially.

Much more information on soil forming processes can be found in most general soil text books such as [7, 7a].

The three photographs on this page illustrate the variety of soil characteristics, which in turn are driven by the interplay of soil-forming factors. This photograph from Tanzania shows a deep, coarse-textured, iron-rich soil that has developed under a tropical climate. The darker band just below the surface (0–20 cm) is the result of ploughing. (VL)

A fine-textured soil from Ethiopia with high levels of swelling and shrinking clay minerals under a crop of teff (*Eragrostis tef*). Initially derived from the weathering of basic rocks such as basalt, the clays were later redeposited in still water conditions. The dark colour indicates that iron is virtually absent in this soil. Note the cracks and smooth surfaces of sheer planes which are evidence of churning within the soil as a result of shrinking and swelling in wet and dry conditions. The churning has even pushed up a big piece of limestone bedrock. (KV)

A coarse-grained soil composed primarily of quartz particles deposited by the wind, This soil from Morocco has developed in a semi-arid climate. Strong winds have transported sand grains from the Sahara. In such soils, organic matter levels and water holding capacity are very low. Trees can grow in such soils because they can send roots to access groundwater deep below the surface. (EM)

Africa

Africa is the world's second-largest and second most populous continent, after Asia. Covering an area of around 30 million km², Africa covers 20% of the Earth's land surface area. With just over one billion people living in 55 countries, Africa accounts for about 14% of the human population.

Separated from Europe by the Mediterranean Sea, Africa is joined to Asia at its northeast extremity by the Isthmus of Suez. The Sinai Peninsula is generally regarded as Africa since it is actually part of the Great Rift Valley, the great fracture in the Earth's crust that begins in East Africa and runs up the Red Sea. The continent is bounded by the Indian Ocean to the east and the Atlantic Ocean to the west. Madagascar and various island groups such as the Azores, the Canaries, the Seychelles, Comoros and Cape Verde are also associated with the continent.

Map showing the main geographical elements of the African continent. (LJ)

The distance from the most northerly point of the continent, Ras ben Sakka in Tunisia (37°21'N), to the most southerly point, Cape Agulhas in South Africa (34°51'S), is approximately 8000 km. While the journey from Cap-Vert in Senegal (17°29'W) to Ras Hafun in Somalia, (51°27'E) is approximately 6900 km. Taking the Cape Verde Islands as the western-most expression of the continent would add a further 560 km. Due to its generally smooth shape, the coastline of Africa is estimated to be around 28000 km long, compared to 32000 km for Europe, which covers only about a third of the surface of Africa.

The highest mountain is Kilimanjaro on the Kenyan-Tanzanian border with an elevation of 5 895 m while the lowest point is Lake Assal in Djibouti at 156 m below sea level. The average elevation of the continent is around 600 m but many regions are significantly higher (e.g. Ethiopia, Morocco, South Africa).

Of the fifty-four sovereign states that make up Africa, Algeria is the largest country. The smallest (and with the lowest elevation) is the Seychelles. The smallest nation on the continental mainland is The Gambia.

Readers are encouraged to view the UNEP Africa Atlas [20] which provides some striking views of the African environment.

Africa – the name!

There is no outright certainty in the origin of the word Africa; but three theories are commonly proposed:

- *Afri*, the Latinised version of the Phoenician word afar meaning dust was used by the Romans to describe Carthaginian territory around modern Tunisia. The suffix *–ca* in Latin denotes a country. The term was gradually extended to the whole continent.
- In ancient Greek, the prefix *a-* indicates an opposite; hence, the phrase *phrike* (φρίκη), meaning "cold and horror", becomes "without cold and horror" implying a warm and inviting land.
- The Egyptian word "*af-rui-ka*" literally means "to turn towards the opening of the mother's womb" and recognises Africa as the birthplace of their earliest ancestor

Africa is the most multilingual continent in the world. UNESCO has estimated that around two thousand languages are spoken. The four major indigenous language families are Afro-Asiatic, Nilo-Saharan, Niger–Congo and the Khoisan.

Soil-forming factor 1: Parent material

Parent material refers to material from which the soil has been derived and, in most cases, is of geological origin (see peat on page 30). The nature of the parent material can have a profound influence on the characteristics of the soil. For example, the texture of sandy soils is determined largely by the parent materials, which in turn controls the movement of water through the soil. The mineralogy of the parent material is mirrored in the soil and can determine the weathering process and control the natural vegetation composition. For example, lime-rich soils are generally derived from calcareous rocks (e.g. limestone, chalk) or sediments derived from such deposits. In turn, lime-rich soils can offset the development of acidic conditions but may not support plants that are not tolerant of alkaline soil conditions (e.g. rhododendrons).

Two types of parent material are recognised: a) unconsolidated deposits or loose sediments that have been transported by ice, water, wind or gravity and b) weathered materials directly overlying the consolidated hard rock from which they originate. In both cases, the parent material can be weathered through physical destruction of rock (freezing or drying cycles) or chemical reactions (dissolution of elements). Weathered parent material is often referred to as saprolite.

While the forces created by the expansion and contraction of minerals, induced by daily temperature variations, cause rocks to shatter and exfoliate (especially in hot deserts), in most cases water is the dominant agent in weathering processes. Water can cause rocks to shatter through repeated freezing and thawing of water trapped in rock cavities. Water also initiates solution and hydrolysis (the destruction of a compound through a reaction with water that produces an acid and a base) that liberate minerals contained within the rock. Water also supports life which, in certain situations, is a major contributor to the weathering process. Plant roots can cause physical weathering as they grow and expand inside cracks in the rocks. Roots and decaying vegetation also produce organic compounds such as solvents, acids and alkalines that enhance the actions of percolating rainwater.

The degree of weathering depends on a number of environmental factors such as temperature (determined by climate, exposure and altitude), the rate of water percolation (determined by texture, relief, climate), the presence of oxygen (again texture and climate), the surface area of the parent material (largely determined by the geological structure) and the mineralogy of the parent material (for example, quartz is much more stable than olivine).

Weathering continues in the soil following a sequence from the least to the most stable minerals. For example,

- Early weathering: clay fraction of young soils, often characterising dry conditions

  Gypsum, Calcite, Hornblende, Biotite

- Intermediate weathering: temperate soils, often with natural grass or forest vegetation

  Quartz, Muscovite, Vermiculite, Montmorillonite

- Advanced weathering: clay fraction of highly weathered soils of humid/tropical regions

  Kaolinite, Gibbsite, Hematite, Goethite

Minerals undergo changes that cause the formation of secondary minerals and other compounds that are soluble in water (to varying degrees).

The distinctive features for Africa from a geological point of view are four-fold:

- most of Africa is made up of very old rock, often exposed to the surface. In most cases it is crystalline and derived from igneous sources (i.e. magma) and has often been altered chemically (metamorphised);
- the continent is slowly being torn in two along the great East African Rift Valley - volcanic activity is common;
- large parts of the African land surface have been geologically stable for millions of years which gives rise to deep weathering profiles;
- large parts of Africa are covered by recent sediments, in particular, wind blown sand.

A thorough summary of the geology of Africa is given in [8].

Examples of soil formations on continuous, hard bedrock in Tunisia **(left; GT)** and transported sediments in East Africa **(right; EM)**, in this case, of fluvial origin. Where consolidated parent material lies close to the surface, soil depth is generally shallow and horizon development is weak. Unconsolidated sediments can completely mask the characteristics of the underlying bedrock.

Rock types

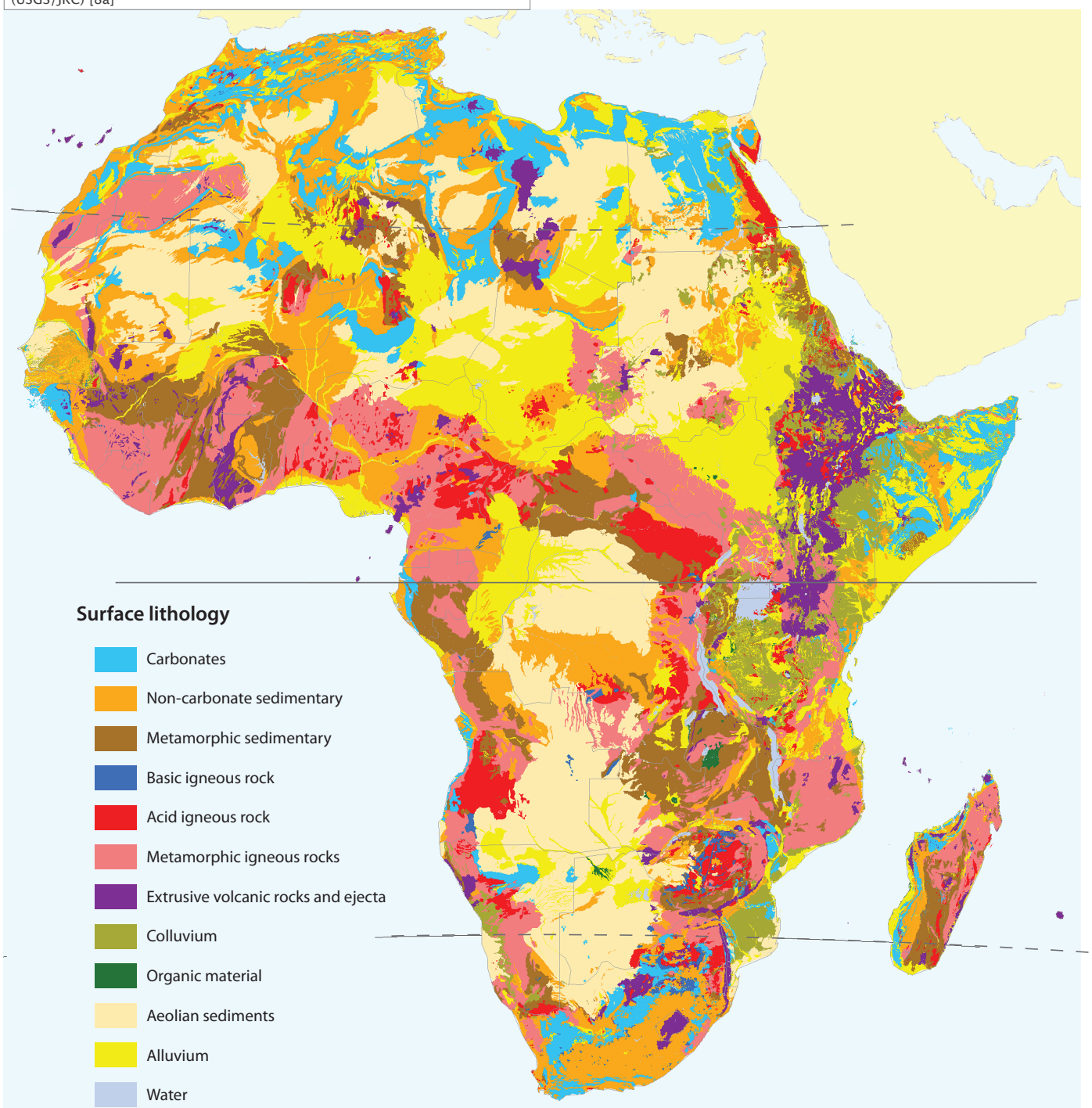
Igneous rocks are formed by the solidification of molten magma and are the original source of all other rocks. They include rocks such as granite, dolerite and basalt and are generally divided according to the presence of the mineral quartz.

Sedimentary rocks are formed by the deposition of weathered material by wind or water. Shales are deposited on ocean floors. Conglomerates and sandstones are composed of resistant fragments of other rocks while limestones and chalk are created through the precipitation of calcium carbonate from solution.

Metamorphic rocks are igneous or sedimentary rocks that have been transformed by intense heat or pressure resulting in changes in mineralogy and structure. Examples include gneiss, marble and slate.

The map below shows the lithological properties of the surface geology of Africa. Lithology describes the mineral composition and structure of geological material which is based on rock formation (i.e. whether it is igneous, sedimentary, metamorphic) and mineralogy (e.g. carbonate, silicic, mafic). This map is a good proxy for soil parent material as it only reflects surface conditions and not the underlying bedrock. It should be noted that the general nature of this map means that at a local level, the conditions may be quite different to that shown.

Other than the terms alluvium (deposited by water), aeolian (deposited by wind), organic (peat deposits) and colluvium (transported by gravity), all of which denote recent deposition, the age of material is not indicated. The preponderance of wind-blown sediments across Africa is striking as are the volcanic areas. Please consult the glossary at the end of the atlas, the adjacent text box and page 28 for an explanation of the geological terms. (USGS/JRC) [8a]



Soil-forming factor 2: Topography

The shape of the land surface, also referred to as relief or topography, is a key soil-forming factor as it has an important influence on local climate, vegetation and the movement of water. Mountains can affect the amount and intensity of precipitation and vegetation growth while locally, the angle or slope of the ground controls drainage and movement of material. Even small variations in elevation can be important in flat lands. River terraces or small depressions can lead to localised improved drainage or waterlogging respectively. Micro-topography can be particularly important if saline groundwater occurs close to the surface as it will affect evaporation rates.

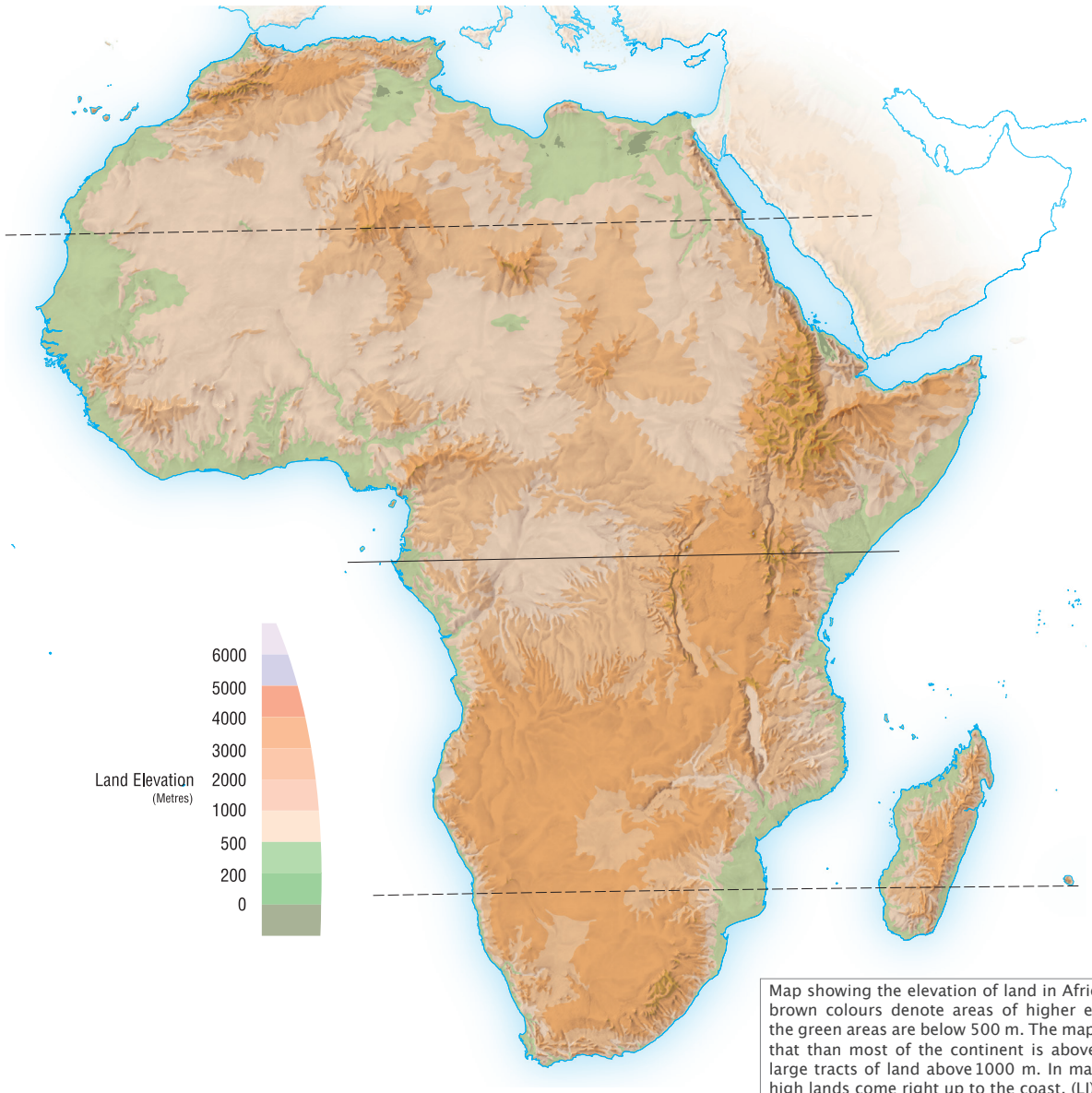
The position in the landscape is very important. Generally, soils found at the top of a slope tend to be freely draining while those at the foot of a slope or in the valley bottom are often poorly drained (see page 40). In some cases, the water table may be near or at the surface. In this situation, different soils may form on the same parent material, climate and even vegetation type (e.g. a grass-covered slope). Soils occurring on the middle of slopes receive sediment and solutions from higher up but at the same time lose material to soils below. In these cases, the actual shape of the slope is important as smooth, irregular, convex or concave slopes will result in different soil characteristics.

The map on the **right** shows the variation in elevation of the land surface of Africa in metres above sea-level. The map is based on measurements made by a specially modified radar sensor carried onboard the Space Shuttle as it orbited the planet. (WorldClim [9])

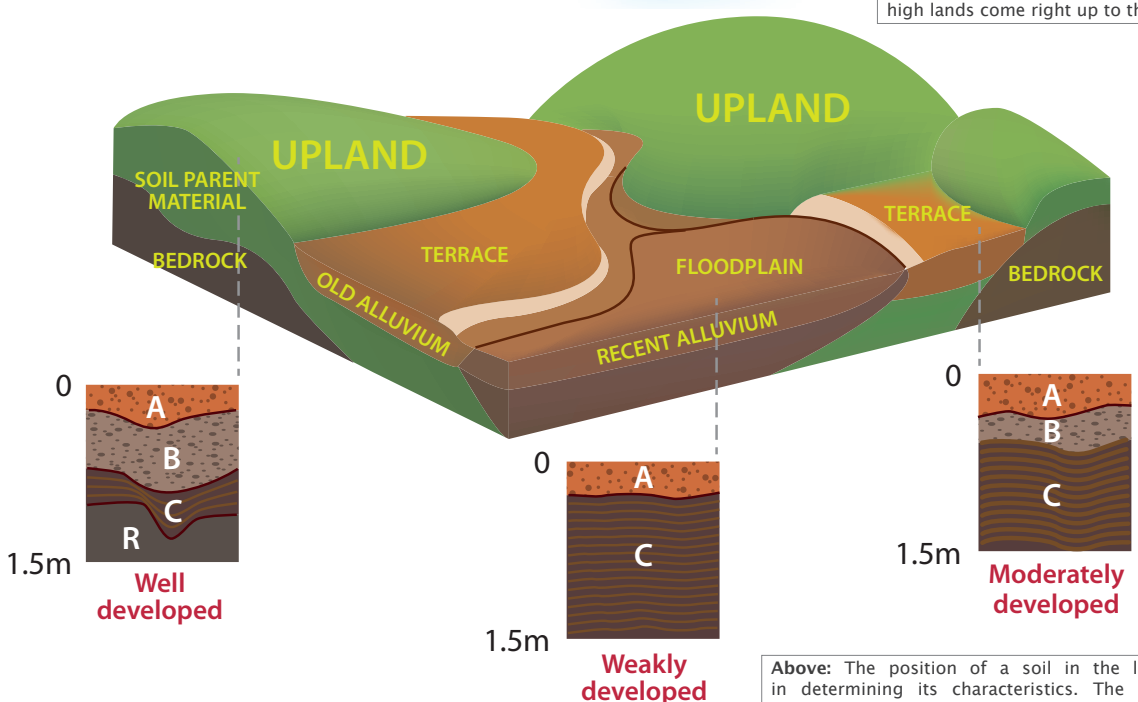
The turquoise and dark green colours represent areas below or just above sea-level respectively: the low-lying salt lakes of North Africa are particularly evident. The light green areas show the extent of low relief landscapes such as plains which are generally flat or only gently undulating. Light pink denotes the high plains where the landscape begins to show evidence of soil erosion on steeper slopes. The orange colours signify upland regions which in some places give way to mountains (dark brown). The highest elevations in the region (light blue) are found in East Africa where Kilimanjaro reaches a height of 5 895 metres above sea-level, closely followed by Mount Kenya (5 184 m), the Ruwenzori Range (5 060 m) and the Ras Dashen mountains of Ethiopia (4 550 m). The average elevation of the African continent is approximately 600 m above sea level. In contrast with other continents, Africa is characterised by a comparatively small area of either very high or very low ground. It is interesting to note that only 6% of Africa has an elevation of below 100 m. Moderately elevated tablelands are the characteristic landscape, broken by higher peaks and ridges.

As a general rule, the higher tablelands lie to the east and south, while a progressive diminution in altitude can be observed towards the west and north. The Atlas Mountain Range is unconnected with and separated from the south by a depressed basin. The high grounds of Hoggar and Tibesti are constituted of volcanic material standing on broad uplifted areas. The third area of high elevation is formed by the Ethiopian Highlands, a rugged mass of mountains forming the largest continuous area of altitude in the whole continent where hardly any of its surface drops below 1 500 m. The region is often called the 'roof of Africa'.

The lowest points on the African continent are Lake Assal in Djibouti, which is 156 m below sea level, and the Danakil Depression in Ethiopia, which is 125 m below sea level.



Map showing the elevation of land in Africa. The darker brown colours denote areas of higher elevation while the green areas are below 500 m. The map clearly shows that than most of the continent is above 500 m, with large tracts of land above 1000 m. In many places, the high lands come right up to the coast. (LJ)



Above: The position of a soil in the landscape is important in determining its characteristics. The graphic illustrates the conceptual differences in the development of soil profile according to a specific topographic setting (UM/TC).

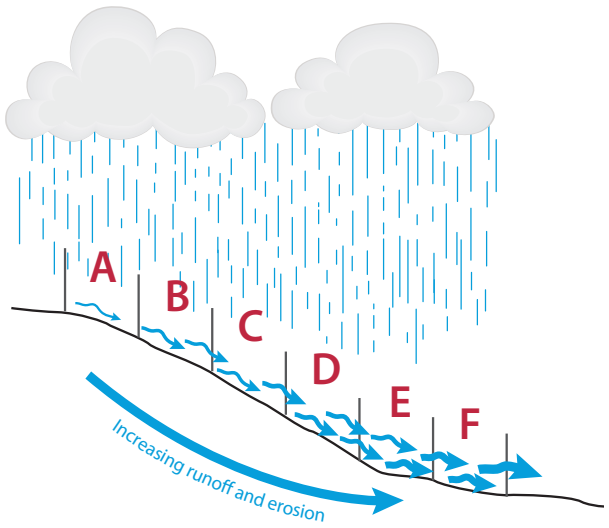
Below: Soils occurring at the foot of slopes receive greater amounts of water and sediment compared to those on higher ground. While erosion is considered a threat to soil functions, it can also be regarded as a soil-forming process by depositing new parent material at the foot of slopes. However, soil at location A will probably be well drained while at location F, waterlogging or saturated ground may be common. (JRC/LJ)

The Catena

From the Latin for chain, the catena is a term that describes the sequence of soils occurring on slopes, where the parent material is common. In this case, the influence of relief dominates other soil forming factors. The theory of the catena originates from a soil reconnaissance survey that was carried out by an agricultural officer, Geoffrey Milne, in what is now Tanzania during 1935-36. The catena concept reflected the understanding of landscape that these early surveyors brought to field work in Africa. Additionally, they utilised the local farmers who had an indigenous but sophisticated understanding of the role of topography in determining soil types.

Milne became a one of the outstanding figures in international soil science. His concept of the soil catena linking soil development to topography provided the foundation for soil surveying. Milne's initial ideas were set out in a paper published in 1947 [10]. His early records, the basis for his subsequent mapping of soils in the savannah landscape, are kept in the WOSSAC archive (see page 139).

The photograph shows a very weathered granite outcrop in Sukumaland, Tanzania. In fact, this is the upper section of the original catena described by Geoffrey Milne in 1936 (see box left). The pronounced horizontal crack in the rock is a pressure release surface (also known as a desquamation slab). The soil at the base of the catena is a Petric Plinthosol – characterised by an accumulation of iron that hardens irreversibly when exposed to air and sunlight (see page 26 for corresponding photograph). (JD)



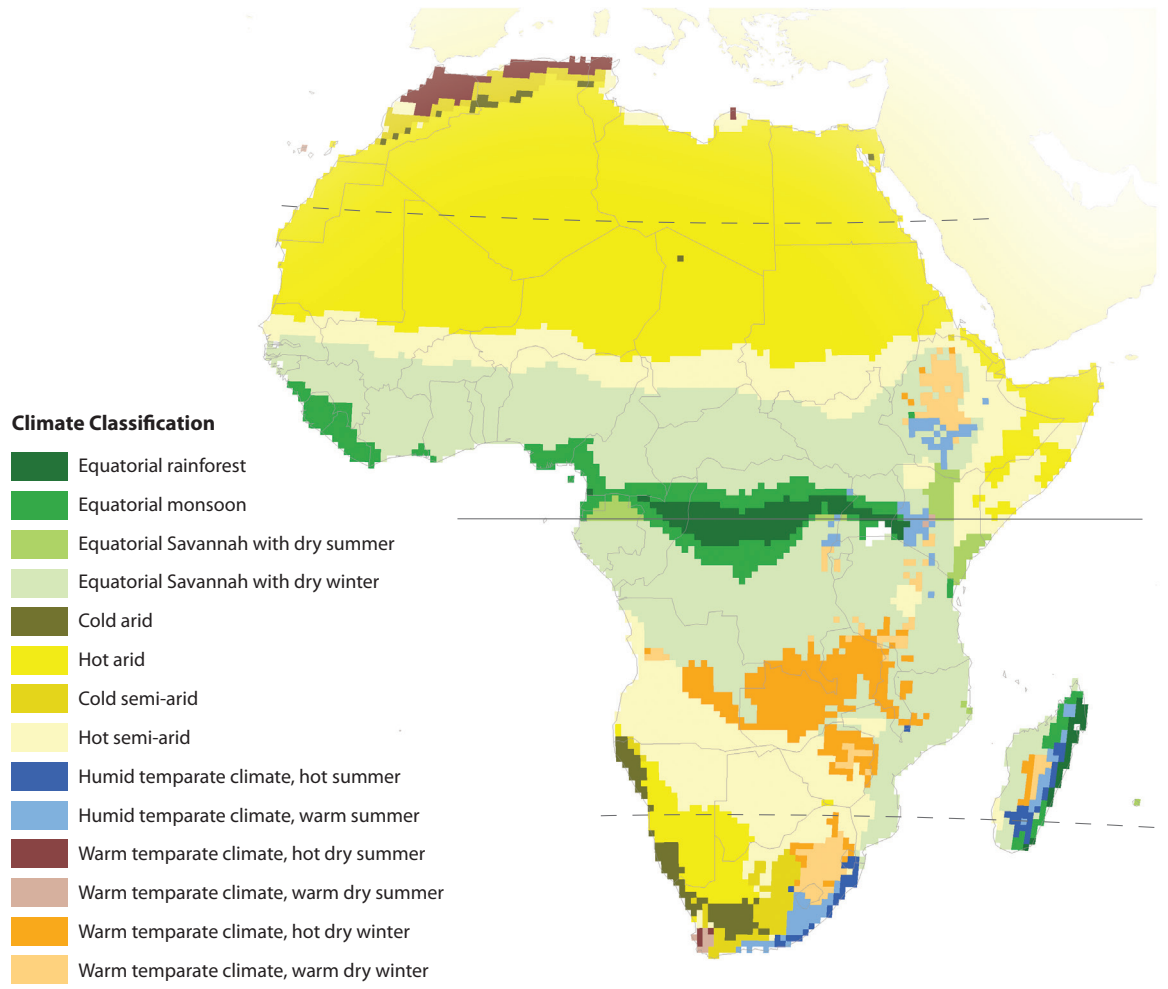
Soil-forming factor 3: Climate

Climatic zones

Soil formation depends enormously on the climate as temperature and moisture levels affect weathering processes and biological activity. Where precipitation exceeds evapotranspiration, leaching or saturated soils can occur. When the opposite is true, salts can rise to the surface. Chemical weathering will be very active in areas with high temperatures and high humidity while physical weathering will dominate in hot, dry desert regions.

With the equator running through its centre, Africa has the largest tropical area of any continent and about 75% of the land area lies within the tropics. In countries south of the equator the seasons are the opposite to the countries that lie north of the equator. The broad climatic pattern of Africa is driven by its position around the equator, the impact of cool ocean currents and the absence of mountain chains serving as climatic barriers. Seven main climatic zones can be distinguished:

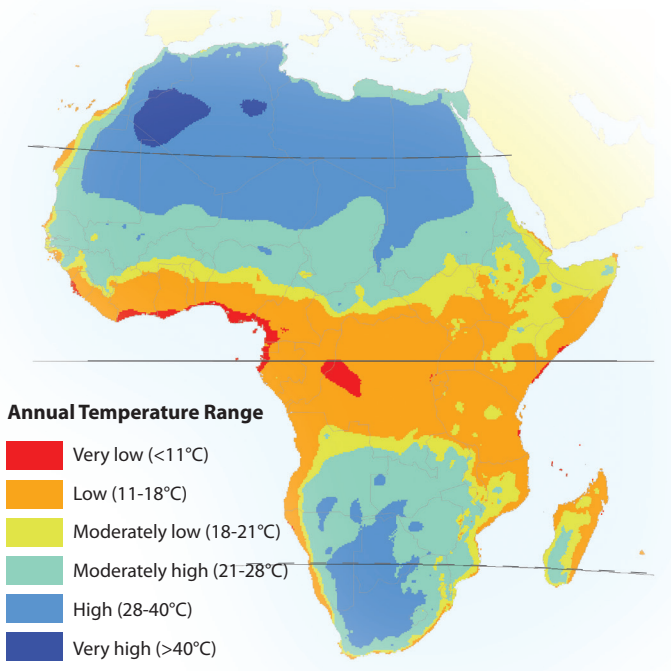
- Hot, humid zone around the equator where annual rainfall exceeds 1 500 mm - covering 14% of Africa;
- To the north and the south is a sub-humid savannah zone with annual rainfall between 600 mm and 1 200 mm, covering 31% of the land area. Rainfall becomes increasingly seasonal further from the equator;
- Semi-arid steppe zone with an average rainfall equaling or less than 600 mm which falls only in the summer months, covering 8% of the total land area;
- Dry desert zone occupying nearly half of the African land area (47%). Annual rainfall is erratic, less than 100 mm – in some areas this is zero. Daily and seasonal extremes of temperatures are large with the average summer temperature greater than 35°C;
- Mediterranean climate in the extreme north and south with high temperatures in the summer and warm autumn and winter months with rainfall;
- The highlands of eastern Africa, particularly in Kenya and Uganda, where rainfall is well distributed throughout the year and temperatures are constant throughout the year;
- The high plateau of southern Africa which has a temperate climate;
- On a few high mountain summits, a cool temperate climate can be found, even on the equator!



Map of the major climatic zones of Africa according to the updated Köppen-Geiger classification scheme. Most of Africa has a warm or hot climate, but the humidity and amount of rainfall varies dramatically from area to area. Eight per cent of Africa has a tropical climate with 10–12 months of rainfall. The remaining area experiences climatic contrasts with either not enough water when needed or an excess of water which cannot be used. Half of the continent has inadequate precipitation. Within these zones, altitude and other localised variables produce distinctive regional climates. Regionally, the climate varies cyclically over periods of decades or centuries. Climate change, especially indicated by prolonged drought is one of the most serious hazards affecting the agricultural sector of the continent since most of the crops are rain fed. As has been shown several times in the past 100 years, adverse changes in climate can have a devastating effect on the livelihood of people. (JRC) [11]

Annual temperature range

Temperature and fluctuations in temperature have important bearings on soil-forming processes. The map on the right shows the annual temperature amplitude for Africa based on the difference between the mean temperature of the warmest and coldest months. This change depends on the annual cycle of incoming solar radiation, which in turn depends on the latitude and altitude, and the proximity of the ocean. Clearly, the continent of Africa exhibits tremendous variations in annual temperature ranges. The map shows nearly mirror patterns of zones either side of the equator. The differences in the extent of the patterns is controlled by the shape of the continent: broad in the north while tapering to a point in the south. The region with the least variation is the equatorial zone. While a significant area displays a modest fluctuation of between 11 – 18°C, the range for the coastal fringe of the Gulf of Guinea and eastern DR Congo is only around 5 – 8°C. Away from the equator, the more temperate climate of the savannah regions, the Sahel, the Maghreb and large parts of southern African are clearly evident. What may surprise many people is that the main desert regions display high temperature ranges, with parts of the Sahara registering variations in excess of 40°C. This is caused by a set of constant high-pressure cells over the tropic of Cancer which give rise to cool winters (c. 13°C) and hot summers (> 45°C). Snowfall in winter is commonplace in parts of the High Atlas Mountains of Morocco.



Map showing the annual temperature amplitude or range for Africa based on the difference between the monthly mean temperature of the warmest and coldest months. (WorldClim/JRC) [12, 12a]

The Tropics

The tropics denote the area on the Earth where the sun is directly overhead at least once during the solar year. It is limited by the Tropic of Cancer, at approximately 23° 26' 16"N, and by the Tropic of Capricorn at 23° 26' 16"S, which marks the points where the Sun is directly overhead at the summer solstice (June 21 and December 21 respectively).

The term "tropical" is sometimes used in a general sense to denote a climate that is generally warm andmoist all year-round and where there is often with a lush vegetation. However, in a strict sense, a tropical climate is not arid and all months have an average temperature > 18°C.

Intertropical Convergence Zone

One of the main drivers of climate in Africa is a feature known as the Intertropical Convergence Zone (ITCZ). Winds originating from high pressure cells in the northern and southern hemispheres come together over the equator, where they are heated by the sun and driven upward. This rising movement cools the air, forcing the moisture out, which falls as precipitation. The dry air cycles back toward the subtropics where it descends, producing arid climates at approximately 20 degrees north and south of the equator. In Africa, the ITCZ is located just south of the Sahel at about 10°N. Around July, the ITCZ moves northwards bringing rain to the Sahel. From December to January, when the sun has moved to its southern limit, the situation is reversed, the convergence zone moves southward and rain falls over parts of Southern Africa. Seasonal variation in this position can result in drought conditions.

Variations in this cycle can result in drought conditions.

The variety of climatic zones in Africa gives rise to a tremendous diversity of landscapes. **Above:** A Saharan sand sea in Libya – while dune fields are not that common, large parts of Africa have a desert or semi-arid climate where annual precipitation is less than 250 mm and is often, much lower. Vegetation is very low or non-existent. Soil-forming processes are limited. (BN)

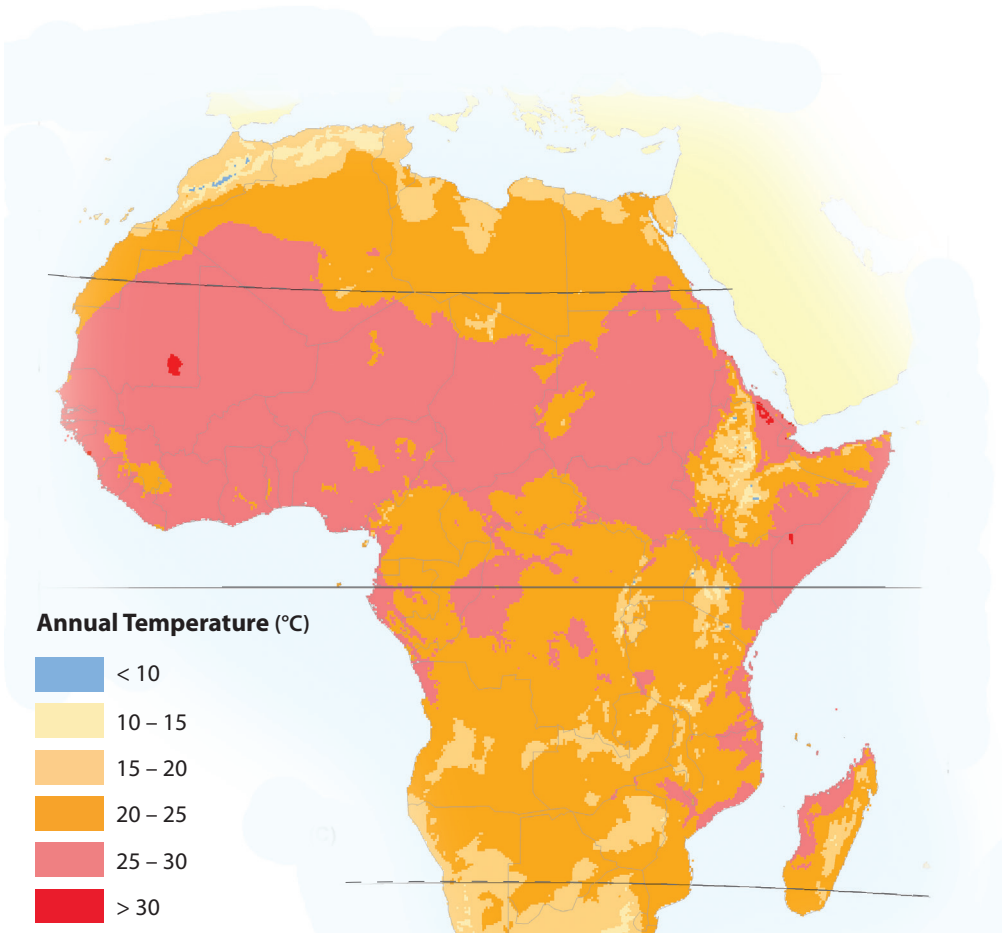
Below: Tropical forest along the Sanaga River in southern Cameroon. Here water is plentiful and vegetation can flourish. The slow and winding river carries lots of sediment which serves as parent material for soil. The soils of this part of Cameroon are very different to those of the Libyan desert. (RJ)

Temperature

The map shows the patterns of mean annual air temperature for the African continent. Africa's highest temperatures (dark red colour) occur in Mauritania, Ethiopia and Somalia. The highest temperature ever recorded in the world was 58°C in the shade at Al Aziziyah, Libya, on September 13, 1922. At I-n-Salah, Algeria, and along the Red Sea coast, July temperatures often reach 46°C or higher almost every day. In fact, the daily temperatures in the Danakil Depression of Ethiopia and the Eritrean lowlands are consistently more than 40°C and can regularly soar to 50°C. During the night, temperatures may drop sharply. The Sahara also has the greatest seasonal range of temperatures in Africa. Winter temperatures in the Sahara average from 10°C to 16°C.

To many people's surprise, temperatures near the equator are not excessively high with average daily temperatures being a constant 24 - 27°C throughout the year. Extensive cloud cover and heavy rainfall prevent temperatures from rising much over 33°C. The diurnal temperature change (i.e. between day and night) is usually between 2°C and 5°C which is greater than the annual temperature range of 2°C.

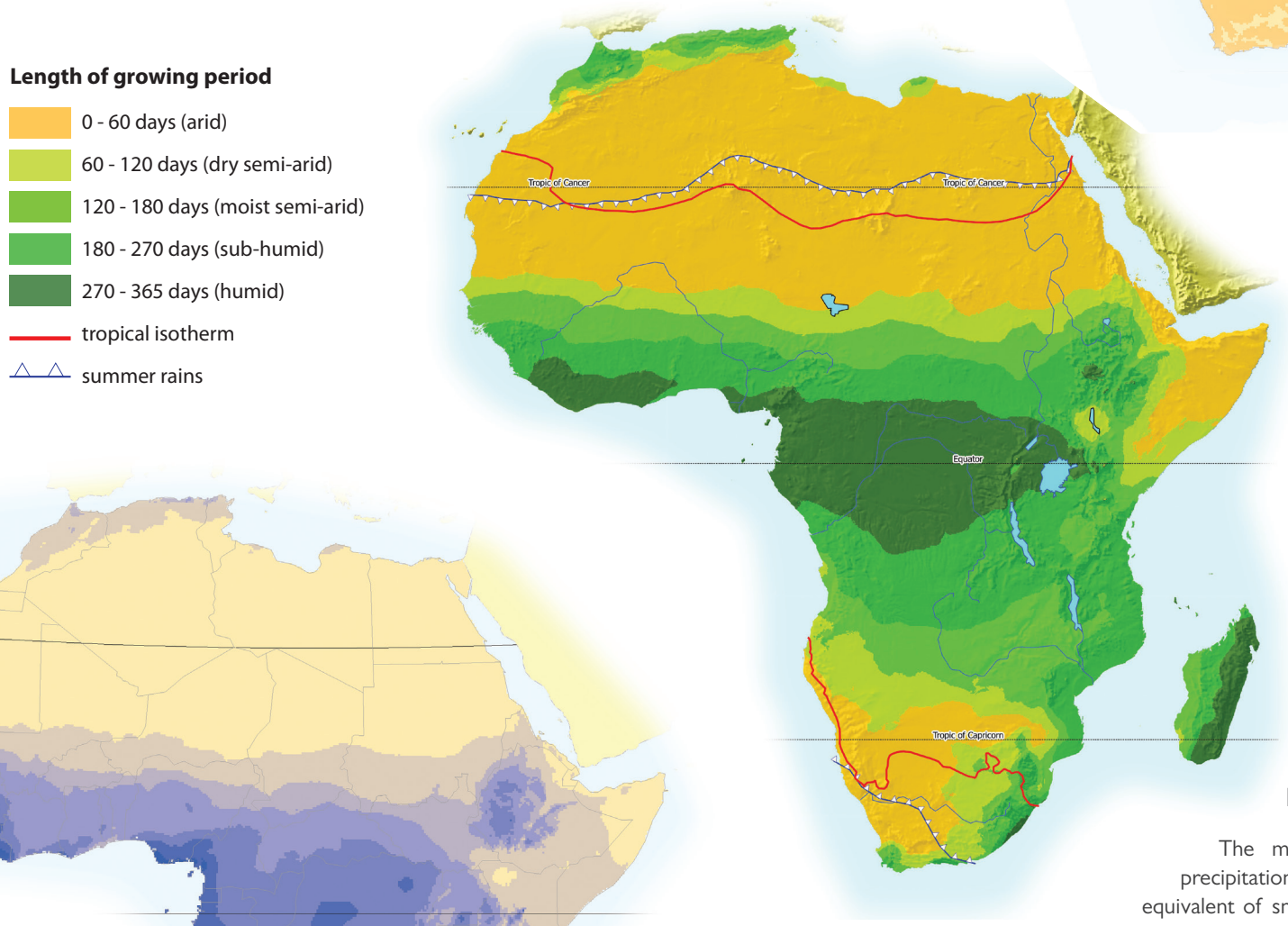
The coolest regions in Africa (blue colour) are in the northwest of Morocco (the Atlas Mountains) and eastern South Africa. The coldest place in South Africa is Sutherland in the Western Roggeveld Mountains where midwinter temperatures can reach as low as −15°C. Frost and snowfall are common on the high mountains of Africa. Glaciers can be found on Mount Kilimanjaro, Mount Kenya and the Ruwenzori mountains.

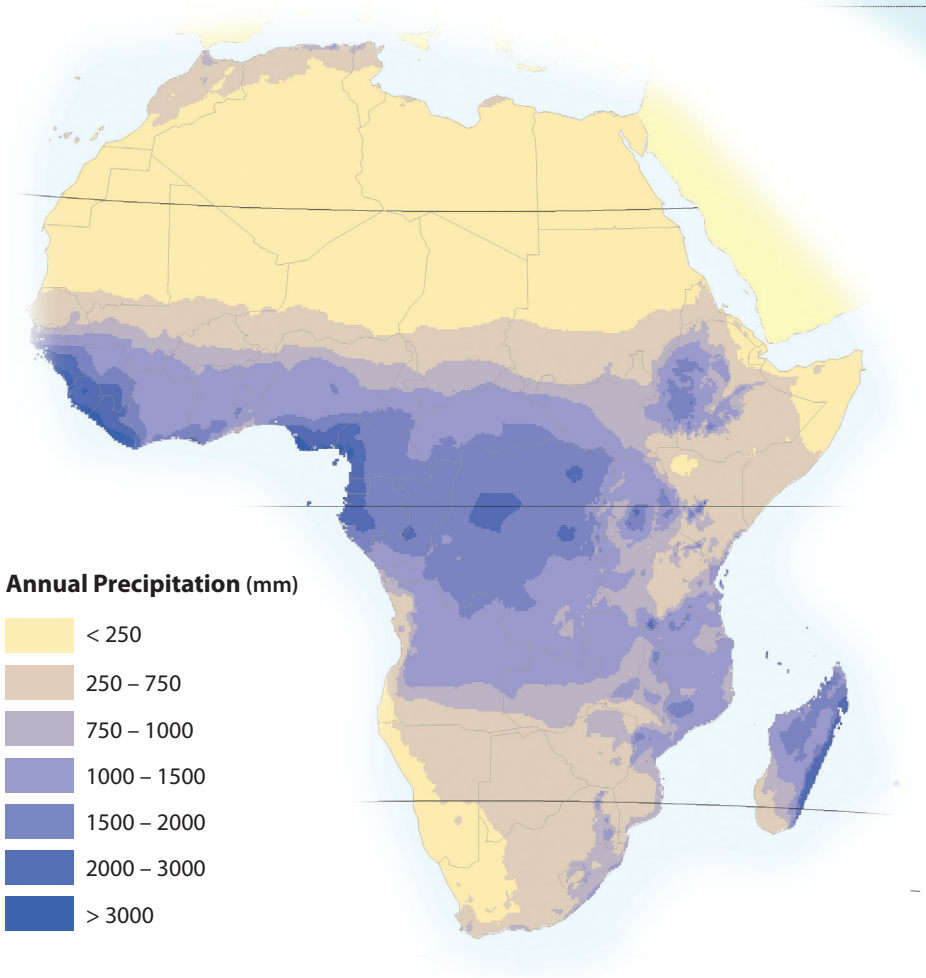


Above: Map showing the pattern of mean annual temperatures for Africa. Most of the continent has a mean temperature of above 20°C while some areas are much hotter. (WorldClim/JRC) [12, 12a]

Middle: Agro-ecological zones map of Africa based on the Length of Growing Period (LGP) and showing the climatic limits of the tropics. (GAEZ/SDD) [55b]

Below: Map showing the pattern of mean annual precipitation for Africa. Large parts of the continent have a mean annual rainfall of less than 750 mm (see correspondence with temperature map above). However, some parts of west and central Africa receive more than 5 m of precipitation every year and are among the wettest places in the world. (WorldClim/JRC) [12, 12a]





Length of growing period in the tropics

The Length of Growing Period (LGP) is the duration in days where rainfall is higher than half the reference evapotranspiration plus a period which is required for evaporating 100 mm of water that is presumed to be stored in the soil. The tropics are those areas with average monthly temperature in all months, corrected at sea level, of more than 18°C. Regions to the north and south of the tropics are known as the sub-tropics and have one or more months with temperatures between 5°C and 18°C. Areas with summer rains receive rainfall during the hottest time of the year. In the extreme north and south of Africa most rains fall during the coldest months of the year and are therefore called winter rainfall areas.

Rainfall

The map shows the pattern of mean annual precipitation (millimetres of rainfall and the water equivalent of snowfall). Rainfall is distributed very unevenly in Africa. Many areas receive either too much rain or too little. In parts of the west coast, for example, annual rainfall averages more than 3 000 mm. In the city of Monrovia, Liberia, more than 1 000 mm of rain falls on average during the month of June alone. In contrast, more than half of Africa receives less than 500 mm of rainfall yearly. The Sahara and the Namib Desert usually receive less than 250 mm a year and in some parts rain may not have fallen for six or seven consecutive years. The wettest place in Africa is Debundcha, in Cameroon. Situated on the south-western base of Mount Cameroon and facing the Gulf of Guinea, it receives a staggering annual average rainfall of 11 000 mm. In the forests of the Congo Basin and the coastal regions of western Africa, rain falls throughout the year. In the tropical rainforest climate, all twelve months have an average precipitation of at least 60 mm. The rest of Africa has one or two seasons of heavy rainfall separated by dry periods. In some regions of Africa, the amount of rainfall varies sharply from year to year rather than from season to season.

In relation to soil formation, humid conditions lead to more chemical weathering, higher levels of organic matter and leaching of minerals and organic matter. Heavy or prolonged rain can lead to soil erosion and saturated soils. A lack of rain will give rise to the development of crusts and accumulation of salts. Africa's climate has made agricultural improvement difficult. Rainfall records show that Africa's average annual rainfall has decreased since 1968 leading to prolonged and widespread droughts, especially in 1973, 1984 (when almost all African countries were affected) and 1992 (mostly restricted to Southern Africa). These failures have caused much suffering in which millions of people have died of starvation and related causes.

Weathering and climate

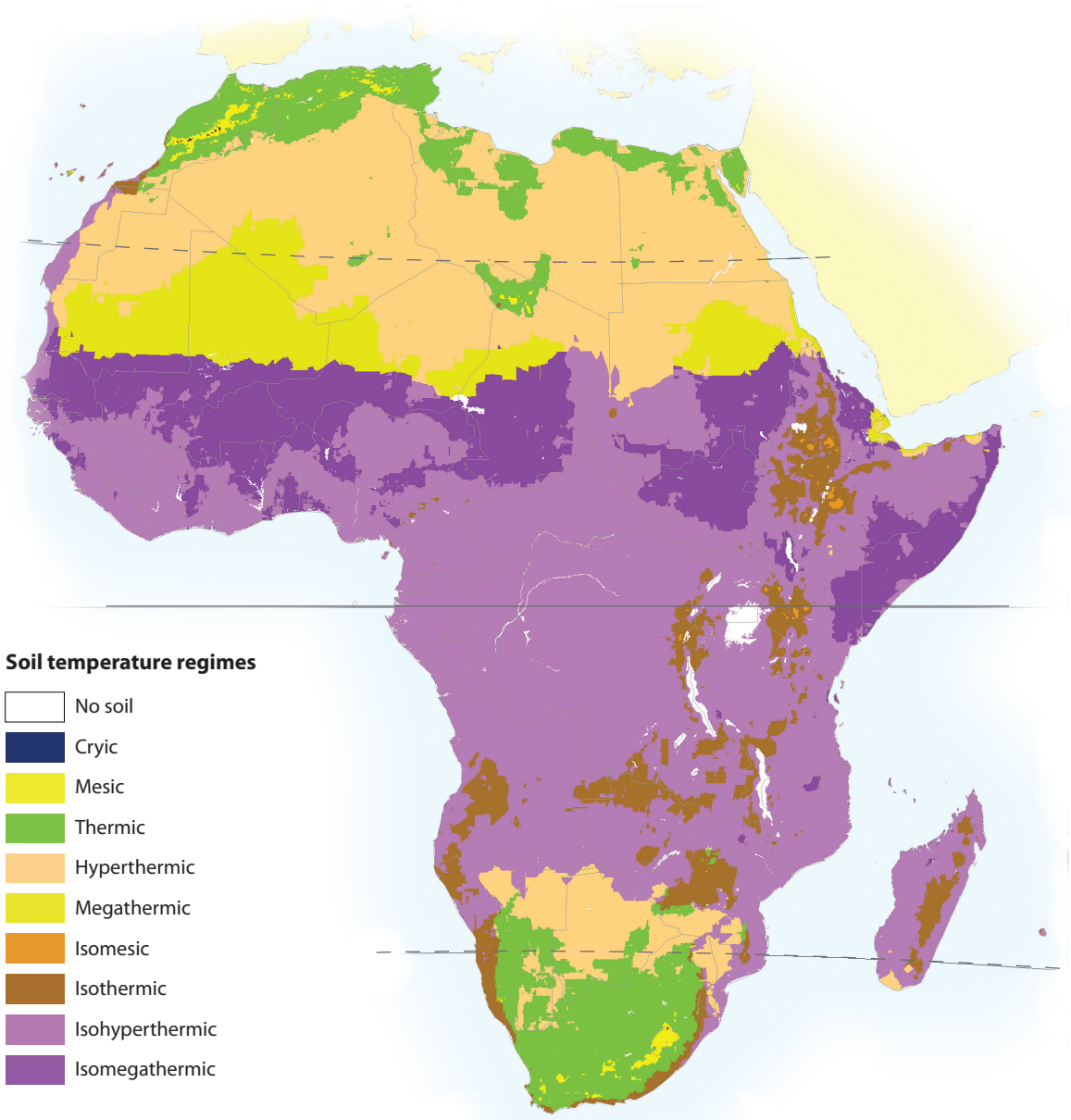
Studies have shown that tropical weathering rates, where temperature and moisture are at their maximum, are three and a half times higher than the rates found in temperate environments.

Soil temperature regimes

Soil temperature is an important attribute and key environmental factor in determining soil-forming processes, the natural distribution of plants and controls biological processes in the soil. Soil temperatures above or below critical limits severely inhibit seed germination, even if there is adequate soil moisture. The life cycles of many soil-borne pests and diseases are controlled by soil temperature. Soil temperature at a depth of 50 cm lags behind air temperature, commonly by one or two months. The length of lag depends on climate, shade, aspect, the thickness of organic layer and the thermal conductivity and heat capacity of the soil (governed by factors such as mineralogy and porosity).

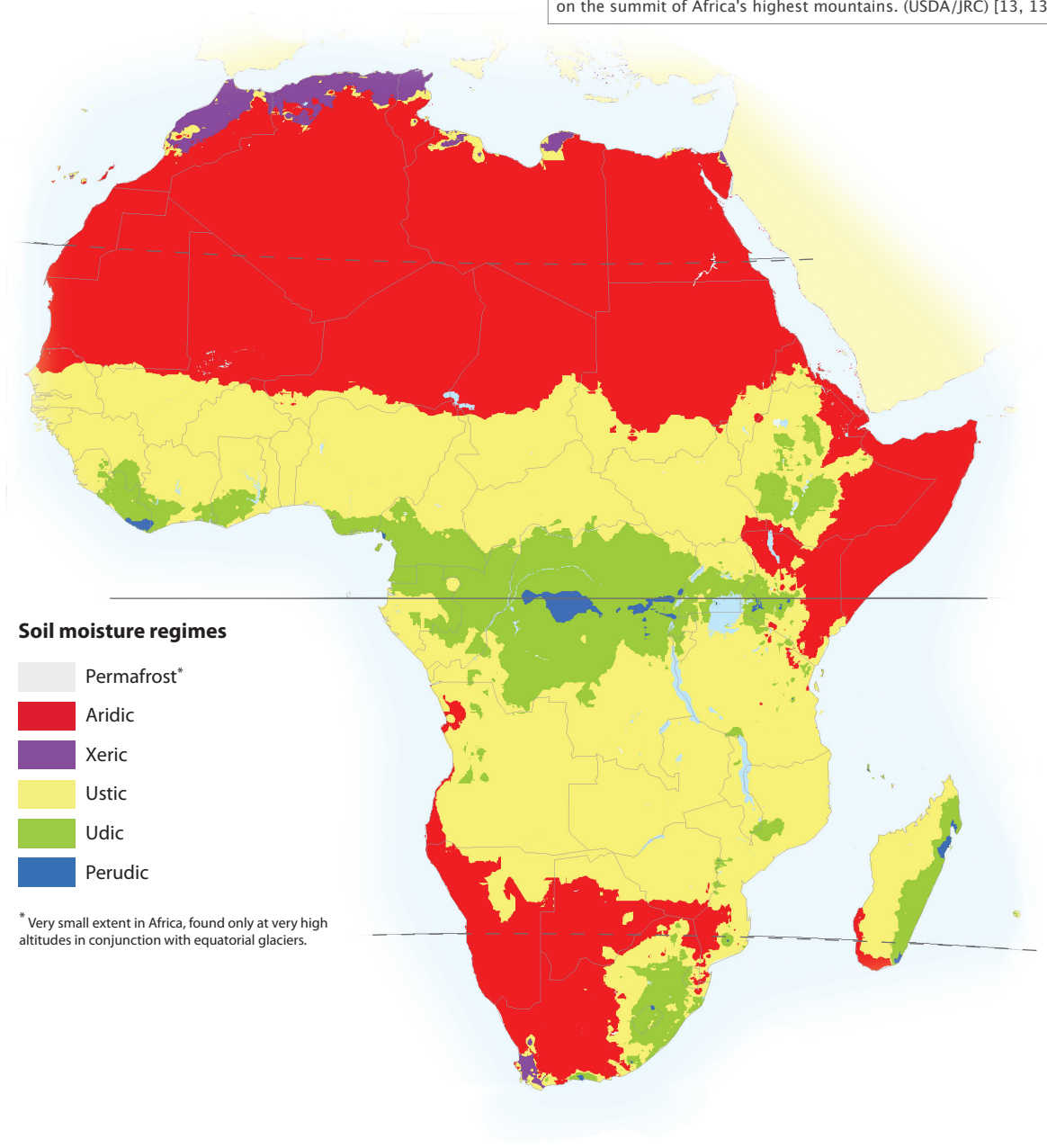
The map on the right shows the main soil temperature regions of Africa.

- Cryic: Very cold soils (mean annual temperature < 8°C but no permafrost) – very small extent in Africa, found only at very high altitudes in conjunction with equatorial glaciers.
- Mesic: Mean annual soil temperature (MAST) is 8°C or higher but lower than 15°C, difference between mean summer and winter soil temperatures ≥ 5°C.
- Thermic: MAST ≥ 15°C but lower than 22°C, difference between mean summer and winter soil temperatures ≥ 5°C.
- Hyperthermic: MAST ≥ 22°C and difference between mean summer and winter soil temperatures ≥ 5°C.
- Megathermic: MAST ≥ 28°C.
- Isomesic: MAST ≥ 8°C but lower than 15°C, difference between mean summer and winter soil temperatures ≤ 5°C.
- Isothermic : MAST ≥ 15°C but lower than 22°C,difference between mean summer and winter soil temperatures ≤ 5°C.
- Isohyperthermic: MAST ≥ 22°C, difference between mean summer and winter soil temperatures ≤ 5°C.
- Isomegathermic : Difference between the mean summer and mean winter soil temperatures ≤ 5°C.



Above: Map showing the pattern of soil temperature regimes for Africa, an important factor in determining soil–forming processes and biological processes operating in the soil. (USDA/JRC) [13, 13a]

Below: Map showing the pattern of soil moisture regimes for Africa. While the permafrost class may not be visible at this scale, permanent snow and ice exist on the summit of Africa's highest mountains. (USDA/JRC) [13, 13b]



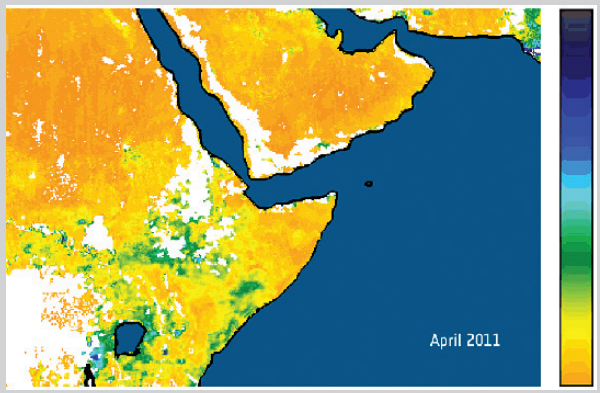
Soil moisture regimes

Soil moisture regimes are based on the watertable level and the presence or absence of water that can be used by plants. Soil moisture regimes affect soil formation and the use or management of soils. Soil moisture regime classes include:

- Aridic: arid climate, usually dry. Irrigation required for crop production. Dry soils for significant periods.
- Xeric: semi-arid or Mediterranean climate. Dryland crop possible from stored soil water. Soils can be wet in winter but dry in summer.
- Ustic: semi-arid climate. Rain falls during the growing season. Generally dry in summer.
- Udic: humid climate. Soils usually moist and so irrigation is not generally required for crop production.
- Perudic: precipitation exceeds evapotranspiration in all months, but soil is not saturated for long periods.
- Aquic: soil is saturated by water long enough to cause anaerobic conditions (not visible on the map).

Soil moisture from satellites

In recent years, increasingly accurate assessments of actual soil moisture conditions have been provided by sensors on-board satellites. The image below shows soil moisture levels for Eastern Africa as mapped by the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission. The orange and yellow colours denote dry soil conditions and graphically illustrate drought conditions over Somalia (July is normally the rainy season). (ESA) [14, 14a]



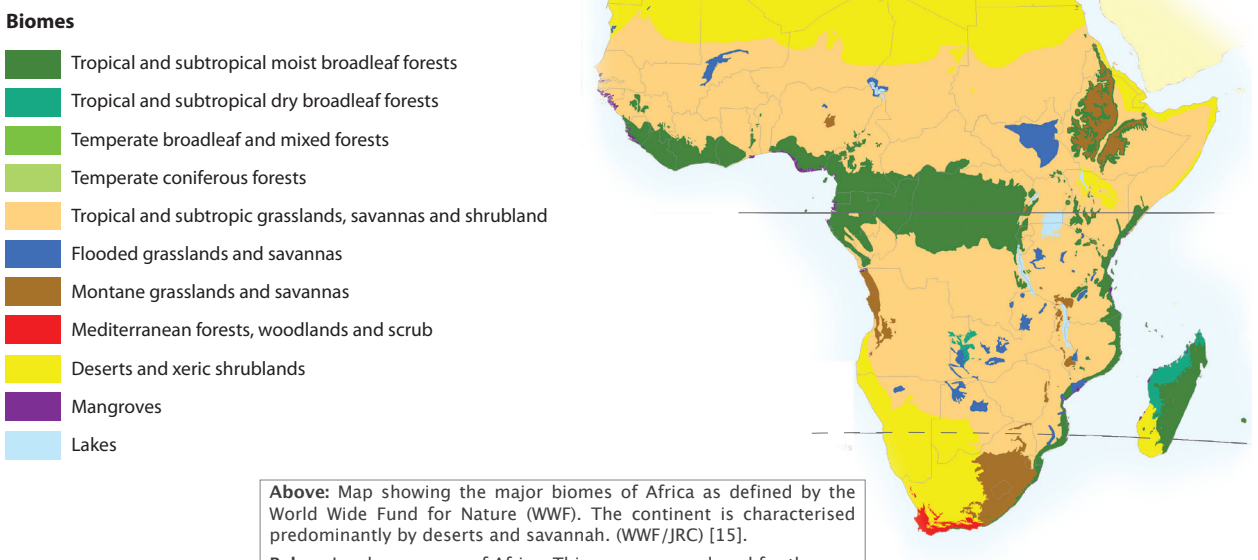
Soil-forming factor 4: Living organisms

All plants and animals (from microorganisms to humans) affect soil formation. Living organisms add organic matter - a key component of soil - through the breakdown of litter and the decomposition of roots. Microorganisms, such as fungi and bacteria, facilitate chemical exchanges between roots and the soil to produce essential nutrients. Both animals and plants allow moisture and gases to seep into deeper layers along burrows and root channels. Humans can impact soil formation through land management practices that disturb natural processes and change the chemical and physical characteristics of the soil. Cultivation practices and burrowing animals mix soil from different horizons, especially from the organic-rich surface layers. The nature of biological activity in the soil is governed by climate, topography and soil characteristics such as depth, texture, structure and chemistry (e.g. pH, salinity).

Ecoregions and biomes

Ecoregions can be defined as relatively large units of land or water containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change. The limits of ecoregions generally follow continental boundaries or major barriers to plant and animal distribution (such as the Himalayas and the Sahara). Africa south of the Sahara Desert, including the island of Madagascar, lies in the Afrotropic ecoregion. With the exception of Africa's southern tip, the Afrotropic ecoregion has a tropical/subtropical climate. The Sahara and northern Africa lie in the Palearctic ecoregion.

Ecoregions are classified by the presence of biomes, which are major plant communities determined by rainfall and climate. Forests, grasslands (including savannah and shrubland) and deserts are distinguished by climate (e.g. tropical, subtropical, temperate) and water conditions. In addition, forests are divided into conifers, broadleafed or mixed.



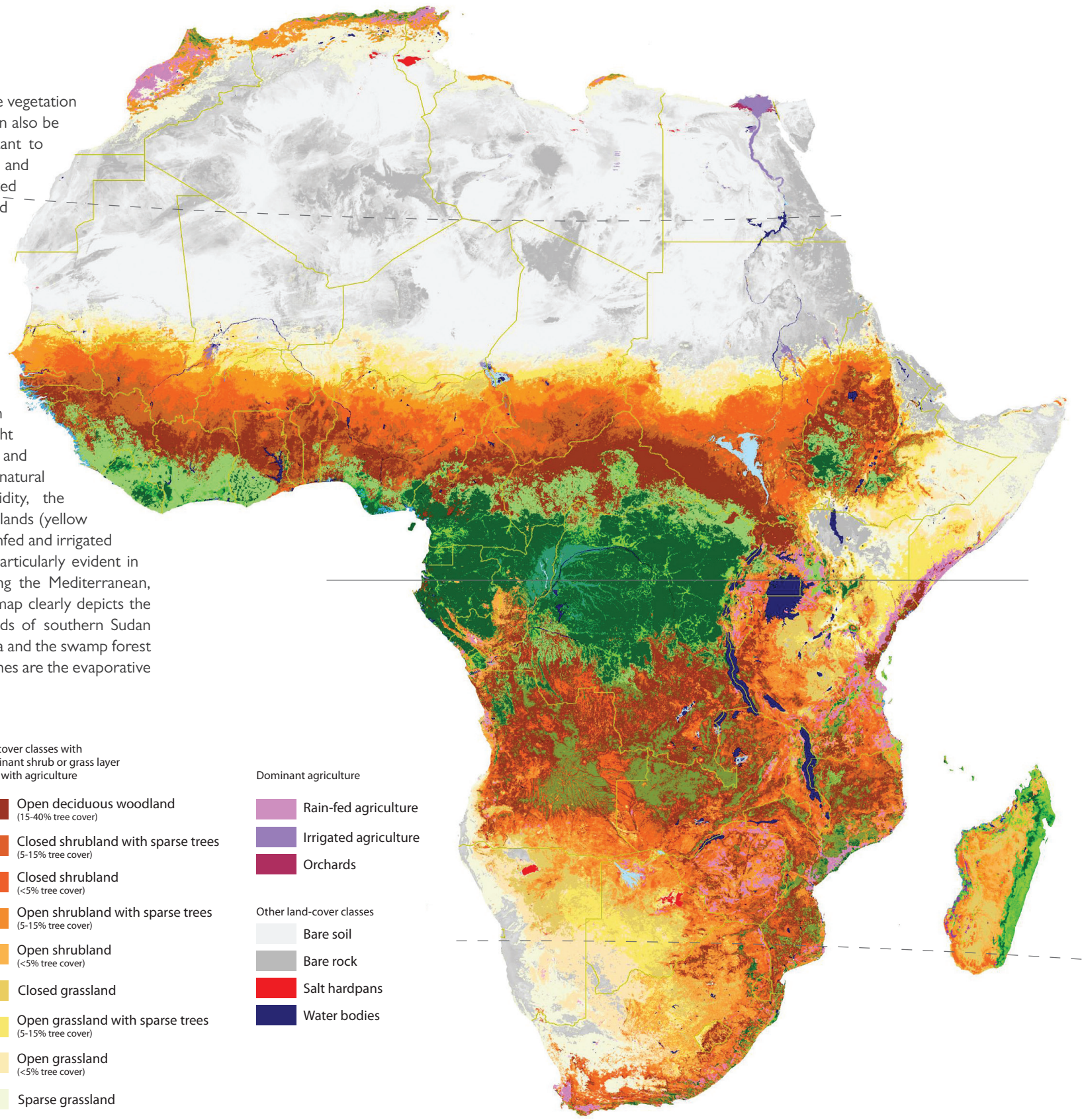
Above: Map showing the major biomes of Africa as defined by the World Wide Fund for Nature (WWF). The continent is characterised predominantly by deserts and savannah. (WWF/JRC) [15].

Below: Land cover map of Africa. This map was produced for the year 2000 using data collected by sensors on satellites. (JRC) [16, 16a]

Land cover

The term 'land cover' is used to describe the vegetation covering the surface of the planet (which can also be bare ground or unvegetated). It is important to distinguish between the terms 'land cover' and 'land use'. For example, a land cover of mixed shrubs and grass could be a park, an orchard or in an African context, savannah.

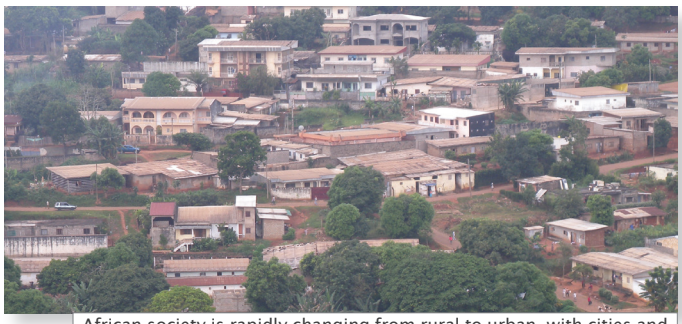
This map on the lower-right shows the principal land cover types of Africa for the year 2000 as mapped by sensors on-board satellites orbiting the Earth [16]. The map shows that the central regions are covered by extensive tropical forests (dark green) which merge to the north and south with open woodland and grasslands or savannah (brown and orange). In between, the light green areas denote a mosaic of cropland and forest that indicates the human alteration of natural vegetation patterns. With increasing aridity, the savannah grades into open and sparse grasslands (yellow colours). Where water is more plentiful, rainfed and irrigated agriculture exists (pink). These areas are particularly evident in Zimbabwe, around Lake Victoria and along the Mediterranean, East African and South African coast. The map clearly depicts the enormous extent of the vast Sudd wetlands of southern Sudan (light blue), the Okovango Delta in Botswana and the swamp forest of the Congo Basin. The distinctive red patches are the evaporative salt flats and pans of the desert margins.



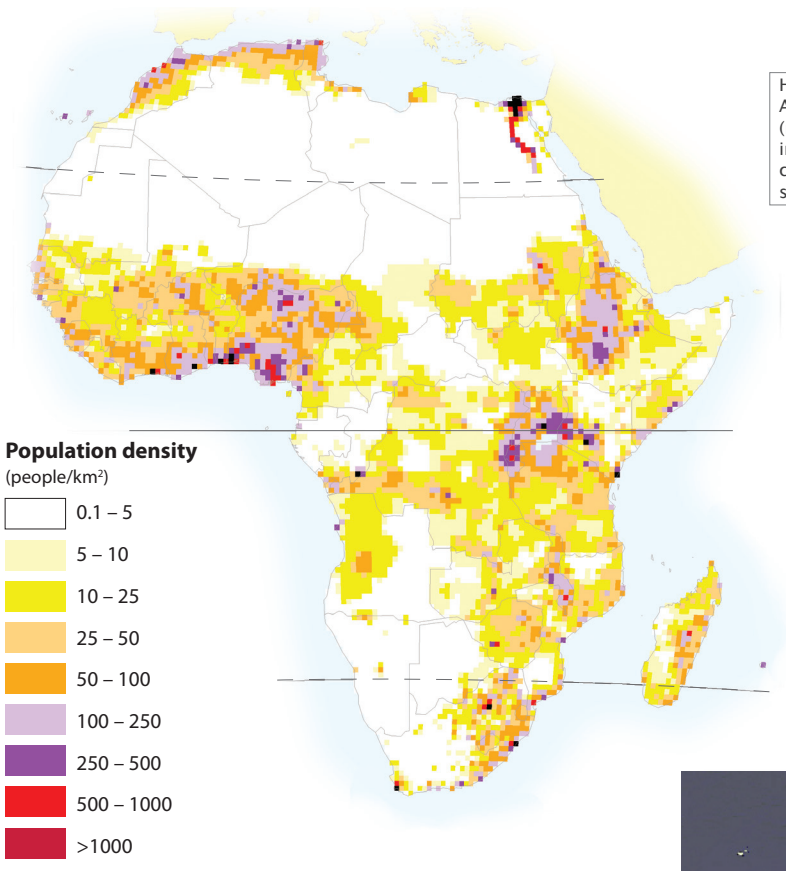
Soil-forming factor 5: Human activities

Originally, human settlement was closely dependent on climate, the availability of water, the length of the growing period and the presence of fertile soils for crops and fodder. As a consequence, the urban pattern and infrastructure network that is visible today reflects the areas that match these conditions. The map on the right shows population density for Africa (technically this is the estimated number of people living within one square kilometre). This map denotes where people are concentrated; from the less populated (white) areas to the densely populated red and purple regions. The pattern of linear settlements associated with major transport corridors is very evident.

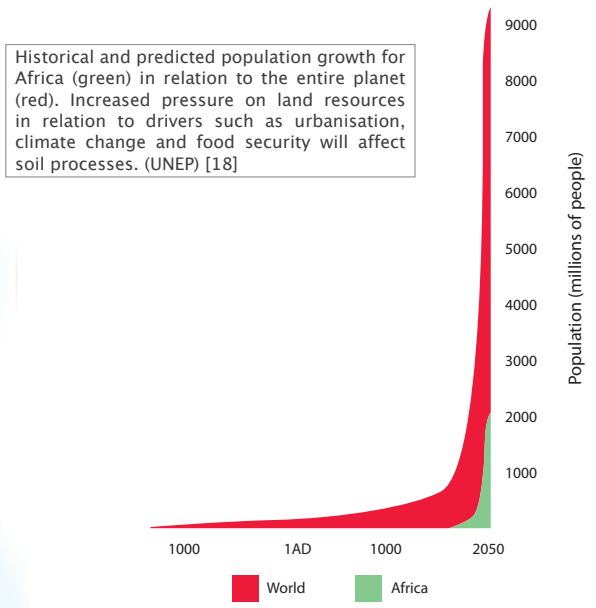
Population density is very low in the arid and mountainous regions while the Nile Delta, the Maghrebian coast and the Gulf of Guinea are amongst the most densely populated areas on the continent (see also the adjacent map of accessibility). Population density in the centre of Cairo is over 35 000 people / km^2, reaching 48 000 in parts of Lagos. The most densely populated country in Africa is the island of Mauritius with nearly 600 people / km^2. Rwanda has close to 300 people / km^2 while Namibia (2 people / km^2) and Western Sahara (1 person / km^2) are among the least densely populated territories on the planet.



African society is rapidly changing from rural to urban, with cities and towns expanding dramatically, in terms of both population growth and extent. The sealing of rural land, agriculturally productive soils and contamination are major issues associated with urbanisation. (AJ)



Map showing the population density of Africa. The values denote the number of people living in one square kilometre. The main urban sprawls (e.g. Cairo, Lagos, Johannesburg and the northern fringe of Lake Victoria) are clearly evident as are the dense population of Rwanda and Burundi. Urban populations rely almost entirely on third-parties for food production, which in turn puts increasing pressure on rural soils. (CIESIN/JRC) [17]



Historical and predicted population growth for Africa (green) in relation to the entire planet (red). Increased pressure on land resources in relation to drivers such as urbanisation, climate change and food security will affect soil processes. (UNEP) [18]

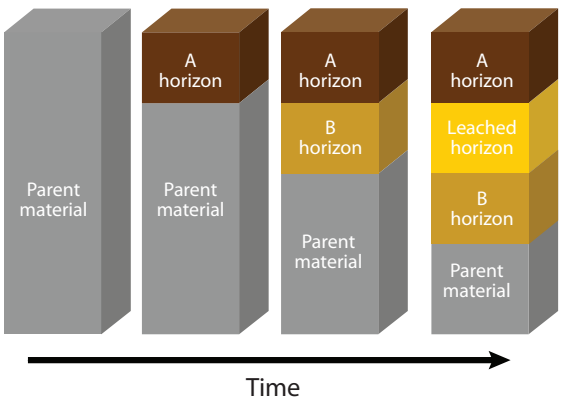
Europeans once referred to Africa as the dark continent due to vast areas of 'unexplored' land. However, this night-time satellite image **(right)** conveys a similar sense. The bright dots are lights from built-up areas. While Western Europe and much of the North African coast is glowing with night lights, the Sahara and much of south-central Africa are largely devoid of illuminated cities. It should be noted that this pattern also reflects the lack of infrastructure in many rural communities where a constant electricity supply is not available or not used for lighting. Two of the most striking features on this image are the high concentration of cities on the River Nile, along the Mediterranean coast of North Africa, the Gulf of Guinea and the urban conglomeration of Pretoria and Johannesburg in South Africa. (NASA)

Soil-forming factor 6: Time

While soils are formed through the combined effect of physical, chemical and biological processes which operate over hundreds or thousands of years, these factors rarely remain constant. Time determines the duration for which a set of factors is active. Over geological timescales, new sources of parent material can be introduced to the landscape while changes in global climate patterns are usually accompanied by changes in sea-level, erosion and deposition regimes, vegetation patterns and the shape of the landscape.

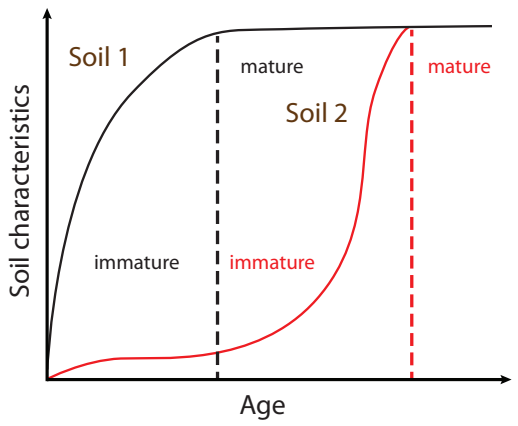
Over much shorter timescales (100 – 1 000 years), major changes can occur in the amount and nature of biological activity or hydrological conditions within a soil. Even annual fluctuations in weather patterns (e.g. drought versus above-average rainfall) or changes in the use of the land (conversion of forest to arable farming) can affect soils.

Dramatic changes in soil-forming factors can either lead to an increase in the rate of soil formation or to the destruction, or even complete removal, of the soil. Given constant environmental conditions, all soils must eventually tend towards a state of equilibrium or maturity where the rate of soil formation is equal to the rate of soil loss. However, situations may arise naturally where the rate of destructive processes exceed the rate of accumulation and retention of materials from weathering, plant growth and aerial deposition. At this point, the soil becomes vulnerable to degradation processes such as wind and water erosion.



Above: The figure shows a theoretical soil development over time in a humid environment. Unweathered parent material is subjected to weathering. The accumulation and decomposition of organic matter on the surface eventually leads to the development of an A horizon. Much later, soil processes will lead to the development of a B Horizon with accumulations of organic material, clay, iron or aluminium – often derived from the A horizon. In humid environments the upper part of the soil profile may become leached and an eluvial horizon (or E horizon) is formed. (JRC)

Below: Over time, soils settle into a steady state in which the rate of formation is equal to its rate of destruction (soil 1 and 2 develop on different parent materials). This state is referred to as being mature where soils characteristics are stable and support complex ecosystems. A key issue for land managers is how to preserve a soil while using it for crop production – an activity which inevitably changes the soil-environment balance. (JRC/LJ) [based on 6]



Young soils

In arid or mountainous areas, clear evidence of any ongoing soil-forming processes, other than the weathering of the parent material, may be difficult to find. Profile development can be negligible as a consequence of the young age and/or slow rate of pedogenic processes because of unfavourable climatic conditions for plant growth (e.g. prolonged drought, low temperatures). The paucity of altered products means that the characteristics (i.e. colour, chemistry) of the soil are very similar to those of the parent material. The development of a thin, unstratified surface horizon or subtle changes in the colour and/or structure below the surface horizon are sometimes the first steps towards the development of an A horizon. With time or changing conditions, the expression of horizons becomes stronger and the soil properties begin to differ markedly from that of the C horizon.

How old are soils?

Accurate assessments of the age of soils are very difficult to make. Since soil-forming factors continue to affect soils during their existence, evidence of earlier cycles may have been destroyed.

Ancient human artefacts found in the soil can be used to date development as long as the material has not been buried by other people! If organic matter is found at depth then a method can be used for dating its age based on the natural radioactivity present in all organic carbon matter. Alternatively, if the time that has elapsed since the last exposure of the parent material is known, then the age of the soil development can be deduced. Studies have shown that the rate of soil formation varies form very rapid (around 100 years for 2-5 cm) on volcanic ash in the warm, humid tropics to very slow (1 cm in 5 000 years) on hard rocks in cool temperate climates. A commonly quoted value is 100 years for 1 cm of soil development under permanent grasslands in temperate climates.

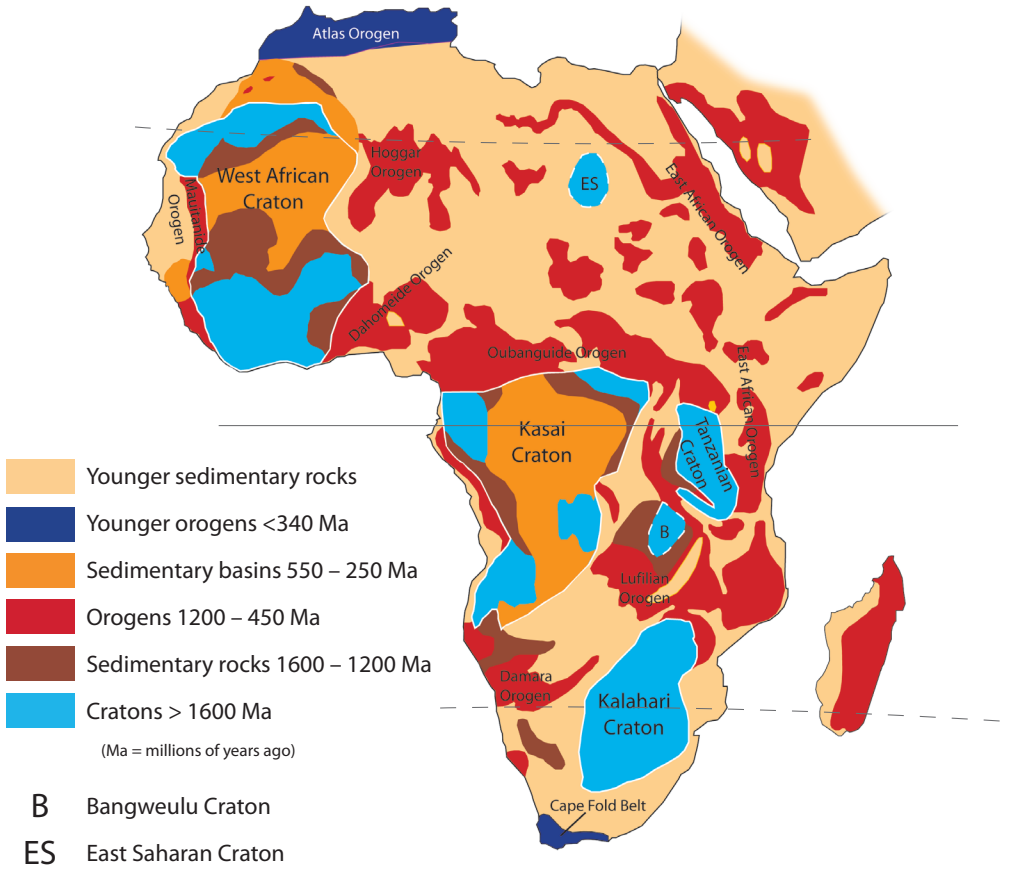
There is much debate as to the age of soils in the tropical region of Africa. Many scientists believe that some soils in the tropics (see page 31) are millions of years old. Large parts of tropical Africa have been land surfaces for 60 – 100 million years and that flat terrain has preserved old soils. Some scientists propose that the deeply weathered, iron-rich soils of the tropics, which can be up to 50 m deep, require very long timescales to develop to such a depth. Since these soils display very little textural variation or evidence of horizons and almost all clay minerals have been destroyed, then by reasoning, they must be very old.

Countering this argument is the view that soil-forming factors are operating only at the surface of deeply weathered sediments. In this way, the soil-forming factors are dominated by current climate and vegetation conditions. Given this argument, the soils must be relatively young!

In reality, the sediments of tropical Africa contain evidence of several soil-forming phases, often reflecting changing climatic conditions.

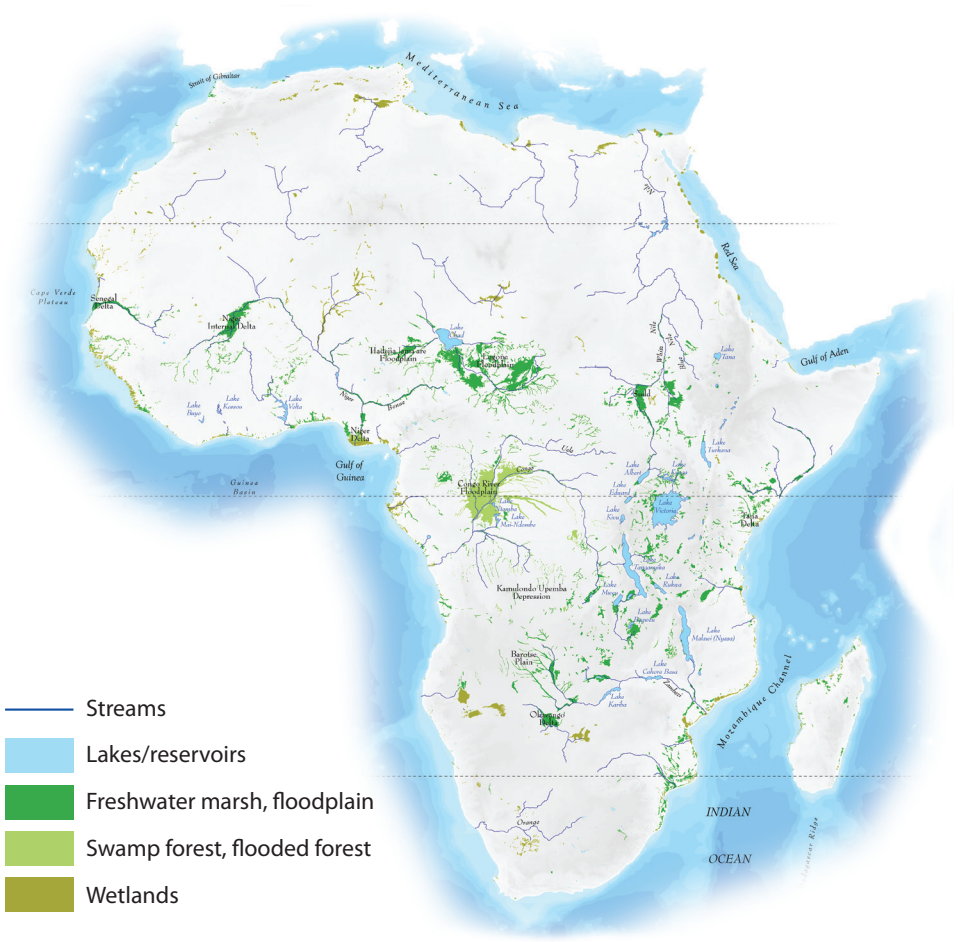
Additional information

Geological structure



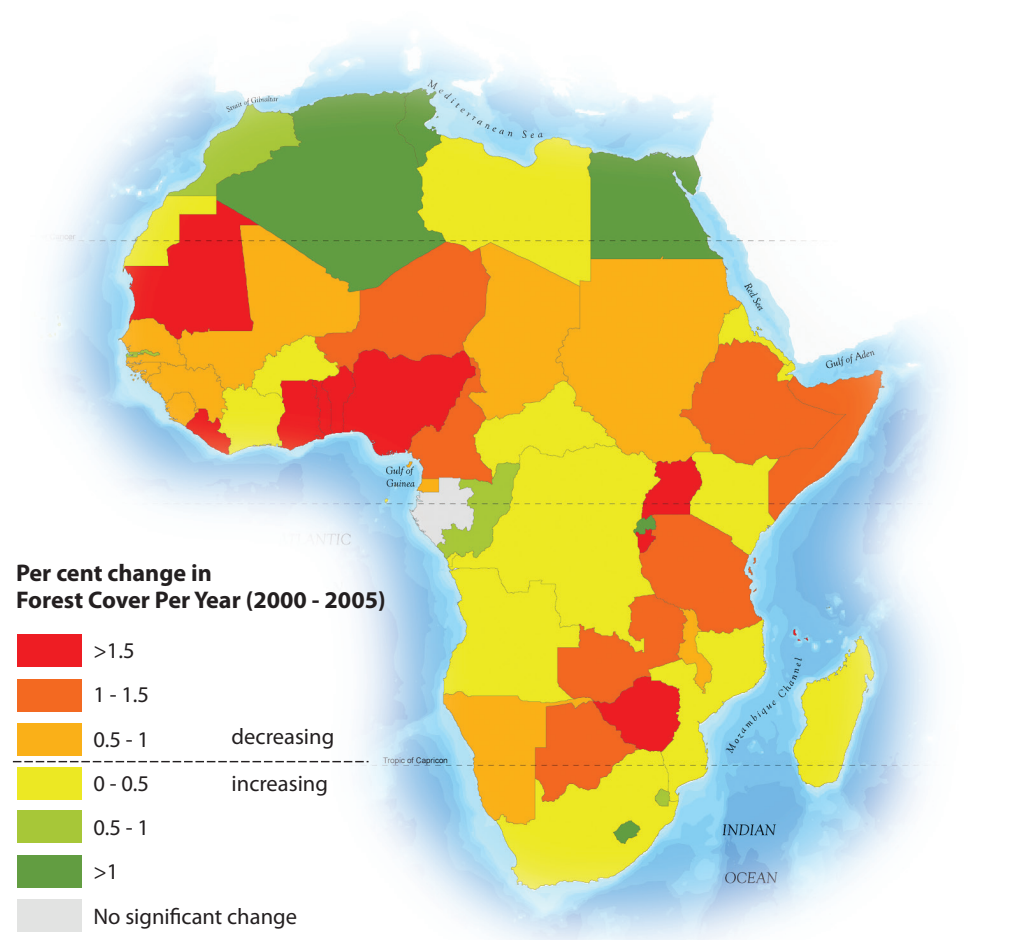
This map shows a simplified view of the geological structure and tectonic features of Africa, which in turn define cycles of erosion and soil formation. Orogens are zones of highly deformed rock caused by the collision of tectonic plates, the primary mechanism by which mountains are built on continents (the Atlas Mountains in North Africa were created by the coming together of the African and Eurasian plates). The age range denotes when the event took place. Cratons are an old and stable part of the continental crust and are generally found in the interiors of tectonic plates. Composed of ancient crystalline rock, cratons are often referred to as shields. Parts of the Kalahari Craton (in Limpopo, South Africa), have been dated to around 3.6 billion years – the oldest piece of crust on the planet. As may be seen, large parts of the African surface have remained stable for millions of years. (USGS) [19, 8]

Surface water bodies



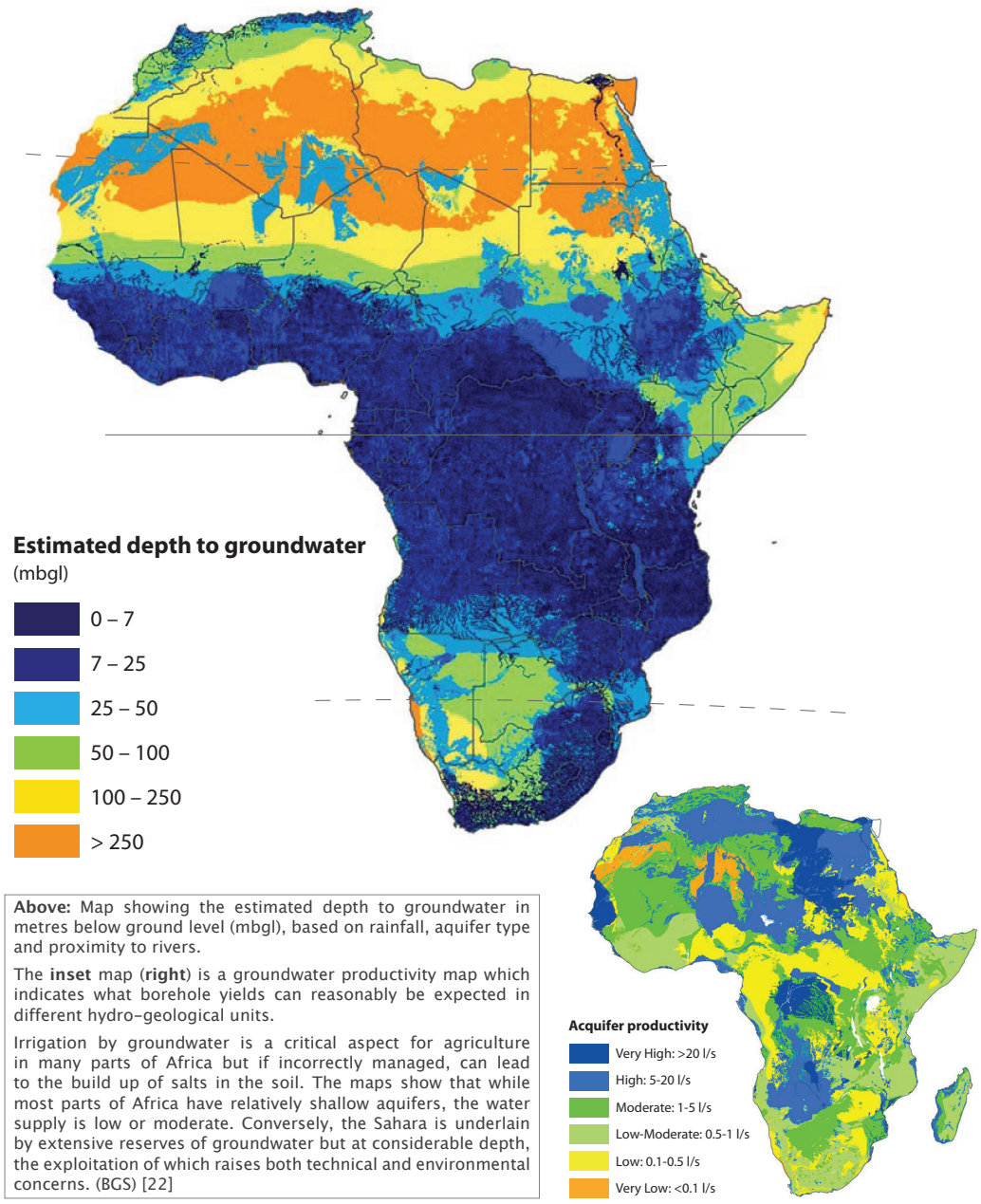
The map shows the surface hydrological features (rivers, lakes and wetlands) of Africa. The humid and sub-humid regions of Africa possess abundant water resources in the form of seventeen large rivers and 160 lakes with a surface area greater than 27 km². The Nile is the world's longest river and only the Amazon discharges more water than the Congo. Many rivers show dramatic seasonal variability. East Africa has numerous lakes including Lake Victoria (3rd largest in the world by area and largest tropical lake in the world) and Lake Tanganyika (3rd largest by volume and 2nd deepest lake on Earth). Surface runoff in Africa is, on average, much lower than the average precipitation as a result of high evaporation and evapotranspiration. Groundwater provides nearly two-thirds of the drinking water on the continent, and an even greater proportion in northern Africa. Land that is regularly saturated by surface water or groundwater is important from an ecological perspective, but in Africa, wetlands cover only about 1% of the continent's total surface area. The watersheds of the major African rivers is presented on page 22. (UNEP) [20]

Deforestation and land cover change



Map showing the change in forest cover by country across Africa between 2000 and 2005 as measured by earth observation satellites. The results show that apart from a few exceptions, forest cover displays a marked decreasing trend across the continent. Strongly affected countries are Benin, Ghana, Liberia, Mauritania, Togo, Uganda and Zimbabwe. The main drivers are commercial logging, clearance for large-scale agricultural development and small-scale subsistence farming. In areas where forest has been cleared, a marked increase in soil erosion has been observed. More than 70% of Africa's remaining rainforests are located in the Congo Basin countries of the Democratic Republic of Congo, Congo and Gabon and cover and estimated 1,875 million km² (see also page 152). (UNEP/FAO) [21]

Groundwater resources



Above: Map showing the estimated depth to groundwater in metres below ground level (mbgl), based on rainfall, aquifer type and proximity to rivers.

The **inset** map (**right**) is a groundwater productivity map which indicates what borehole yields can reasonably be expected in different hydro-geological units.

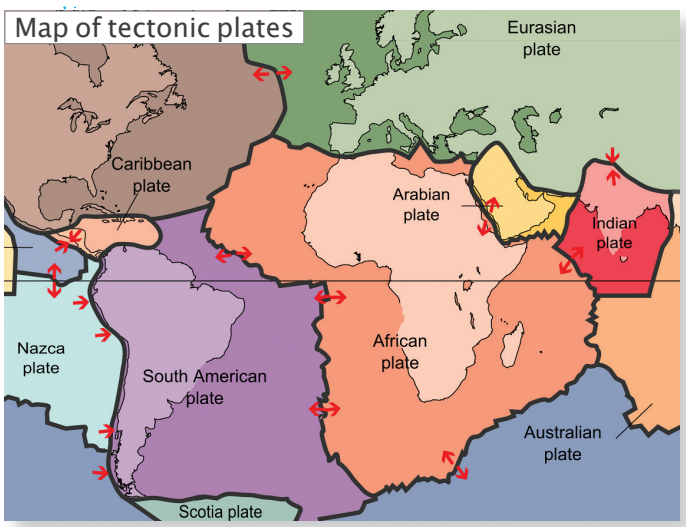
Irrigation by groundwater is a critical aspect for agriculture in many parts of Africa but if incorrectly managed, can lead to the build up of salts in the soil. The maps show that while most parts of Africa have relatively shallow aquifers, the water supply is low or moderate. Conversely, the Sahara is underlain by extensive reserves of groundwater but at considerable depth, the exploitation of which raises both technical and environmental concerns. (BGS) [22]

Africa – the political view

Political

City	Inhabitants
Lagos	10-20m
Johannesburg	5-10m
Casablanca	1-5m
Aswân	250,000 - 1,000,000
Lubango	100,000 - 250,000
Bondo	Less than 100,000
ABUJA	National capitals are shown in CAPS.

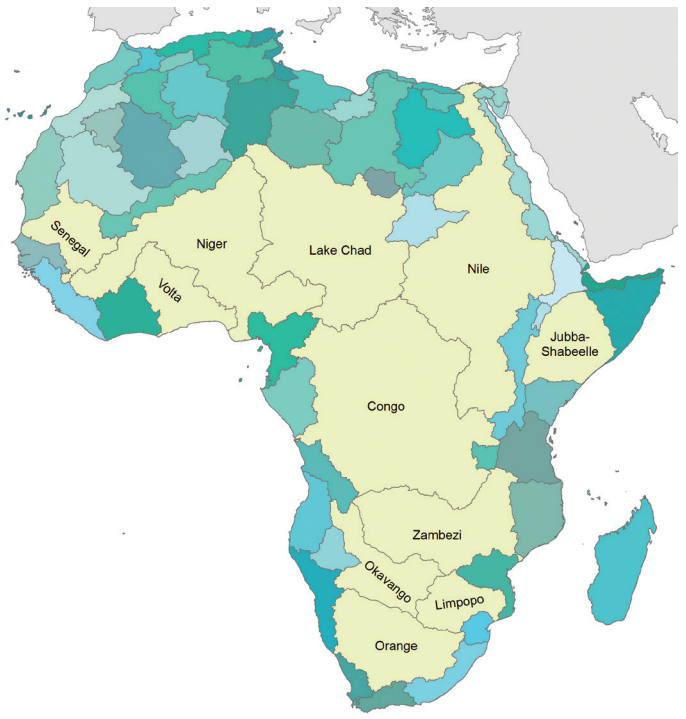
International boundary
State boundary
Disputed/Undefined boundary



Above: Political map of Africa. At this scale, national boundaries are only indicative. Political boundaries are only indicative. (LJ);

Inset: Map showing the extent of the African plate and associated tectonic elements. (USGS);

Below: A map of the major river basins of Africa. Many river basins have no outlet to the sea. (JRC)



From a geological perspective, the African tectonic plate is significantly larger than the visible continental land mass (see inset above). Originally the Arabian plate was part of the African plate but it is now separated by the Red Sea Rift. Red arrows on the map indicate the current direction of tectonic movement. The northward collision of the African plate with the Eurasian plate is responsible for the formation of the Alps, volcanoes in Italy and earthquakes in southern Eurasia.

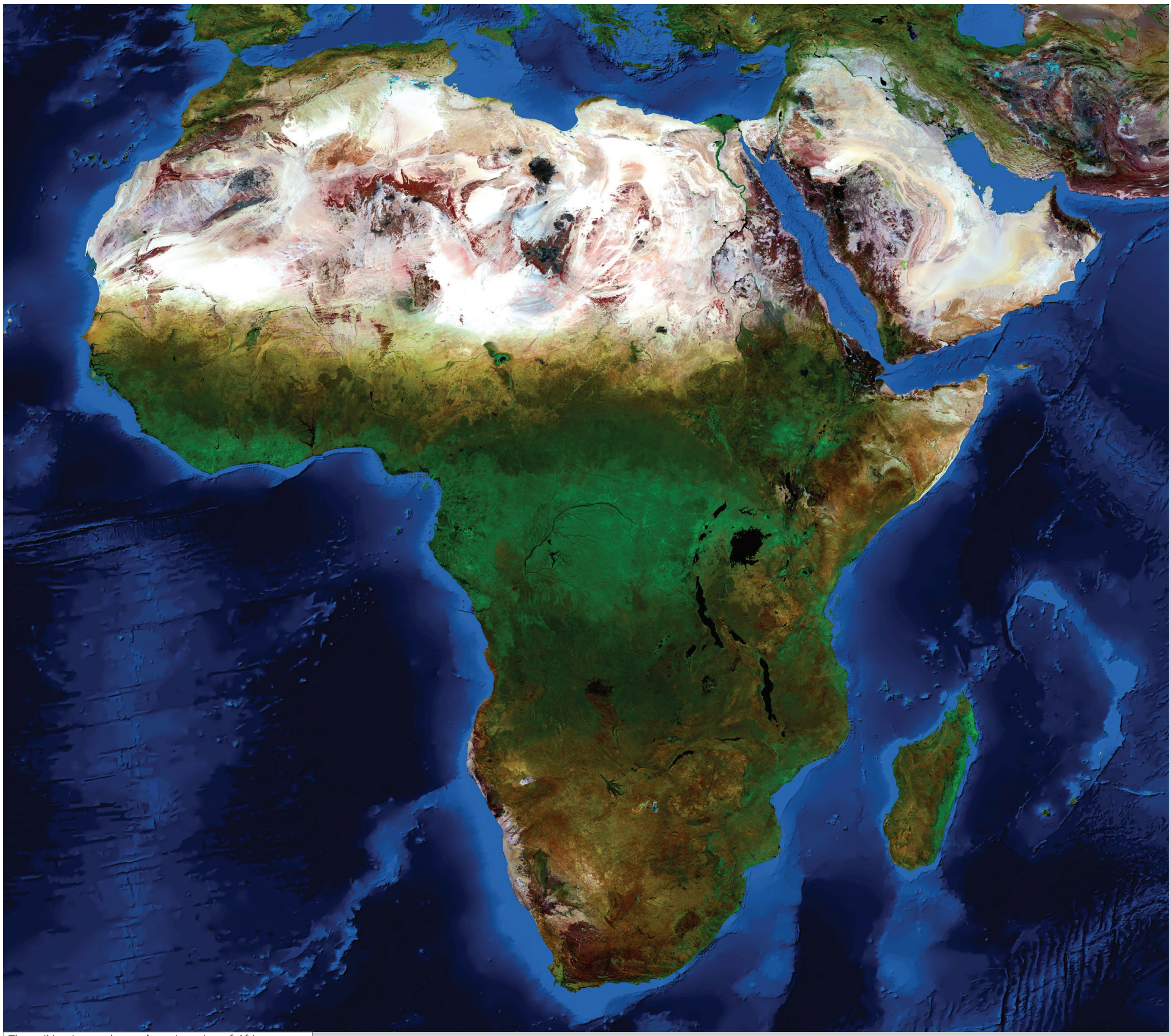
For the purposes of this atlas, soil information is provided for the entire continental land mass of Africa and all islands located on the African plate (see map spreads on pages 80-127 and summary texts on pages 158-161). This includes Malta, parts of France (Réunion, Mayotte and a small number of uninhabited islands around Madagascar), Italy (Lampedusa and Lampione), Portugal (Madeira and surrounding islands) and Spain (the Canary Islands, the Autonomous Cities of Ceuta and Melilla, and small islands off the coast of Morocco). No information is provided for the volcanic Mid-Atlantic Ridge islands of St Helena, Ascension and Tristan da Cunha Socotra (administrated by the United Kingdom) nor for the island of Soqotra, which is part of the Asian state of Yemen. Although the Sinai peninsula is considered geologically as part of Asia, it is included in the atlas as it is part of the Egyptian state.

In terms of geographic area, Africa is the planet's second-largest continent covering an area of 30.3 million km^2. Africa's largest country is Algeria while the smallest is the Indian Ocean archipelago of the Seychelles. The smallest country on the continental mainland is The Gambia in West Africa.

With just over a billion people, it is the second-most populous continent in the world and accounts for just over 14% of the world's human population. Politically, Africa consists of the fifty-four states that are fully recognised by the United Nations and the Sahrawi Arab Democratic Republic which is a member of the Africa Union (Morocco is not currently a member of the AU). Of these fifty-five states, forty-nine are found on the actual continent while six are island nations.

Nigeria is by far the most populous state with 166 629 000 inhabitants while the Seychelles are home to only 87 000 people spread over 115 islands. The population of most African countries is growing by more than 2% per year, with Niger at 3.6% (all population estimates are from the UN for 2012).

Africa – the real view?



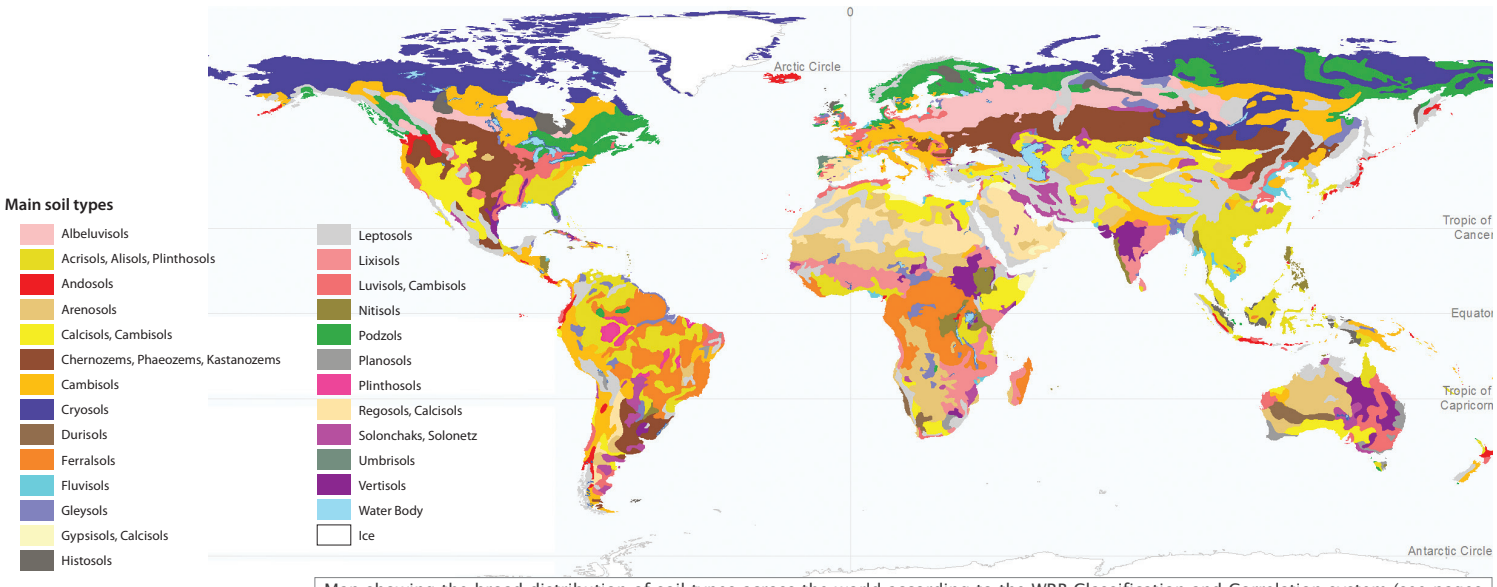
The striking image shown **above** is a view of Africa as seen from space. This overview has been made up of dozens of smaller, cloud-free segments acquired by the NASA MODIS sensor (Moderate Resolution Imaging Spectroradiometer) from June to September 2001. The MODIS sensor is carried on-board a satellite that orbits the Earth every 1–2 days at an altitude of 705 km and is an example of remotely sensed data, which, through computer enhancement, can be viewed as an image. In this case, the image is displayed in near true colour which means that it appears almost as if viewed by a person in space. Green tones correspond to vegetated areas: the tropical rainforests in the Congo Basin and on the east coast of Madagascar are very evident, as are the intensively cultivated soils of the Nile Delta, and the vegetation around Lake Chad and the highlands of Ethiopia. Darker green areas around the tropical forests denote a mosaic of woodland and cultivated land. The mottled brown/light-green areas to the north and south of the equator denote a reduction in tree cover and the increasingly open grassland environments of the savannah. The distinctive, isolated dark-green area in Botswana is the Okovango Delta.

In the arid, unvegetated regions of the deserts, white and bright yellow colours correspond to sand seas while the dark red (almost blackin some cases), brown and orange hues indicate bare rock surfaces – the mountain ranges of Ahoggar, Tibesti and the Aïr Massif are strikingly apparent in the Sahara. The movement of sand in relation to prevailing wind patterns is noticeably apparent.

The almost black features in central Africa are water bodies, with the path of the East African Rift Valley being clearly delineated by its lakes. The path of the Nile and Niger are clearly visible as are the numerous tributaries of the Congo. The line of turquoise areas running from Tunisia to Algeria (and also south of the Okovango) are salt lakes. At this scale, urban areas are difficult to visualise.

The spectacular details in the ocean are derived from the General Bathymetric Chart of the Oceans. (NASA/JRC)

The soils of Africa in a global context



Map showing the broad distribution of soil types across the world according to the WRB Classification and Correlation system (see pages 50 – 61). The different colours indicate variations in the chemical, physical, and biological characteristics of soils which, in turn, are a reflection of the principle soil-forming factors described on the preceding pages. The map clearly shows that Africa has a unique pattern of soils that is not replicated on the other continents. Lacking the organic-rich peats, Podzols and permafrost-affected soils of the northern latitudes, the largely tropical African continent is nevertheless characterised by huge contrasts. The weakly developed soils of the Sahara, Kalahari, Namib and Horn of Africa appear to surround a central core of tropical soils reflecting differences primarily in climate and parent material. The prominent Gleysols of the vast African wetlands on the Niger, Congo and Zambezi Rivers denote seasonally waterlogged soils while the large expanse of heavy clays of the Vertisols in Nile Valley in Sudan is very evident. (FAO/ISRIC/JRC) [23]

Soil-forming processes

Principle processes

The specific properties of an individual soil are determined by pedological processes that operate during its lifetime. These biological, chemical and physical actions add, transform, move (translocate) and destroy or remove material within the soil. It is important to recognise that soil-forming processes can evolve and change over time in response to factors such as climatic variability and land use. Due to their old age, many African soils exhibit several distinct and different phases of soil formation.

Weathering

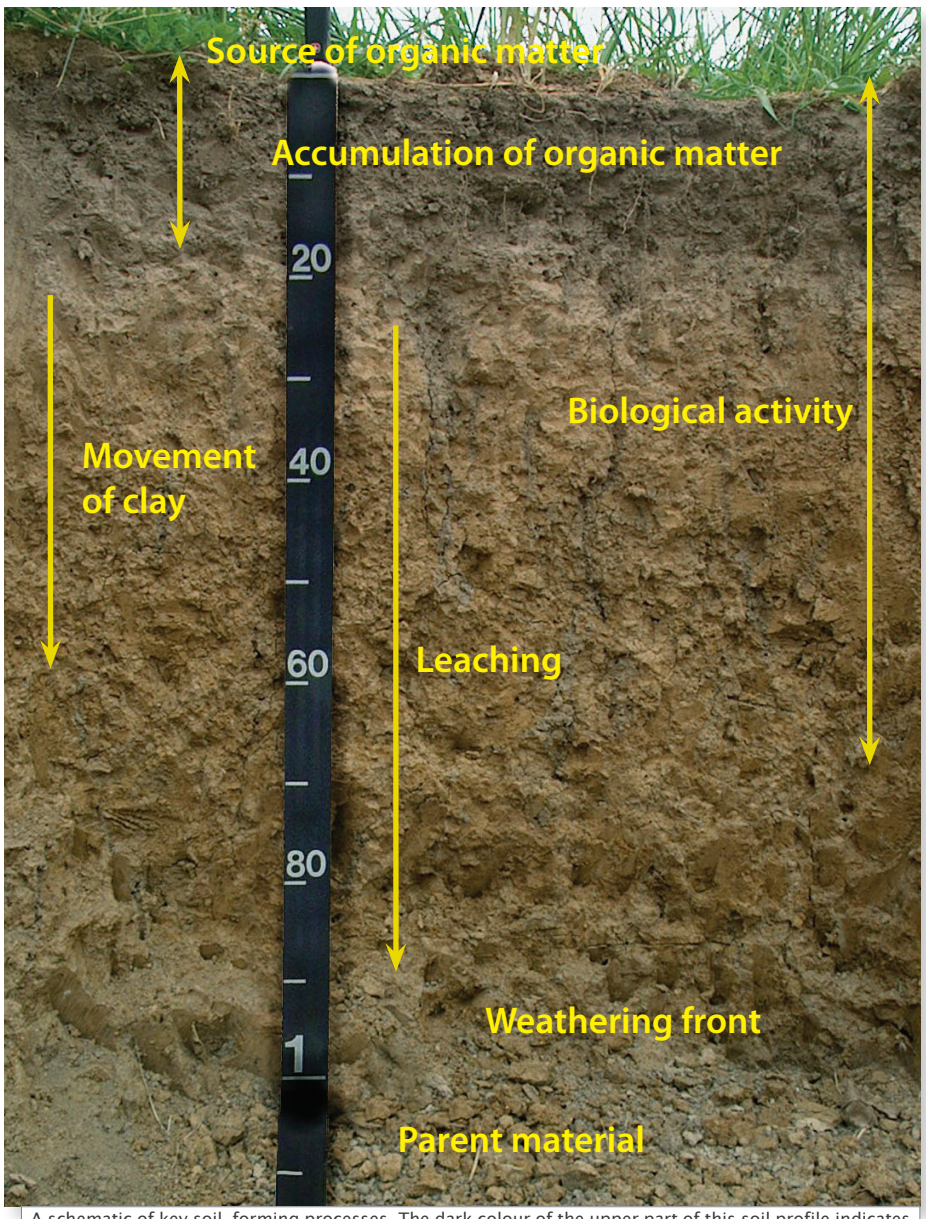
Below the soil we usually find solid rock or unconsolidated sediments in (or on) which the soil has developed (see page 14). In reality, all sediments are derived from solid rock by a process known as weathering. Weathering proceeds by a physical destruction of the rock structure which in turn facilitates chemical changes to the constituent minerals.

In principle, there are two main types of weathering: physical and chemical. Some people also consider biological weathering but, in reality, it is a manifestation of physical and chemical actions (see below).

Physical Weathering

In physical weathering, rocks disintegrate without changing their chemical composition. Typical examples of these processes are the splitting of rocks by the daily warming of the sun and cooling during the night (typical of desert environments) or by the repeated freezing and thawing of water (when water freezes, its volume increases by 10%, causing tremendous pressures if it occurs in confined spaces such as crevices in rocks).

Physical weathering produces a layer of loose material which covers the underlying solid rock. This material is known as regolith and can vary from a few milimetres to tens of metres thick. Regolith layers in some parts of west Africa have been found to be more than 150 m thick. There is often a sharp boundary between the bottom of the regolith and the bedrock. This narrow zone is known as the weathering front and is the focus of active weathering.



A schematic of key soil-forming processes. The dark colour of the upper part of this soil profile indicates that significant amounts of organic matter have accumulated in the topsoil through the decay of vegetation and root material. The lighter colour between 20 and 40 cm is due to a combination of the leaching of mobile iron and loss of clays by percolating rainwater. In the subsoil, the iron has coated soil particles with a thin, reddish film. The bedrock from which the soil has developed and the weathering front is clearly visible at the base of the profile. Biological processes are generally more active in the topsoil. (EM)

The destruction of bedrock through both physical and chemical weathering is clearly visible in this photograph from South Africa. The red rock is a dolerite dyke that has intruded into granite (visible to the left). Weathering processes have caused blocks of granite to break away while the dolerite breaks down more easily to produce the distinctive red coloured finer material that is accumulating at the foot of the slope. It is very evident that the dolerite is weathering more rapidly than the granite. The dolerite is receding into the cliff face and approximately 15 cm of soil has developed above it while bare rock is still visible on the surface of the granite. (EM)

Minerals vs Nutrients

A mineral is a naturally occurring solid substance formed through geochemical processes with a characteristic chemical composition. Rocks are composed of several minerals.

Nutrients are chemical elements required by organisms to live and grow. Nutrients can be produced by the organism or must be taken in from its environment. Plants absorb nutrients from dissolved minerals in the soil which, in turn, are consumed by herbivores and then by the people who eat the herbivores. In this way, minerals move up the food chain.

Chemical Weathering

Chemical weathering is a gradual and constant process. It is driven primarily by the reaction between water or an acid and elements within the parent material which lead to the creation of secondary minerals from the original compounds present in the rock. Chemical weathering is much stronger if temperatures and humidity are both high (e.g. in the humid tropics).

Water is the key factor in chemical weathering. Most people are unaware that rainfall is slightly acidic with a pH of around 5.6 in unpolluted environments. Atmospheric carbon dioxide dissolves in the rainwater to produce a weak carbonic acid. Some minerals, due to their natural solubility (e.g. evaporites such as highly soluble salts and gypsum) or inherent instability relative to surface conditions (e.g. primary silicate minerals such as feldspar, mica, augite, hornblende and olivine), will slowly dissolve to form secondary products such as clay minerals (e.g. kaolinite, illite, vermiculite and smectite), iron and aluminium (hydr)oxides, carbonates and nutrients such as calcium and potassium.

One of the most well-known solution weathering processes is de-calcification which occurs on parent material such as limestone and chalk that are rich in calcium carbonate. Rain combines with carbon dioxide or an organic acid to form a weak carbonic acid which then reacts with calcium carbonate in the limestone to form calcium bicarbonate, which is then removed. This process can be even stronger if gases such as sulphur dioxide and nitrogen oxides are present in the atmosphere. These oxides react in the rainwater to produce stronger acids with a pH as low as 3).

Water molecules can break up into positively charged hydronium (H_3O^+) and negatively charged hydroxyl (OH^-) particles (see Glossary for ion and cation). These small and mobile particles can actually penetrate the crystal lattice of silicate and carbonate minerals. Those with positive charge upset the balanced state of the mineral in question causing various cations to be released into the soil.

This process is known as hydrolysis and is one of the underlying factors of soil fertility (see page 32).

Another chemical process involves the simultaneous loss (referred to as oxidation) and gain (referred to as reduction) of electrons in substances. These exchanges are referred to as redox reactions. As materials become oxidised, the unbalanced charge will degrade a material's structural composition.

Biological weathering is caused by the activities of living organisms and has both physical and chemical aspects. Examples of physical biological weathering include the loosening of rock by roots growing into cracks and burrowing creatures such as termites that mix or churn the soil.

Chemical biological weathering can be caused by bacterial activity or by strong organic acids from plant roots or litter. A recent study demonstrated a 3 – 4 fold increase in weathering rate under lichen-covered surfaces compared to recently exposed bare rock surfaces. Biological weathering factors in Africa are highly significant.

A clear example of a weathering front on limestone in Tigray, Ethiopia. The photographs shows the breakdown of the underlying bedrock along vertical joints and horizontal bedding planes. (JD)

Common processes in humid conditions

Many parts of Africa are characterised by a climate that provides a precipitation surplus during some parts of the year (i.e. when rainfall is greater than evaporation rates). This surplus fills up the spaces or voids in the soil, which might have been emptied during the dry season, and then percolates down through the soil body to accumulate as groundwater. In doing so, the water drives three important soil forming processes:

1. Leaching

When water passes through the soil, it dissolves soluble salts (such as chlorides, nitrates, sulphates and carbonates) and flushes them, together with organic and chemical solutes, into the deeper parts of the soil. In the drier climates, these salts can be re-precipitated, for example, as a calcium carbonate-rich horizon in the subsoil. In more humid regions, significant amounts of materials can be completely removed from the soil by leaching.

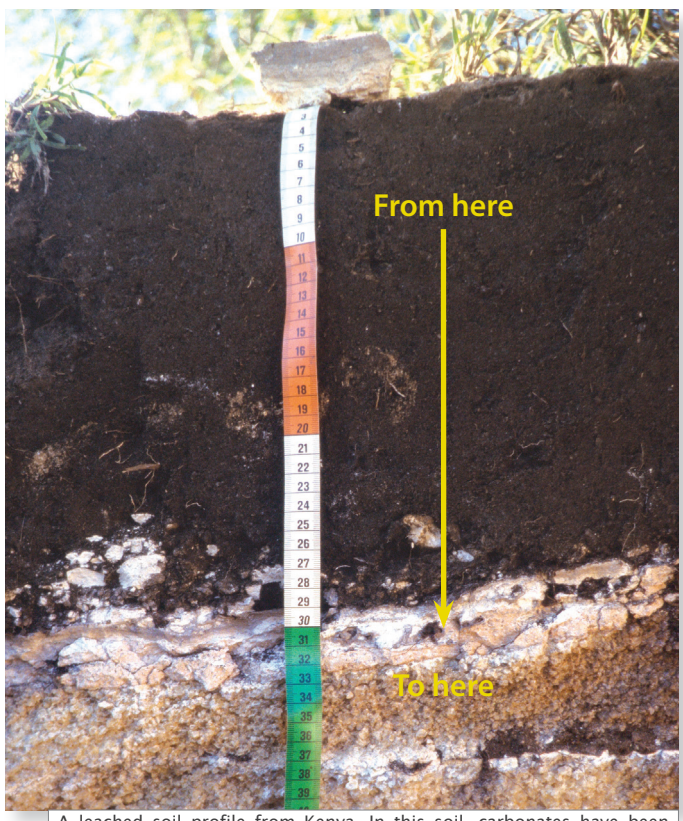
This loss of mineral and organic solutes due to percolation is known as leaching. The rate and extent of leaching depends on two factors:

- the mobility of an element, which in turn is based on its solubility in water and the effect of pH on that solubility – chlorides and sulphates are very mobile while titanium is insoluble even at a pH of 2.5;
- the rate of water percolation, which in turn depends on climate, soil texture and structure, porosity and the slope of the ground – in dry regions, even the most mobile compounds (e.g. sodium chloride) tend to stay in the topsoil and eventually give rise to saline soils.

As humidity levels increase, losses of salts, organic compounds and silica in the topsoil increase and the soil is regarded as being leached.

Leaching is a major controller of soil fertility. As long as calcium carbonate is present, the pH of the soil will be above 7 (see page 11) and the soil will often be whitish or light coloured. When the calcium carbonate is dissolved and leached away, the pH will drop and calcium, magnesium and sodium will be released from the surfaces of clay minerals and humus to be replaced by hydrogen and aluminium. Unless there is a change in the soil-forming factors or there is human intervention, the pH of soil will fall below 7 and under such conditions the soil is referred to as acid.

Highly acidic soils are not very suitable for the cultivation of food crops. Such soils will require the addition of calcium carbonate (a practice known as liming) in order to raise the pH to a more acceptable level for plant production. A reduction of pH below 5.5 can cause a release of aluminium cations in the soil solution, which is toxic for some plants, crops and nearby water bodies.



A leached soil profile from Kenya. In this soil, carbonates have been leached from uppermost 30 cm of the topsoil which is represented by the dark, humus-rich surface horizon. The white layer below 30 cm shows the accumulation of the leached carbonates deeper in the soil (OS).

In some instances, immobile elements can be leached when they are combined with organic compounds (e.g. organic and amino acids) derived from the humification of litter or from soil microorganisms. This process, known as cheluvation, is an important mechanism for increasing nutrient availability to plants. Chelates are very important in micronutrient management.

2. The movement of clay particles

A common soil-forming process is the movement or translocation of clay particles from one soil horizon to another. This involves the mechanical transfer (illuviation) of clay particles from the upper part of the soil by percolating water and their re-deposition deeper in the soil on the surfaces of soil particles or in soil pores and cavities.

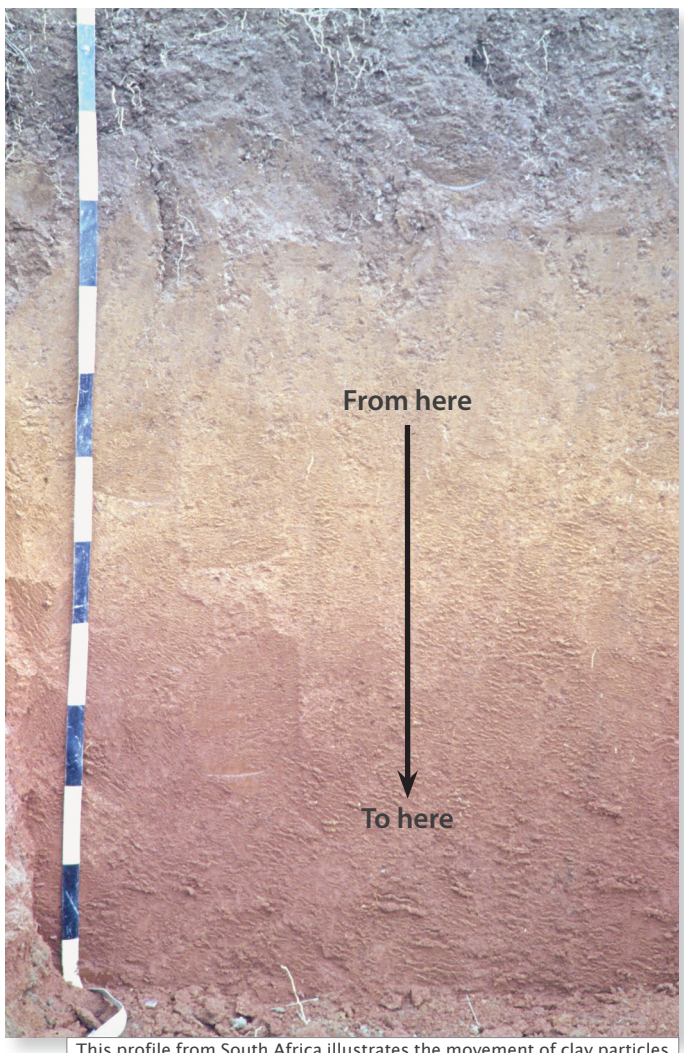
This process is dependent on the soil texture, structure and chemistry. If a continuous and coarse pore system exists in the soil, percolating water can then transport the clay particles downwards. Such conditions will develop as the soil shrinks and cracks during dry seasons. The clay will accumulate where the cracks end and water movement almost ceases or where the water penetrates into the dry aggregates and the clay particles are filtered at the ped surfaces forming clay layers or skins called cutans or argillans.

Another process that can lead to low clay content in the topsoil is raindrop erosion where splashes move the finer particles down the slope leaving behind silt and sand. This process is believed to be widespread and appears to be enhanced by shifting cultivation practices on sloping terrain.

3. Clay destruction

A significant soil process is the destruction of clay. The leaching of base cations leads to the build up of hydrogen ions on clay minerals and organic matter. This state is unstable and leads to the eventual disintegration of the crystaline structure of the clay, releasing aluminium and silica in the process.

As a result, the soil exhibits less clay and a lower pH in the topsoil and subsoil immediately below the topsoil than in the main part of the subsoil. Similar clay distribution can be found in soils where the clay in the topsoil has been redistributed rather than being destroyed (see below).



This profile from South Africa illustrates the movement of clay particles from the topsoil to the subsoil. The photograph clearly shows an upper grey layer (0 – 25 cm) which is a ploughed horizon where the soil has been mixed by cultivation. Directly underneath is a light-toned layer (between 25 – 70 cm) resulting from the destruction and removal of brown and red coloured clay particles. The darker coloured subsoil (> 70 cm) reflects the accumulation of clay particles from above. This process is known as illuviation. (ISRIC)

Clay

In English, the word 'clay' can have three distinct meanings:

i A soil particle, less than 2 µm in diameter;

ii A textural class containing more than 40% clay particles and less than 45% sand and less than 40% silt;

iii A naturally occurring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents that will harden when dried or fired. Although clay usually contains phyllosilicates, it may contain other materials that impart plasticity and harden when dried or fired.

This profile illustrates the initial stages of soil formation. The development of soil structures and changes in colour are the only apparent pedogenic processes. This example from the Usambara Mountains in Lushoto, Tanzania shows a thin accumulation of organic matter on the surface and the leaching of iron (lighter patches). Such soils are widespread in Africa, especially in recently deposited parent material or in regions that have been tectonically uplifted. (JD)

Podzolisation

Given a specific combination of humid climate, quartz-rich, coarse-grained parent material and particular vegetation characteristics, then a characteristic soil forming process known as podzolisation can occur. Soluble organic substances released during the decomposition of plant litter can bind with iron and aluminium oxides in the soil and, given suitable chemical conditions, be leached from the topsoil. Percolating water redeposits these elements, together with organic matter, deeper into the soil, leaving behind a zone of bleached, immobile sand grains. The redeposited mix of organic matter, iron and aluminium can form a massive (hardened or cemented) horizon which acts as a barrier to the passage of organic matter and roots. Over time, organic matter accumulates on this obstruction where a dark, humus-rich sub-surface horizon develops. Precipitating iron can give a uniform orange-red colouration to this horizon.

The end product of this procees is a soil type known as a Podzol which is characterised by the presence of a subsurface deposition horizon (known as a spodic horizon). The exact characteristics of the Podzol depend on the relationship between the parent material, moisture conditions and vegetation type (see page 59).

While Podzols are found on all continents (and predominantly in the temperate and boreal regions of the Northern Hemisphere), they are generally rare in Africa. Tropical Podzols occur in two distinct ecological situations. The first one coincides with thick deposits of quartz sands in the lowlands; the second one is characterised by a cool isomesic temperature regime that prevails at high elevations in areas that have often been influenced by volcanic ash. The cool tropical Podzols are typical of mountain slopes that are hit by clouds producing orogenic rains (e.g. DR Congo, Zimbabwe and South Africa).

Soils processes under a wet tropical climate

A significant part of central Africa possesses a humid tropical climate where constant high temperatures (average annual temperature is around 26°C), copious rainfall (over 2 000 mm annually) falling daily and high humidity occur throughout the year. In addition, much of tropical Africa is characterised by old, geologically stable, shield areas that have been deeply weathered. Under such conditions, chemical weathering, leaching and translocation combine to produce a number of distinctive soils where the geology of the bedrock determines the underlying chemical properties of the soil.

In summary, the soils of the wet tropics are old, characteristically red or yellow in colour, and strongly leached. They are deep, finely textured, contain no more than traces of weatherable minerals, have low-activity clays (see page 27), less than 5 percent recognizable rock structure and gradual soil boundaries. The most typical divisions are:

• soils with a ferralic horizon

In deeply weathered sediments, a combination of high soil temperature and intense percolation, dissolve and remove all weatherable primary minerals from the soil body. Less soluble compounds, such as iron and aluminium oxides, the clay mineral kaolinite and coarse quartz grains, remain behind. This process eventually leads to the formation of a ferralic horizon. High concentrations of the iron oxide hematite give a distinctive red colouration to the soil while in more temperate conditions, goethite tends to dominate giving soils a more yellow colour. To be effective, the process requires low soil pH, geologically stable land surfaces and basic parent material containing abundant levels of iron and aluminium in the form of easily weatherable minerals but little silica (the process is much slower in acidic parent material).

Clay content and texture are relatively constant with depth due to the mixing of the soil by biological activity (primarily termites). Soils matching these characteristics are referred to as Ferralsols (see page 53).

While such soils can support luxuriant natural vegetation (e.g. rain forest), their cultivation for crops is problematic. Plant nutrients (e.g. Ca, Mg, K, P) are generally lacking. The low pH, coupled with a high levels of iron and aluminium oxides causes phosphorus fertiliser to bind to the soil and become unavailable to plants. Dense natural vegetation can flourish on these soils due to a self-sustaining nutrient cycle. If this cycle is broken (e.g. as a result of deforestation or through the export of agricultural products to urban areas), the soil quickly loses its fertility and is prone to degradation processes such as erosion. Traditional agricultural practices of temporary forest clearance and shifting cultivation recognise this cycle.

Typical Ferralsol from near Jimma, Ethiopia, displaying a characteristic deep, homogeneous, red profile lacking any distinct horizon features. (JD)

• soils with a nitic horizon

In the highlands (>1 000 m) of Ethiopia, Kenya, Congo and Cameroon, a derivation of the ferralisation process can lead to the development of soils containing a characteristic 'nutty', polyhedric, blocky structure with shiny ped faces. Typically, the soil body is deep, developed in fine textured weathering products of intermediate to basic parent material and contains high levels of kaolinite and iron (hence the red colour). In some respects, these soils could be seen as young examples of the ferralisation process. Following the intensive hydrolysis of minerals and leaching of silica and base cations, alternating micro-swelling and shrinking processes produce well-defined structural elements with strong, shiny pressure faces.

The soil body can become highly mixed through biological pedoturbation - the action of termites, ants, worms and other soil fauna – which results in a characteristic crumbly or subangular blocky soil structure and diffuse soil horizon boundaries. The spatial distribution of this process is highly dependent on subtle variations in the landscape and parent material. Soils matching these characteristics are known as Nitisols (see page 55).

A clear example of the typical nut–shaped soil structure from a nitic horizon in Ethiopia. The dark red colour is indicative of a significant amount of clay and active iron. Such soils are associated with the weathering of basic rocks such as basalts. (EM)

• soils with a plinthic (or petroplinthic) horizon

Where the land is level or gently sloping and subjected to fluctuating groundwater levels in iron-rich parent material, a substance known as plinthite can develop (from the Greek *plinthos*, meaning brick). Plinthite, also known in the past as laterite (see box), is a subsurface accumulation of iron(hydr)oxides, kaolinitic clay and quartz. Plinthite is generally formed by the segregation of iron in soil material that has been saturated with water during the year. The iron has probably been transported by soil water from higher ground as ferrous iron under anaerobic conditions. Alternatively, iron concentrations may increase due to the removal of silica and base cations through the leaching of dissolved weathering products. The resulting ferrous iron is precipitated as soft, clayey, red or dark-red ferric iron concretions. Soils matching these characteristics are referred to as Plinthosols (see page 56).

Plinthite cap on the soil surface in Ghana. Plinthosols are formed in low-lying locations where iron-rich water from adjacent uplands can accumulate, precipitate and harden. (EM)

A Petric Plinthosol in lowland position of Sukumaland, near Mwanza, Tanzania. The indurated iron stone cap is clearly evident. This is the place where the Catena concept was developed by G. Milne in 1934 (see page 15). (JD)

When enough iron has been precipitated and the soil starts to dry out, the soft clay begins to harden irreversibly. This is often initiated by removal of the vegetation as this triggers erosion of the surface soil and exposure of plinthite to the open air. Hardened plinthite occurs in concretionary (skeletic) form or as a continuous layer (petroplinthite), also referred to as ironstone. Soils with petroplinthite are especially abundant in the transition zone from rain forest to savannah, especially in areas that were once much wetter.

In other cases the plinthite concretions may not be sufficiently concentrated to form a continuous layer but harden irreversibly as pisolites in a dense layer of nodules. Such layers can sometimes be found close to the surface due to the removal of the soil between the pisolites by termites for building their nests.

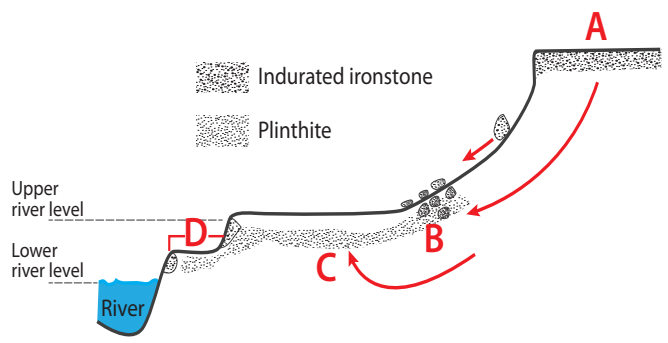


Figure illustrating the four distinct landscape positions where plinthite and ironstone occur. (LJ) [after 24]

A: indurated ironstone (massive iron pan or gravel) capping an old erosion surface. Ironstone caps form a shield against erosion. The result is an inversion of the original relief where parts that initially were the lowest of the landscape become the highest.

B: plinthite and ironstone (gravel and boulders) in a colluvial footslope (subject to iron–rich water seepage)

C: plinthite in soils of a low level plain (river terrace) with periods of high groundwater

D: along the banks of rivers where plinthite becomes exposed and hardens to ironstone

Laterite

The term laterite was developed by British scientists at the beginning of the 19th century to describe the red and creamy mottled clay which was dug out of the ground in India and shaped into bricks. The term was used to describe highly weathered, red subsoils, predominantly under tropical forests, that were rich in iron and/or aluminium oxides, quartz and kaolinte and are nearly devoid of base cations and primary silicates.

Today, the use of the term laterite is discouraged, with preference being given to stricter definitions such as plinthite and petroplinthite.

Acidic or Basic Rocks

The terms acidic and basic are often used to describe rocks or the parent material of soils and does not refer to the pH of the material. In geology, it refers to the amount of silica in proportion to Mg, Fe and Ca.

Magmatic rocks that contain contain significant amounts of silica (at least 66% SiO_2 by mass, which normally occurs as quartz minerals) are referred to as acid. Examples include granite and rhyolite.

Conversely, the term basic is applied to rocks containing minerals such as feldspar and biotite but relatively low amounts of silica. Examples include basalt, dolerite and gabbro. The term mafic is increasingly used in place of basic.

Exposed plinthite may ultimately lead to an inversion of the original relief as it functions as a protective cap against erosion of the underlying soil. Over time, the uncapped soil is removed, leaving the capped soil as the highest parts of the landscape.

• soils with an argic horizon

The climatic conditions in the humid tropics can give rise to a subsurface horizon with a higher clay content than the overlying soil. Such situations can arise as the result of illuviation (see page 25), the destruction of clay in the overlying horizon, the selective erosion of clay, sedimentation or biological activities. Most of the siliceous minerals produced by the original weathering process are subsequently dissolved and leached out of the soil. Depending on the composition of the parent material, clays in the argic horizon can be weathered to liberate large volumes of soluble aluminium. Three common soil types occur in the humid tropics displaying clay-rich subsurface horizons.

- strongly acidic soils that develop on the weathering products of metamorphic rocks containing high-activity clay minerals such as vermiculite or smectite are referred to as Alisols (see page 52). These soils are most common in old land surfaces with a hilly or undulating topography under humid tropical or monsoon climates. The weathering of the clay minerals in the argic horizon gives rise to high levels of aluminium in the subsoil which hinders biological activity.
- strongly acidic soils that develop on the weathering products of acidic parent material (which give rise to an accumulation of low activity clays) in old land surfaces with a hilly or undulating topography under humid tropical climates are referred to as Acrisols (see page 52). Acrisols generally exhibit a strong yellow to red coloured argic horizon overlain by a much lighter (whitish to yellow) bleached horizon.
- where the climate has a pronounced dry season and the soils on old erosional or depositional surfaces are enriched in base cations through different processes (e.g. aeolian dust, biological activity, etc.), the resulting soils are known as Lixisols.

This profile from Ghana contains high levels of aluminium. Such soils occur in the tropics and subtropics, and in the warm temperate regions of the world in relatively young landscapes. The high level of aluminium in these soils is caused by rapid weathering of high-activity clays such as vermiculite and smectite. (EM)

Low and high activity clays

There are two major categories of layered silicate clays within the soil, distinguished on their capacity to retain and supply nutrients such as calcium, magnesium, potassium and ammonium. High activity clays have a cation exchange capacity (CEC) => 24 cmol(+)/kg clay due to their large surface area. Generally, soils with large amounts of high activity clays are not highly weathered and have a high CEC under all pH levels.

In contrast, low activity clays are more highly weathered. Due to their reduced surface area, low activity clays have a lower capacity to retain and supply nutrients (CEC< 24cmol(+)/kg clay) and, depending upon the pH of the soil, supply phosphate, sulphate and nitrate, rather than base cations.

Clay Minerals

Clays form through the weathering of rock fragments, especially those containing a large proportion of silicate minerals. The term 'clay' refers to a naturally occurring particles that are < 2 µm in size and composed primarily of minerals that impart plasticity at appropriate water contents and which harden when dried or fired.

Although the term 'clay mineral' refers to phyllosilicate minerals composed predominantly of silica and aluminium. Aluminium, iron, and manganese oxides (see Glossary) are common components of the clay fraction and play an important role in the chemistry of soils because of their high specific surface areas and reactivity.

Clays are colloidal substances. Their enormous surface-to-surface contact characteristics act as a glue to "stick things together."

Silicate clays have a well-defined, repeating, arrangement of atoms made up of planes of oxygen atoms held together by silicon and aluminium atoms. Thus, the Si^{4+} cation is surrounded by 4 oxygen atoms to form a tetrahedron (4 sided shape). The 6 oxygen atoms needed to fit snugly around the larger Al^{3+} cation form an octahedron (8 sided). The planes of oxygen held together by Si^{4+} cations are referred to as a (silica) tetrahedral sheet.

One plane of oxygen plus a second plane of oxygen atoms (or hydroxyls) held by an Al^{3+} cation are referred to as an (alumina) octahedral sheet. One silica sheet per one alumina sheet is referred to as a 1:1 layer (e.g. kaolinite). With 2 silica sheets per 1 alumina sheet, the lattice is known as a 2:1 type (e.g. illite). In the space between the 2:1 layers, other cations may be present. These cations can be linked with hydroxyls, such as in chlorites. They may also be present as individual cations, which may or may not be hydrated, as in micas, vermiculites and smectites.

A process known as isomorphous substitution occurs when one atom in the crystal lattice is replaced by another of similar size without disrupting the crystal structure of the mineral. In the tetrahedral sheet Al^{3+} usually substitutes Si^{4+}. In the octahedral sheet Fe^{2+}, Fe^{3+}, Mg^{2+}, Ni^{2+}, Zn^{2+} or Cu^{2+} can substitute Al^{3+}. As a result of this process, a net negative charge develops on the clay surface. Clays attract and hold positively charged ions (cations) at their surface. The quantity of cations that can be held, or exchanged, by a given amount of soil is referred to as the cation exchange capacity of that soil. The exchangeable cations are not easily removed by leaching action until they are replaced (exchanged) by other cations. Plants often excrete hydrogen ions (H^+) to the soil solution, which can replace nutrient cations from their exchange sites, thus allowing the nutrients to move to the plant root and be absorbed.

Mineral weathering sequences indicate the likelihood of finding certain clays in various environments. The most resistant products of mineral weathering are those that are the least soluble, such as the iron oxides. During formation, the nature of clay depends on the relative amounts of silica, alumina, iron hydroxides, cations, the pH of the soil solution and the presence of other soluble materials.

Thus, in areas with minimal leaching and minimal weathering, montmorillonite (smectites clays) and vermiculties will form. Some clay minerals are very similar to certain primary minerals (e.g. micas) and may be formed by transformation (slight structural modification).

If the area has more rainfall, relatively more silica will leach away, the pH will be more acidic and kaolinitic clays will form. Under conditions of extensive leaching by rainfall and long-term weathering of minerals in humid, warm climates (e.g. Central Africa), most of the basic cations, silica and some alumina are leached out of the upper soil profile. The remnant materials, which have lower solubilities, are high in alumina and particularly in iron oxides (sesquioxides). Sesquioxides (metal oxides) refer to the clays, which are mixtures of aluminum hydroxide, $Al(OH)_3$, iron oxide, Fe_2O_3, or iron hydroxide, $Fe(OH)_3$. However, TiO_2 and MnO_2 are also often included. These clays can grade from amorphous to crystalline. Iron oxide and iron hydrate commonly colour the soils various shades of red to yellow, respectively.

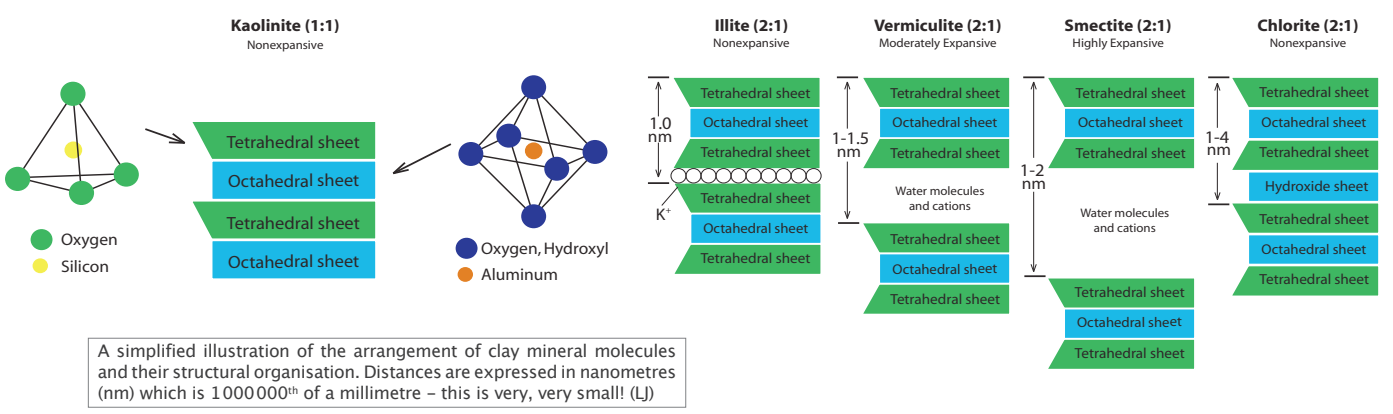
Soil processes on volcanic materials

Soils that develop from ejected volcanic materials such as ash, tuff, pumice, cinders and lava often contain high proportions of volcanic glass. Under a humid tropical climate, intense hydrolysis of the easily weatherable primary minerals and volcanic glass leads to the formation of secondary aluminium- and silica-rich minerals such as allophane and imogolite (under high rainfall) or halloysite (where rainfall is lower). The weathering process liberates aluminium (Al^{3+}) ions, which become tied up with humus in stable Al-organic compounds as the aluminium protects the organic material against bio-degradation. Any free ferric iron (Fe^{3+}) usually precipitates as ferrihydrite (a form of iron oxide).

Such poorly crystalline materials have a large surface area and consequently can absorb large amounts of water. However, due to their high anion exchange capacity (see box left), such materials have a low ability to retain and supply nutrients thus requiring very large additions of phosphorus.

An Andosol that has been buried under a thick basalt flow in the South Ethiopian Rift Valley near Arba Minch. The reddish layer in the centre of the photograph is the baking contact between the old soil and the molten lava. Above this layer, the basalt has solidified and forms the upper part of the cliff. Indeed, the presence of trees on this part denotes that soil-forming processes are active. The pale layer below the baking contact is an old ash deposit from a much older eruption, which was the parent material of the buried Andosol. (JD)

The classic volcanic cone of Ol Doinyo Lengai in Tanzania. In Africa, soils on volcanic deposits are prominent along the Rift Valley (Kenya, Rwanda and Ethiopia), Cameroon, DR Congo and Madagascar. These soils have a high potential for agricultural production but many are not used to their full capacity. By and large, volcanic soils are very fertile, especially on intermediate or basic volcanic ash that is not exposed to excessive leaching. The strong affinity of iron and aluminium (and their oxides) to remove compounds such as phosphorous from the soil solution in a form that makes them unavailable to plants (a process known as sorption) can be a significant problem that requires the application of lime, silica, organic material or phosphate fertiliser. Volcanic soils are easy to till, have good rootability and water storage properties. Landslides and volcanic eruptions are hazards in these areas. (EM)



A simplified illustration of the arrangement of clay mineral molecules and their structural organisation. Distances are expressed in nanometres (nm) which is 1000000th of a millimetre – this is very, very small! (LJ)

Soils conditioned by a dry tropical/sub-tropical climate

In the parts of Africa where precipitation is lower than evapotranspiration and high temperatures cause groundwater to rise to the surface, several soil types exhibit substantial secondary accumulations of calcium carbonate (lime), dihydrate calcium sulphate (gypsum) or silicon dioxide (silica).

• soils with accumulations of calcium carbonate

One of the most widespread soil-forming processes in dry climates involves the movement of calcium carbonate ($CaCO_3$) from surface horizons to an accumulation layer at some depth (a process referred to as secondary accumulation). On wetting (such as after rainfall), lime dissolves allowing Ca^{2+} and HCO^{3-} ions to move downwards with the percolating soil water. When the water eventually evaporates, calcium carbonate precipitates where the percolation stopped (calcium carbonate can also percolate if the concentration in solution becomes high enough). Calcite precipitation is not evenly distributed over the soil matrix. Root channels and wormholes act as channels along which the solution can flow allowing the calcite to precipitate on the channel walls. When narrow root channels become filled with calcite, the resulting cast-like shape of the root is known as pseudomycelium. Other characteristic forms of calcium carbonate accumulation are soft or hard lime nodules (calcrete), platy or continuous layers of calcrete and calcite 'beards' known as pendants below pebbles. In eroding land, lime concretions may occur right at the surface of the soil.

A profile of a calcium-rich soil from Tunisia. The white material around the hammer is a dense lime-rich horizon (calcium carbonate). Much of the free lime in the topsoil has been leached out giving it a darker appearance. (TG)

• soils with accumulations of gypsum

As **gypsum** ($CaSO_4.2H_2O$) is dissolved from gypsiferous parent materials, it is moved through the soil by water and precipitated in an accumulation layer when the water is removed. Where soil moisture moves predominantly upward (i.e. where a net evaporation surplus exists for an extended period each year), a gypsum-rich horizon occurs within the soil body. Gypsum is also leached from the surface soil in wet winter seasons and re-accumulates deeper in the soil as a loose, powdery substance. Over time, gypsum crystals may cluster together as compact layers or surface crusts that can become tens of centimetres thick. Gypsum can precipitate in former root channels (gypsum pseudomycelium), in voids, as coarse crystalline gypsum sand or in strongly cemented horizons (petrogypsic). In places, it forms massive crystalline structures known as desert roses.

A soil exhibiting secondary accumulation of gypsum from Somalia. The upper part of the profile is almost completely lacking in gypsum, has very low organic matter and a weak, sub-angular blocky structure. Below 40 cm, the gypsum has precipitated along vertical cracks in the soil. (RV)

An example of desert rose – the common name given to rosette formations of gypsum with sand inclusions. The rosette shape tends to occur through the formation of crystals during the evaporation of shallow salt lakes in arid sandy conditions. (SH)

• soils with accumulations of silica

In many arid regions (although not exclusively), soils known as **Durisols** contain very hard layers of **silica-enriched** materials in the subsoil. These materials range from silica-cemented sand and gravel to a nebulous matrix enriched with small silica particles. The conditions under which such features develop are uncertain as nearly all occurrences are "fossil" as such soils do not seem to be forming extensively at present. Theories include the precipitation from silica-rich groundwater in arid/semi-arid climates or by intense weathering in a warm, humid climate.

Soils with lower levels of gypsum and calcium carbonate in the upper 30 cm soil layer can support grazing and some drought-tolerant crops when carefully irrigated. The hard duripan material is commonly used for road construction.

A duric horizon from South Africa containing rounded or sub-angular durinodes. These indurated accumulations of silicon dioxide are hard and brittle. (EM)

• soils with accumulations of salt

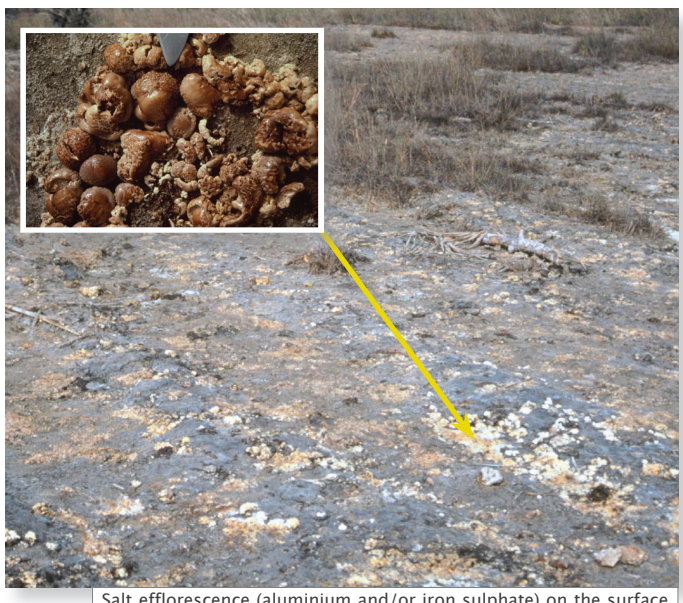
A soil is regarded as saline if the salt concentration is around 2 500 parts per million. Soils affected by soluble salts or by their ions occupy a significant part of Africa. Salt-affected soils are especially prevalent in northern Africa, South Africa, and the less humid parts of central Africa such as northern Cameroon, the Central African Republic, Gabon, Ivory Coast and Liberia.

Soluble salts can be released through the weathering of rocks or because the parent material contains high levels of salt (e.g. old marine sediments or evaporation deposits). However, the majority of salt-affected soils develop where saline groundwater rises to the surface and dissolved salts accumulate in the soil through the evaporation of the groundwater. Salts can also be carried into depressions in the landscape by saline surface water flowing from higher ground. In dry lands, salinity can occur even when the water table is two or three metres from the surface of the soil.

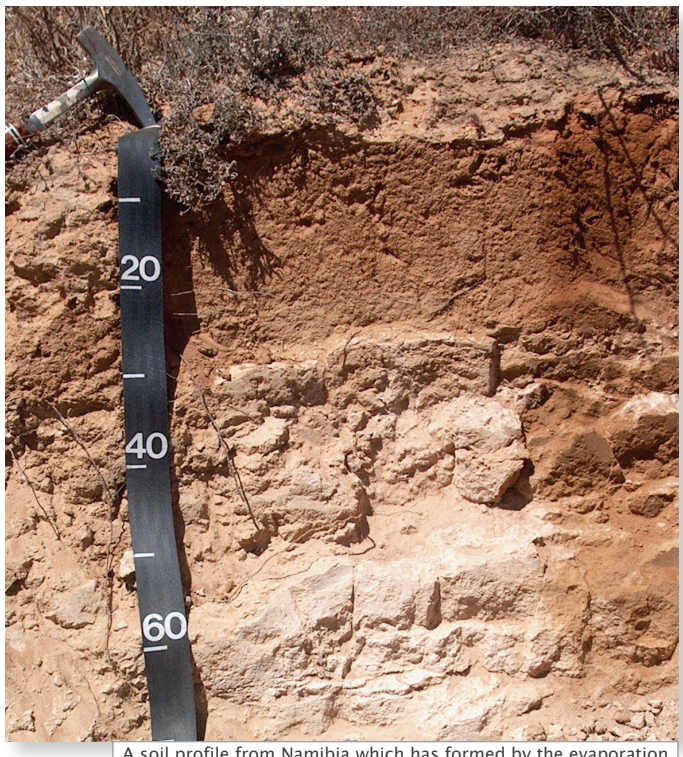
The main ions responsible for salinisation are Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-} and Cl^-. Depending on the chemical composition, the reaction between the soil and salts may differ. Salts containing sodium (Na) cause organic compounds to become mobile and are eventually leached out of the topsoil, resulting in the development of a bleached horizon. The pH of such soil types is typically above 9.

Salts in soil can also occur due to irrigation, since almost all water (even natural rainfall) contains some dissolved salts. When crops use the water, the salts are left behind in the soil and over time accumulate and must be artificially leached out of the root zone by applying additional water. Salination can be increased due to poor drainage or through the use of saline water for irrigating.

Saline soils also occur in ephemeral or closed basin lakebeds, also referred to as salt pans or salt flats. In North Africa, they are referred to as sebkhas, playas, or chotts (e.g. the Chott Djerid in Tunisia).



Salt efflorescence (aluminium and/or iron sulphate) on the surface of a wet, lowland soil near Djiguinoum in Lower Casamance, Senegal. In the past, this area was used for rice cultivation but is now abandoned. (JPM/IRD)



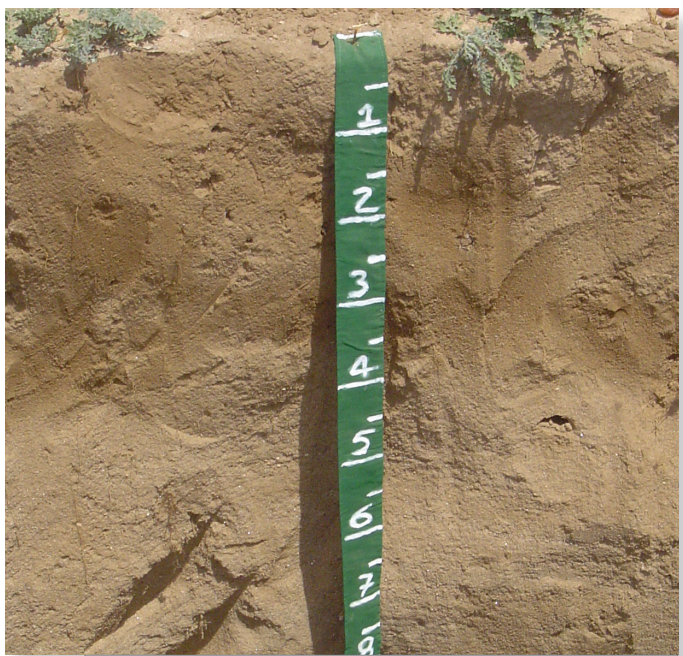
A soil profile from Namibia which has formed by the evaporation of groundwater containing high levels of sodium bicarbonate. The topsoil does not exhibit any well-defined horizons and a salt crust has developed on the surface. (EM)

A close-up of the boundary between the topsoil and subsoil of a sodium-rich subsoil from South Africa. The characteristic columnar structure with rounded tops and the organic coatings on the structural elements are clearly visible. (ISRIC)

• soils in sandy materials

Soils that have developed in coarse material (> 0.063 mm) have poor cohesion and structure coupled with low water retention capacity and organic matter levels. These factors affect soil formation. Large parts of Africa, especially in arid regions are characterised by blown sand (predominantly quartz but other materials, such as gypsum, can dominate). Along desert margins, climatic fluctuations mean that dunes have been fixed by vegetation. In some cases, their aeolian nature is still obvious but in other situations, soil forming processes can give rise to quite different soils (see page 73).

Additionally, soils can develop in the coarse sediments that occur as a result of intense and long-term weathering under tropical climate (see page 28).



A section through a sand dune from Somalia. The soil lacks any structure. There is very little evidence of soil-forming processes. Dune sands display criss-cross bedding that reflect past depositional surfaces (see page 71) . (RV)

What is a salt?

Most people think of salt as the product that they add to food or the substance that makes seawater salty. In most cases, this is the salt sodium chloride (NaCl).

However, salt is the substance formed by the reaction of an acid with a base where the hydrogen of the acid is replaced by a metal ion (some other reactions can also create salts). Hence, sodium hydroxide and hydrochloric acid react to create a salt, sodium chloride, and water. Examples of other salts include copper sulphate, lead nitrate, magnesium chloride and magnesium sulphate.

If solutions of salts are allowed to evaporate, then the salt is precipitated as crystals.

Salts can be clear and transparent or highly coloured and opaque. Different salts can stimulate all five basic tastes. Some salts are odourless while salts of weak acids or weak bases may smell. The solubility of salts depends on their chemistry and the nature of the solvent.

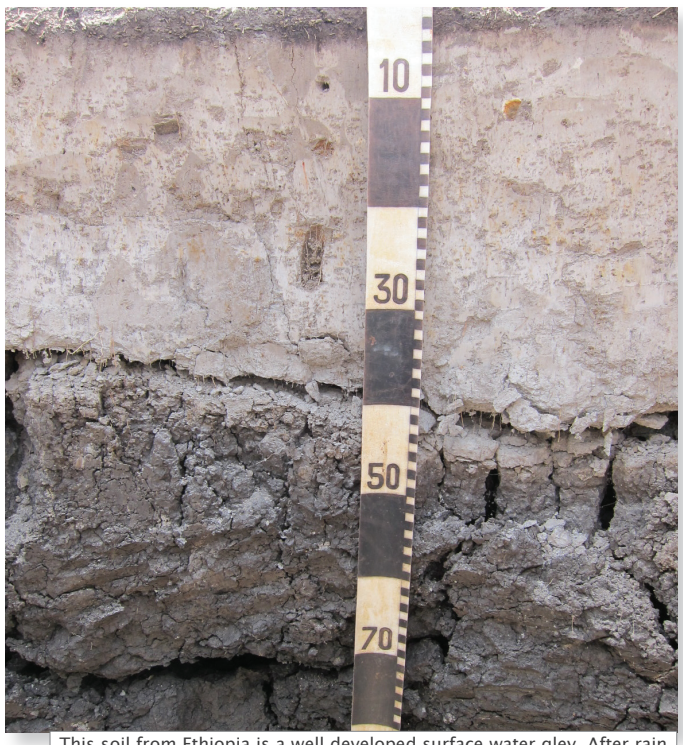
Saline and alkaline soils can seriously affect the growth of plants causing water stress, ion toxicity or the inability to absorb nutrients.

High stocking densities of grazing animals on sandy soils can lead to overgrazing and a reduction in the vegetation cover. Such situations can leave sandy soils vulnerable to wind erosion and, in more arid conditions, more vulnerable to the onset of desertification. The situation can be reversed through effective rangeland restoration practices.

Soils conditioned by water

When it rains, water percolates through the soil and, in many cases, this water drains away. However, in some places the texture of the soil or the presence of an impermeable barrier prevents water from escaping causing pores and cavities to become full of water (also referred to as groundwater). In some soils, groundwater can be found at relatively shallow depths (< 2 m). This situation generally exists due to a slowly permeable substrate, depressions in the landscape which collect water or in marshy areas near to the coast.

The presence of a shallow groundwater table strongly decreases the movement of gases in the soil because oxygen and carbon dioxide diffusion in waterlogged pores is very slow compared to air-filled pores. If organic matter is present in the waterlogged soil, the metabolic activity of the microorganisms will create an oxygen deficit and a state known as 'reduction' develops. In these conditions, ferric iron is converted to the more soluble, and therefore mobile, ferrous iron. While ferric oxides are responsible for giving subsoils their characteristic yellowish- or reddish-brown colours, their disintegration into ferrous oxides will give the soil a distinctive greyish or bluish colour. However, in some of the larger pores where some oxygen may remain, mottles of rust-coloured material indicate the redeposition of ferric oxides. In soil science, two basic types of waterlogged soils are recognised, surface water and groundwater gley.



This soil from Ethiopia is a well developed surface water gley. After rain has fallen, water is held periodically (a state known as stagnant) above an impervious clay-rich horizon (below 40 cm in the photograph). In periods with a precipitation surplus stagnant water can appears on the surface but this will disappear when the soil dries out. This soil is characterised by the presence of grey ped surfaces and root channels while the interior of the peds are enriched by ferric iron. (EVR)

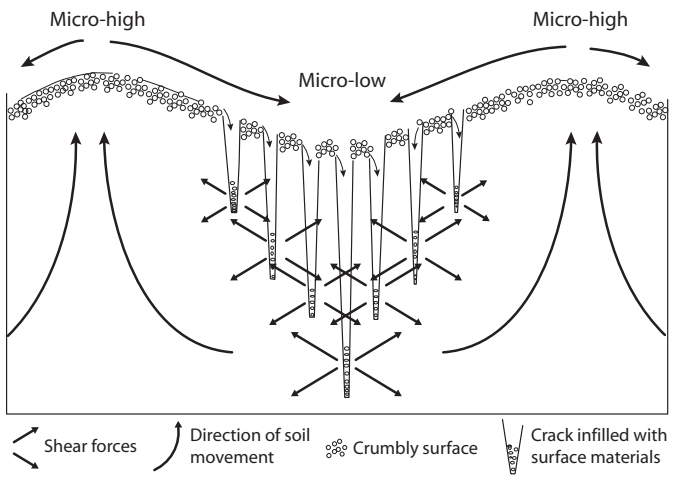
Soils that develop in river (fluvial), lake (lacustrine) and marine (associated with the sea) sediments have a number of distinctive characteristics. The soils of these environments display evidence of stratification (layering) which reflects deposition of the parent material in water. Also these soils are subject to periodic flooding which brings in additional sediments, organic matter and nutrients. Such soils tend to occur on alluvial plains, river fans, valleys and tidal marshes (including mangroves). This picture shows the bank of the Manafwa River in Uganda. The horizontal strata of the fertile loamy sediments are very evident. Changes in colour reflect specific flood events or past soil development. (JD)

Soils conditioned by the presence of swelling clays

In areas with distinct dry and wet seasons and where the parent material contains large quantities of swelling clay minerals known as smectites, soils are characterised by the presence of deep cracks in dry periods which close in the wet season. The closure of the cracks is driven by the expansion of the smectite minerals as they absorb water. Such soils are also defined by the presence of characteristic structural aggregates (spheroids).

Shrinkage of the clay on drying leads to the formation of cracks. In addition, the surface breaks up into granules or crumbs which can fall into the cracks. When the soil is re-wetted, part of the space that the soil requires for its increased volume is now occupied by the granular material in the cracks which results in the build up of shear stress within the soil material. Continued pressures through the uptake of more water eventually cause the soil masses to shear and slide against each other.

The shear planes are known as slickensides and display polished surfaces that are grooved in the direction of shear. Intersecting shear planes produce wedge-shaped angular blocky peds that tend to increase with depth (probably reflecting the moisture gradient). This internal movement of soil, coupled with the deposition of surface crumbs in deep cracks, means that the subsurface soil is pushed towards the surface and mixed. This process is known as churning or pedoturbation. This constant mixing of the soil material results in an extremely deep A horizon. Such soils tend to develop either at the foot of slopes or on plains as a result of the weathering of basalt or redeposition of smectite-rich lacustrine sediments.



A simplified view of the processes operating in soils with swelling clays. During dry periods, the clays shrink causing cracks to open in the soil surface. Over time, crumbs from the surface fall into the cracks. On wetting, clays in the soil body expand causing the cracks close. However, the newly buried surface material causes internal stresses which leads to a mixing of the soil body. This churning often creates a distinctive micro-relief known as gilgai, where the land surface becomes irregular with alternating mounds (puffs) and depressions (hollows). (MF)

Pasture on a soil with swelling clays from the Gonder Region, Ethiopia. The characteristic gilgai microrelief is evident through the dark and light colours of the grass. The darker regions indicate slight depressions. (JD)

Soils with such characteristics are known as Vertisols and are found extensively in Sudan, Ethiopia, Kenya, Cameroon, Chad and parts of South Africa. Vertisols are difficult to cultivate as they can be worked only under a very narrow range of moisture conditions. They are very hard when dry and very sticky when wet. When expanding and contracting, Vertisols can even snap the roots of large plants such as trees.

Soils and the accumulation of soil organic matter

The accumulation and decay of organic matter are critical soil-forming processes. Soil organic matter is derived from the remains and exudes of living organisms (predominantly plants). Organic matter is utilised by a variety of soil microorganisms such as bacteria, fungi and earthworms, as both a source of energy (to function) and materials for building their bodies. During this process, water, carbon dioxide and various organic compounds such as sugars, starches, proteins, carbohydrates, lignins, waxes, resins and organic acids are converted by a process known as mineralisation into inorganic compounds such as ammonium (NH_4^+), phosphate ($H_2PO_4^-$) and sulphate (SO_4^{2-}). This process, together with the release of CO_2 from the soil, is vital for the growth of plants. Some of these compounds are immobilised through being incorporated into the bodies of soil organisms and are only available after the death of the organism.

The annual return of plant and animal residues to the soil varies with the climate, the type of vegetation and how the land is used. Tropical rainforests in West Africa return about 15 tonnes of litter per hectare each year compared to around 8 tonnes for temperate grasslands, 2 tonnes for agricultural soils and 0.1 tonnes for alpine forests. Root decay contributes a further 30-50% of the amount produced from leaf fall.

Litter layer on the floor of a tropical rainforest. Rapid decomposition due to high temperatures and humidity levels leads to a dark-coloured surface soil. (OS)

Peat formation

Peat is a dark, unconsolidated, organic-rich material that has developed when the decay of plant material is repressed as a result of a lack of oxygen in waterlogged conditions (anaerobic) such as those found in bogs, fens, moors, mires or swamps. Three main types of peat are recognised: sapric (very decomposed, hardly any recognisable plant fibres), hemic (moderately decomposed) and fibric (slightly decomposed). Peat accumulates slowly. In Africa, peat deposits occupy relatively small areas: the humid highlands of central and eastern Africa (Burundi, Rwanda, southwestern Uganda, the highland area of the DR Congo, the Aberdane Range and Cherangani Hills in western Kenya), the high-altitude temperate zones of South Africa, Madagascar and the coastal plain of West Africa.

Biko Bog; cool, humid conditions lead to peatland formation at an elevation of 3 400 m in the Ruwenzori Mountains, Uganda. (AJ)

Humus

The decomposition of organic matter leads to the synthesis of new materials, collectively known as humus – a stable, dark brown or black, amorphous material which is less susceptible to decomposition. Humus essentially consists of carbon, oxygen, hydrogen and nitrogen, with organic carbon accounting for 40-60% by weight and is found predominantly in organic-enriched mineral horizons at the soil surface.

Several soil functions are governed by the amount and bio-chemical properties of humus. Humus-rich layers contain considerable nutrient stocks, which are mineralized upon decomposition so that they can be used by plants.

The chemical composition of humus varies and reflects the plants providing the litter, the characteristics of the soil (especially mineralogy and texture) and climate.

Organic v Mineral

Soil material is referred to as organic if it contains more than 20% of organic matter.

Mineral soils by contrast contain less than 20% organic matter but can possess organic surface horizons.

Soils where human activity is a soil-forming factor

Some people argue that all cultivated soils have been affected or altered by human activity through the mixing of topsoil and subsoil by ploughing, changing the chemical balance through liming, or depleting nutrients through intensive farming. However, there are numerous examples throughout Africa where the entire soil body was either totally formed, or at least profoundly modified, through human activities such as the addition of organic materials or household wastes, irrigation or cultivation. Examples include:

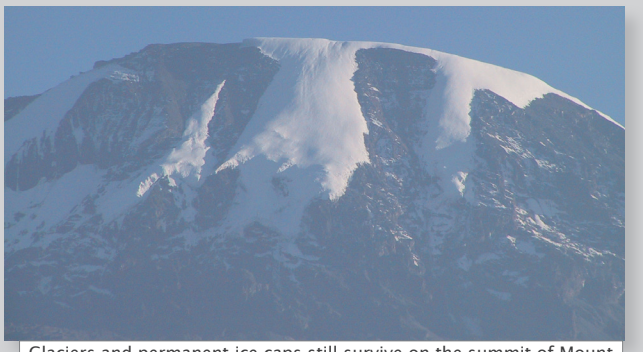
- very deep tillage that is below the depth of normal ploughing – often through the use of terraces;
- intensive fertilisation with organic fertilisers such as manure, kitchen refuse, compost, human excrement;
- continuous application of earth (e.g. sods, beach sand, shells) or sediment through irrigation;
- wet cultivation that involves puddling the surface of the soil or human-induced wetness (e.g. paddy fields for rice cultivation).

Another major human management factor is drainage which affects the frequency and duration of periods when the soil is saturated by water. In waterlogged soils, drainage can allow crops to be grown by allowing oxygen to move within the soil. The drainage of peatlands for cultivation can eventually result in total soil loss from shrinkage and wind erosion if the peat is allowed to dry out completely.

While not spatially extensive, soils that have been heavily modified by human activities are very important at a local scale as they characterise private vegetable gardens that are a crucial support mechanism throughout Africa. In this photograph from the Usambara Mountains, Tanzania, farmers prepare wet valley bottom soils for vegetable cultivation by bringing in soil from the uplands as soil improvers. After many years of such practices, the land surface may be raised considerably. (JD)

Soils in very cold conditions

Most people would not associate Africa with very cold conditions, yet the existence of soils affected by freezing and thawing cycles are, curiously, restricted to equatorial central Africa! Mount Kilimanjaro (latitude 4°00‘ S), Mount Kenya and the Ruwenzori Range, all have peaks above 4 500 m which, coupled with the moist climate, has led to the development of permanent ice fields and glaciers. In this zone, soil water occurs as ice for much of the year. Physical weathering through frost shattering, cryoturbation (mixing of the soil) and the development of patterned ground are present.



Glaciers and permanent ice caps still survive on the summit of Mount Kilimanjaro in Tanzania. At 5 895 m, it is Africa's highest peak. Very cold conditions support cryogenic processes in the soil. However, in such marginal conditions, the permanent ice could soon disappear as a result of global warming and climate change, as has happened on the Virunga Volcanoes of Rwanda and Mount Meru in Tanzania. (WS)

Bokashi – a renewable source of fertiliser in Malawi

In Malawi, agriculture is a key activity, with farmers being challenged to produce more cash crops, such as tobacco, tea, coffee, against a background of increasing resource limitations such as a lack of water, fertilisers and energy. Smallholder farmers, growing such staple crops as maize and vegetables, often cannot afford commercial mineral fertilisers.

One means to address this is to use locally-produced, renewable sources of soil improvement. Several Malawian farmers have been applying a specialist type of compost known as ‘bokashi’, made from a mixture of charcoal/ash, maize bran, top soil, dung and water. Also, depending on availability, yeast and sugar can be added. This is mixed and left in the open, ideally taking between 8-14 days to mature depending on the materials used and the weather conditions. Such piles can attract worms, also beneficial to soil structure.

Best made during the rainy season when water is abundant, bokashi is mixed and then dried to form large pellets. Once made, bokashi can be easily stored for later use. Applications of bokashi have been shown to increase crop yields considerably when used alone or to supplement other fertilisers.

Top: A maturing bokashi pile – normally it is allowed to stand for around two weeks. (RBS);
Right: Close up of some bokashi pellets. (RBS)

Biological processes

A section on key soil-forming processes would not be complete without some reference to the role of living organisms. Increasingly, biological activity, especially the activity of insects, is being recognised as an important factor in regulating soil processes and thereby soil profile development – ranging from the physical breakup of bedrock by roots, nutrient cycling and bioturbation, to the bacterial destruction of clay minerals.

In a broad sense, the activity of organisms in the soil is closely linked to climate. Biological activity is virtually absent in hot, dry desert regions. In low temperatures or in very wet conditions bacterial decomposition is reduced and organic matter accumulates. In the warm and wet conditions of the tropics, both bacterial and fungal activity are intense.

In temperate zones burrowing mammals, beetles and earthworms can have a strong influence on soil processes by facilitating the transfer of water and air along burrows and channels. In the tropics, termites and ants play the major role in nutrient recycling and the redistribution of soil material – the movement of particles of subsoil to the surface by termites is one the main factors responsible for the homogenised profiles that are typical of some tropical soils.

As social insects, termites live in colonies that can contain up to several million individuals. In tropical savannahs, termite colonies appear as mounds that can be several metres high and display a complex internal structure. Studies have shown that the orientation of the mounds is related to thermoregulation and the flow of air inside the colony. This is required to sustain the fungal gardens that the termites need to digest their food. The shape of the mound is usually defined by the species of termite in the colony. In the wet semi-deciduous forests of West Africa, termites inhabit dead trees and branches. In these cases, they transport subsoil material into the tree where they paste it on the walls or plug old galleries. Eventually, a mound of soil particles builds up to cover the wood. In time, the wood decays to leave a landscape containing termite mounds which are paradoxically free of termites as they have left the nest before the wood structure collapsed!

This spectacular photograph shows an 8 m section through a termite mound on the border of DR Congo and Zambia. Analytical studies have clearly demonstrated that fungus-growing termites have a great influence on the properties of Ferrasols. Compared to the surrounding soil, termite structures possess a significantly higher pH, higher amounts of 2:1 clay minerals and a much greater capacity to hold nutrient basic cations. (EVR) [26]

Deeply weathered soils in Central Africa

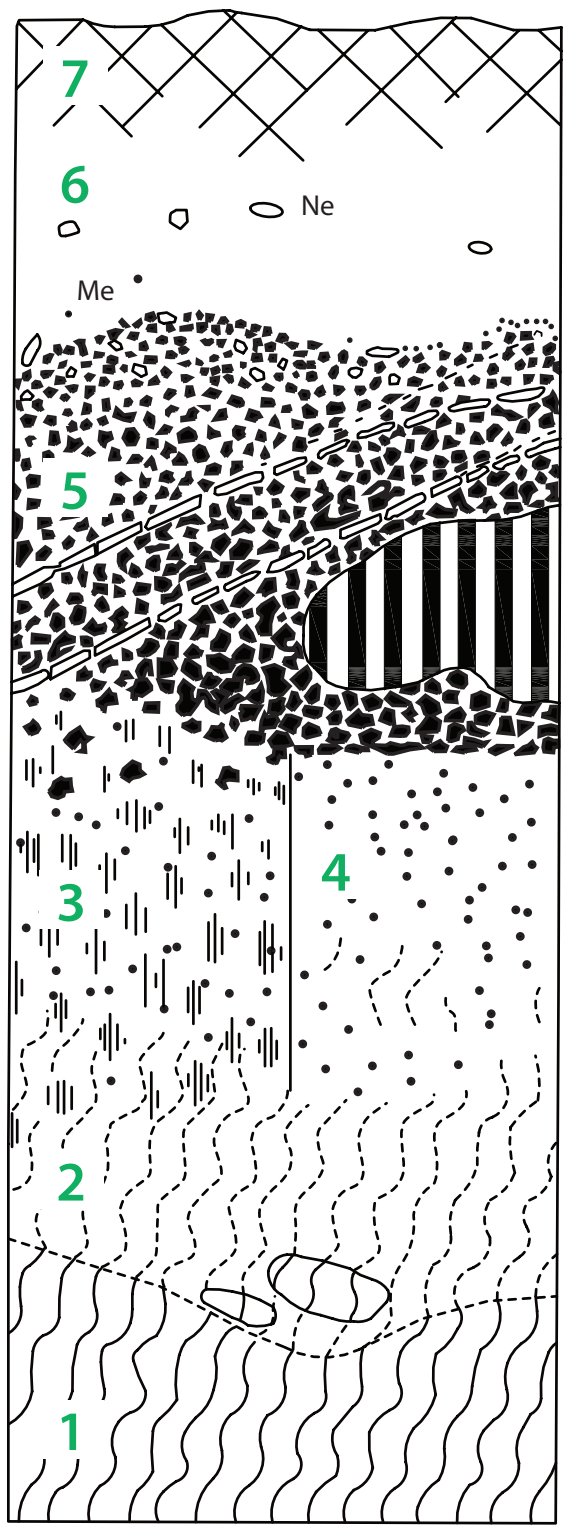
The deep soil profiles that are characteristic of tropical regions are the result of long-term weathering processes, often lasting several million years. Such soils tend to be located on old, tectonically stable plateaus. Chemical weathering under a hot, humid, tropical climate is the dominant process where unstable minerals in the parent material are either dissolved in acidic conditions (carbonates) or decomposed in humid, oxidising environments. Deeply weathered soils also require a moderate relief that allows the leaching of chemically weathered products yet prevents erosion.

Due to their great depth and local variation in the type and intensity of processes, it is difficult to capture all characteristic features of these soils in a single photograph. Therefore, the graphic on the right shows a hypothetical deeply weathered profile.

- The boundary of the weathering front between the parent material {1} and the regolith is characterised by the presence of saprolite {2} or deeply weathered bedrock. It should be noted that on rocks with low silica content (such as limestone, basalt, gabbro, dolerite), this weathered layer is generally absent or very thin.
- If conditions allow, the saprolite can grade into an iron-rich horizon {3} (see page 24) or, if the weathering is very intense, all evidence of the original rock structure (blocks, jointing, veining, etc.) will have been obliterated to form a homogeneous matrix {4}.
- The saprolite layer may be overlain by upper horizons of residual gravels formed from nodules of iron oxide or resistent quartz fragments from the parent material {5}.
- This, in turn, is preserved by residual soils or other sediments deposited over thousands of years {6}. This cover layer may contain stone tools from the Stone Age (which allow the sedimentation to be dated) and is capped by a surface layer containing organic matter {7}.

Truncation of the profile at different depths due to erosion or uplift of the landscape can give rise to a range of different secondary parent materials, hence different soil types. Soils formed in the cover or after slight truncation in the gravel, show ferrallitic characteristics.

Truncation above the saprolite layer results in a parent material suitable for the formation of kaolinitic-rich, highly acidic soils, whereas deeper truncation, reaching the lower saprolite, exposes material where the evidence of soil development is virtually absent.



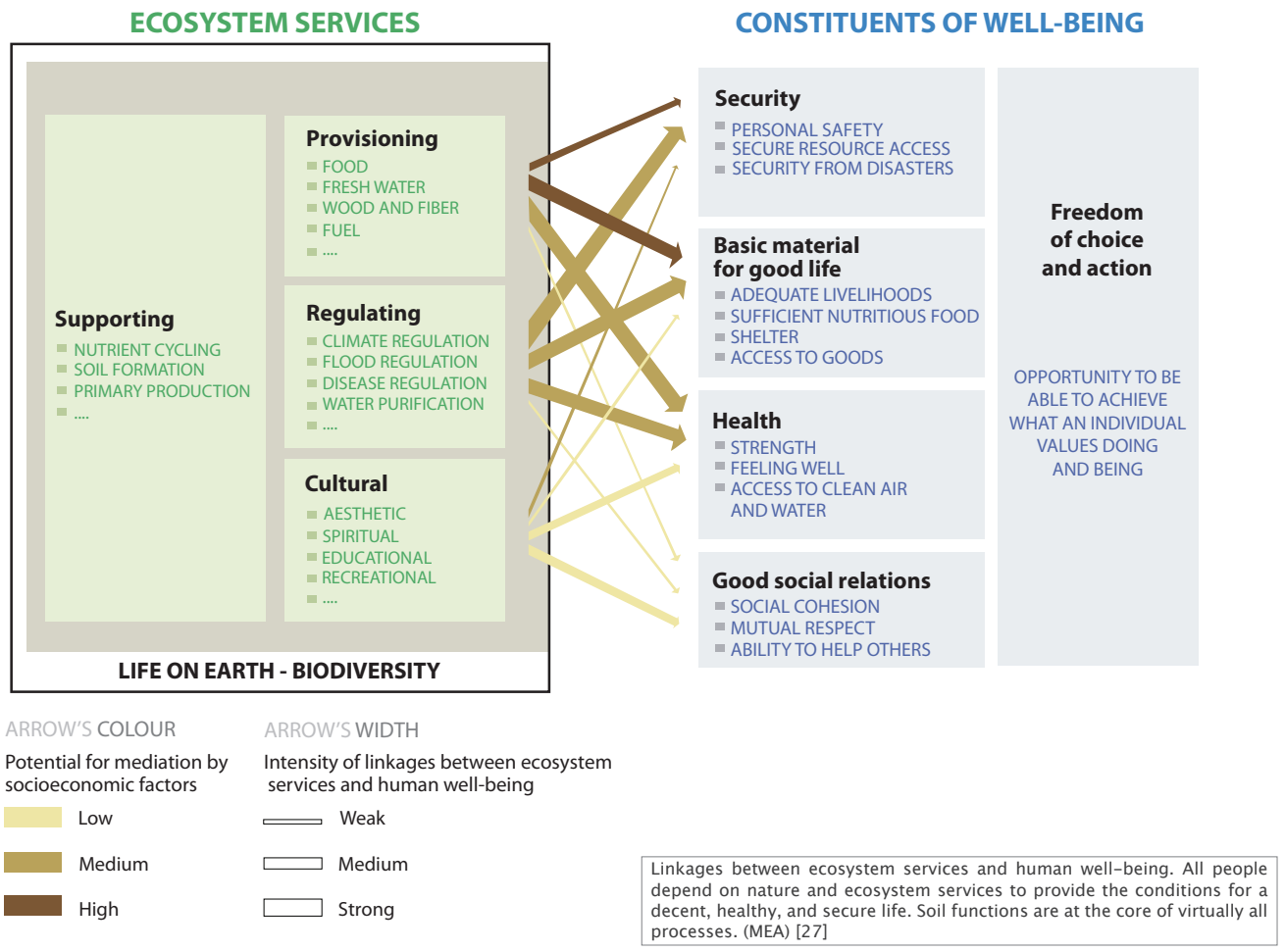
A hypothetical, deeply weathered soil profile from the Congo Basin. (based on GS) [25]

Over many thousands of years, the humid climate of the tropics has lead to the formation of deep and strongly weathered soils. Typical characteristics include the depletion of major elements such as Si, Ca, Mg, K and Na and the relative accumulation of Fe and Al oxides and hydroxides. Cation Exchange Capacity and pH values are generally low, as is the content of soil organic matter. Texture is dominated by sand and clay, with only minor amounts of silt. Soil horizons are often indistinct. (EM)

Key soil functions

While not widely appreciated by most people, soil is actually at the heart of nearly all terrestrial processes on which human and ecological well-being depends. Soil provides, regulates and supports a number of ecosystem services on which issues such as food security, the provision of shelter, access to goods, flood control, combating disease and cultural fulfilment all depend. Soil does all this by performing five essential functions.

- *Growth Medium, Habitat and Biodiversity* - Soil supports the growth of plants and is a habitat for animals and soil microorganisms, usually by providing a diverse physical, chemical, and biological habitat. The provision of food, fibre and fuel from terrestrial crops (including forestry) underpins human societies.
- *Nutrient cycling* - Soil stores, controls the release of, and cycles nutrients and other essential elements. During these biogeochemical processes, analogous to the water cycle, nutrients can be transformed into forms that are easily available to plants, stored in the soil, or even released to air or water.
- *Water cycling* - Soil can regulate the drainage, flow and storage of water and solutes. Soil partitions water for groundwater recharge and for use by plants and soil animals. Soil sealing can destroy this capability, leading to flood events which can kill people and cause untold damage.
- *Filtering and buffering* - Soil acts as a filter that protects the quality of water, air and other resources. Toxic compounds or excess nutrients can be degraded or otherwise made unavailable to plants and animals.
- Support habitation and human health - Soil has the ability to maintain its porous structure to allow passage of air and water, withstand erosive forces, and provide a medium for plant roots. Soils also provide anchoring support for human structures and protect archeological treasures. While a healthy diet is critical to the well being of both animals and humans, soils also support human health as several drugs, for example, antibiotics, were originally synthesised from soil fungi and bacteria.



Linkages between ecosystem services and human well-being. All people depend on nature and ecosystem services to provide the conditions for a decent, healthy, and secure life. Soil functions are at the core of virtually all processes. (MEA) [27]

As for many soil parameters, soil functions are difficult to measure directly, especially over large areas. For these reasons, they are usually assessed by deriving or measuring indicators or proxies that correlate with soil conditions and can be used to assess soil quality and how well the soil is functioning.

Some soil quality indicators are descriptive and can be used in the field (e.g. drainage is rapid) while others are quantitative and must be assessed by laboratory analyses (pH, carbon content). There are three main categories of soil indicators: chemical (e.g. nutritional status), physical (e.g. hydrological characteristics such as water retention by soil structure) and biological (e.g. soil respiration). Organic matter transcends all three indicator categories as it is tied to all soil functions and is itself an indicator of soil quality.

Nutrient cycles

Nutrient cycling refers to the transfer of elements between the soil, vegetation and the atmosphere, which in a natural, balanced ecosystem is self-sustaining and cyclical. The general concepts are illustrated in the adjacent diagram. Most elements have a distinct 'life-cycle' in that they are created by a transformation process and stored in the soil in inorganic or organic forms. If conditions allow, certain elements are then consumed by organisms, which on their death, are returned to the soil so that the process can resume.

Each nutrient has a specific cycle but several elements appear in more than one cycle. Some cycles, such as those of nitrogen, carbon, oxygen and sulphur, involve transfers between the atmosphere, plants and soil while others may only involve movements below ground. The most important parts of the nutrient cycle relate to the exchange of nutrients between three main pools or stores:

Storage in the soil in an inorganic form - during every growing season, plant roots only tap into a small fraction of the soil's inorganic store of P, K, and Ca which is derived from the weathering of minerals, rainfall and dust falling on the surface, the mineralisation of organic matter and the application of inorganic fertilisers. In these cases, the nutrients are made up of ions in the soil solution and exchangeable ions are electrostatically bound to clay minerals and organic matter (see right);

Storage in living organisms below and above the ground – involves nutrients stored in animals, plants and microorganisms. For elements with rapid cycles (e.g. K) the biomass store is very significant. On death, the remnants of living organisms are transferred to the organic pool;

Storage on and in the soil as residues of living organisms - this is the closing loop of the cycle and involves the decomposition of litter, manures and remains of organisms (see page 28).

As a result, there are marked differences in the distribution of elements within the soil. Nutrients that are released at depth by the weathering of minerals are absorbed by plant roots, transported to shoots then deposited on the ground as litter. Inputs from rainfall supplements the surface store. Nitrogen nearly always accumulates in the organic-rich A horizon and then declines gradually with depth. Phosphorus is similar but, due to it's immobility, 90% tends to remain in the top 30 cm of the soil. For potassium, the figure is closer to 50%. Sulphur tends to also accumulate in the surface in temperate environments but in tropical soils, mineralisation and leaching give rise to higher concentrations in the subsoil.

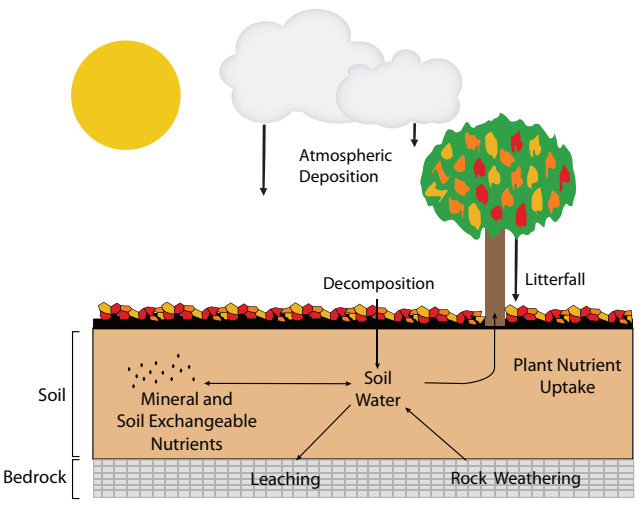
In reality, each cycle represents a balancing act between nutrient inputs and outputs. Inputs can be natural as in the biological fixation of nitrogen or in the form of additions from outside the system (e.g. organic and inorganic fertilisers). Nutrient outputs include a complete removal from the system through crop harvests, wind and water erosion and leaching.

One of the major sources of plant nutrients is soil organic matter which enhances the soil's biological, chemical and physical properties. Plant residues are the main source of soil organic matter while animal manure and urine are secondary sources. In cultivated fields, large quantities of organic inputs must be applied continuously to maintain or improve the level of organic matter. For example, 5 to 10 tonnes/ha of farmyard manure are required to provide a fraction of what would be needed to maintain agricultural production at a desirable level.

However, many current cultivation methods consume many more nutrients than they return to the soil. The situation is particularly evident for the monoculture of cereal crops where almost the entire plant is removed from the soil. For Sub-Saharan Africa, net losses of about 700 kg N, 100 kg P and 450 kg K per hectare have been estimated for around 100 million ha of cultivated land over the past decades [28, 29].

Nutrient depletion contributes directly to a decline in per capita food production in small holdings throughout Africa. Farmers are unable to apply sufficient nutrients due to the high costs of inorganic fertilisers or from a lack of farm machinery. Traditional practices, such as long fallow periods that improve nutrient budgets and restore soil fertility, are difficult to implement due to the increased pressure on land.

Possible solutions involve conservation agriculture which aims to maintain natural nutrient levels through sustainable land management practices or combining organic manures with inorganic inputs. Other sources of organic inputs, such as household organic waste, agro-industrial waste and nutrient-rich sewage and wastewater, could contribute to efficient nutrient cycling but care is needed to avoid contamination of soil and foodstuffs from toxins and pollutants. Finally, a better understanding of the chemical and biological processes that render nutrients available to plants from soil would optimise nutrient cycling and maximise the efficiency of their use.



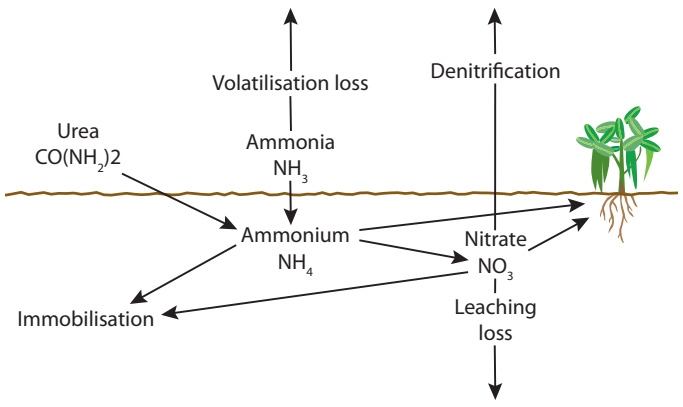
Nutrients in soils may be derived from atmospheric deposition, plant decomposition and mineral weathering. Nutrients are retained by clay particles and organic matter where they can be slowly released into soil water solution for use by plants. However, nutrients may be lost from soils through leaching. (CSS)

The nitrogen cycle

Nitrogen is a critical component of plants. It is a structural component of chlorophyll, nucleic acids (DNA, RNA) and proteins. While abundant in air, nitrogen in the atmosphere cannot be used directly by either plants or animals and must be converted into a usable state. Rainfall often contains substantial quantities of nitrogen in the form of ammonium (NH_4^+) and nitrate (NO_3^-). On contact with the soil, both ammonium and nitrate enter the soil solution easily and are absorbed by plant roots. The microbial decomposition of organic matter results in the mineralisation of organic nitrogen to release the ion NH_4^+ to the soil. Depending on temperature, moisture, the level of soil aeration and presence of some plant species, NH_4^+ is oxidised to NO_3^- , both of which are readily available to plants. Nitrogen may also occur in the soil as the result of mineral weathering, animal urine and through the application of mineral fertilisers (see page 11).

Certain types of bacteria (e.g. Rhizobium) can convert atmospheric nitrogen (N_2) to ammonia (NH_3) through a symbiotic relationship with the root nodules of leguminous plants such as clover (*Trifolium*) or soybean (*Glycine max*). This process is known as nitrogen fixing. Plants convert the ammonia to nitrogen oxides and amino acids that form proteins and other molecules. In return, the plant provides sugars to the bacteria. In order to fix nitrogen, plants such as legumes maintain an oxygen-free (anaerobic) environment near their roots so that the bacteria can exist. Soil pH, organic matter levels and the availability of trace elements such as copper can influence the distribution and activity of these specialised bacteria.

In natural ecosystems, plant growth is relatively slow and the annual uptake of nitrogen is comparatively low (e.g. 30 kg N ha^{-1}). Cultivated crops are much more demanding with nitrogen uptakes that are several orders of magnitude greater (e.g. 500 kg N ha^{-1}). In these cases, the natural nitrogen cycle is unable to maintain optimum growth and artificial inputs must be added to the soil. Harvesting is a critical process as organic matter that would have normally decomposed on the soil surface is often physically removed from the field for processing. This means that there is an export of nitrogen and other elements from the soil to the marketplace. Corrections of N shortages through the addition of mineral fertilisers result in an increase in vegetative growth, much higher protein levels and greater yields of grain and fruit. However, excess amounts of N, above what can be used by plants, are often flushed out of the soil to accumulate in water bodies. Under the right conditions, nitrogen-driven bacterial growth can deplete the oxygen in nearby water bodies to the point that fish and other aquatic organisms die. This process is known as eutrophication.



The principle pathways and transformations of the nitrogen cycle. Nitrogen is important to all life. Nitrogen in the atmosphere or in the soil can go through many complex chemical and biological changes, be combined into living and non-living material, and return back to the soil or air in a continuing cycle. Animals and plants deposit organic nitrogen into the soil. Bacteria convert organic nitrogen to plant-usable ammonium and ammonium to plant-usable nitrates. Denitrification describes the bacterial decomposition of nitrate in the soil to atmospheric nitrogen while volatilization turns urea fertilisers and manures on the soil surface into gases that go directly to the atmosphere (see also page 11). (LJ)

Nutrient depletion in Africa

Several studies have highlighted significant nutrient losses from African soils [28-31]. Models estimate that on average, 660 kg N ha^{-1} have been lost during the past 30 years from about 200 million ha of cultivated land in 37 African countries (excluding South Africa). The FAO estimates that Africa is losing 4.4 million t N every year from cultivated land - these rates are several times higher than Africa's annual fertiliser consumption of 0.8 million t N [28, 32]. N loss is driven by cultivation on nutrient-poor soils, a breakdown of traditional soil-fertility practices and poverty in rural Africa which does not permit effective fertiliser management practices.

The phosphorus cycle

Phosphorus is another vital plant nutrient that forms the backbone of DNA and RNA molecules, forms cell membranes and regulates cell division, root development and protein formation.

Phosphorus deficiency can occur in areas of high rainfall, on acid, clayey or poor calcareous soils. Symptoms include poor growth and leaves that turn blue/green but not yellow. Due to the movement of phosphorus in plants, the oldest leaves are affected first. Fruits are small and taste acidic.

Due to its high reactivity, inorganic phosphorus is never found as a free element, and geologically occurs as phosphate rocks (PO_4^{3-}). In natural ecosystems, phosphorus is released by the decomposition of organic matter as compounds known as orthophosphates (e.g. $H_2PO_4^-$, HPO_4^-). These are rapidly adsorbed by soil particles or immobilised by phosphorus-consuming bacteria (e.g. *Aspergillus*). The pool of phosphorus that is readily available to plants is found in solution or loosely bound on to soil particles.

Because of low concentrations of P in soil solutions and the competition from soil microorganisms, many plants have developed a symbiotic relationships with mycorrhiza – a type of fungus – which in essence extend the root network and provide an improved pathway for the rapid transfer of phosphorus.

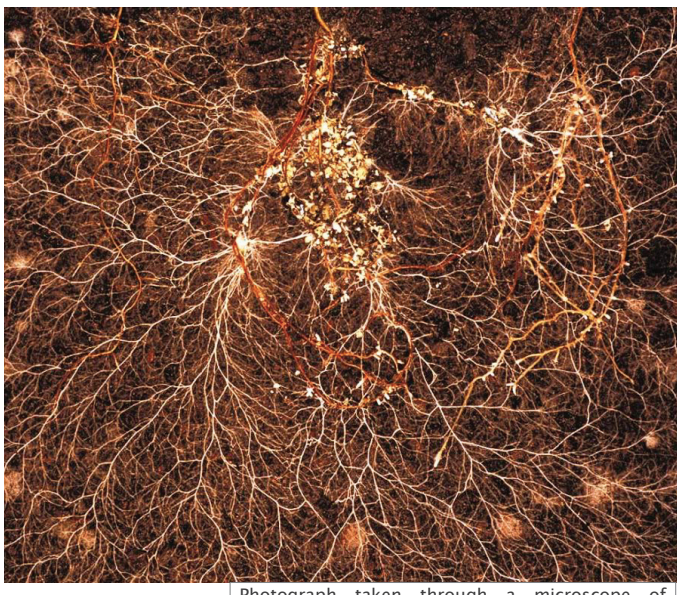
The highly weathered, iron-rich tropical soils of Africa tend to be deficient in plant-available phosphorus. The low pH together with high levels of iron and aluminium oxides, tend to imobilse phosphorus onto soil particles thus denying its availability to plants. In such situations, large quantities of phosphorous fertiliser must be added to the soil to make a difference in crop yields. Lime-rich soils also imobilise phosphorus.

As in the case of nitrogen, it is estimated that around 0.5 million tonnes of phosphorus is lost every year from cultivated soil in Africa - double Africa's annual P consumption [22].

The future of phosphorus?

Due to the essential nature of phosphorus to living organisms, the low solubility of natural phosphorus-containing compounds and the slow natural cycle of phosphorus, the agricultural industry is heavily reliant on fertilisers containing concentrated phosphoric acids (H_3PO_4). About 50% of the global phosphorus reserves are in North Africa and the Middle East. Large deposits of phosphate-bearing apatite exist in China, Russia, Morocco and the USA.

Recent reports have suggested that production of phosphorus may have peaked, leading to the possibility of global shortages by 2040. However, some scientists now believe that a "phosphorus peak" will occur in 30 years and that reserves will be depleted in the next 50 to 100 years. [33]



Photograph taken through a microscope of mycorrhiza (the faint, thin filaments) growing around the roots of a plant (brighter features). Such symbiotic relations can help plants extract phosphorus from soils. (PDI)

The role of soil elements in plant growth

Macronutrients

Macronutrients are elements that are essential to plant growth and are needed in significant amounts. For more details, see [7a].

Potassium (K) is crucial to most plant functions including stomatal control, the maintenance of turgor pressure and charge balance during selective ion uptake across root membranes. It is also an enzyme in many biochemical reactions. Potassium is highly mobile and is easily leached from leaves to be taken up in high quantities by soil microorganisms and roots. In soil, potassium may be found in minerals such as micas and feldspars, secondary aluminium silicates (e.g. illite) and some salts. Potassium is available when attached to clay and humus colloids and easily available when in solution. Potassium dissolved in soil solution as an ion is highly leachable, although loses of potassium from runoff and erosion is not a significant problem.

Calcium (Ca) is used to build cell walls in plants. It helps keep P available in the root zone by binding it with other ions. Because it is bound within cell walls, it does not leach from leaves nor circulate within the plant. Calcium deficiency leads to stunted plant growth, the curling of young leaves and death of terminal buds. Calcium can be easily leached from the soil and is largely absent in the soils of central Africa.

Magnesium (Mg) is the central atom of the chlorophyll molecule and is an important enzyme. It is very mobile in plants. Magnesium deficiency in plants causes yellowing between leaf veins. Low soil pH decreases the availability of magnesium to plants.

Phosphorus (P) is crucial to many plant functions, a key component of most fertilisers, and often lacking in non-fertilised soils. Phosphorus forms the backbone of DNA and RNA molecules and regulates cell division, root development and protein formation (see adjacent text). Phosphorus is responsible for crop yield increases.

The benefits of **nitrogen** (N) are described in the adjacent text.

Micronutrients

Micronutrients are elements that are essential to plant growth but are required in very low concentrations (<100 µg/g). They are generally metabolically active in plants as important enzymes.

Iron (Fe) primarily originates from chemical weathering of minerals and is not absorbed by plants in appreciable quantities; the amount found in plants is several orders of magnitude lower than the amount in the surrounding mineral soil. Iron serves as an electron carrier in enzymes. It also plays a role in nitrogen fixation and chlorophyll formation. Its movements in soil are due to chemical processes rather than an association with organic matter or uptake by plants. The presence of iron oxide gives a reddish tint to soil horizons.

Manganese (Mn) is critical to many plant functions, including photosynthesis, respiration, and nitrogen metabolism. Manganese is generally plentiful in acid soil and may reach toxic levels if pH is below 6.5. It generally leaches out of acidic soils.

Zinc (Zn) is a key component of growth control hormones in plants and is used in protein synthesis. Almost half of the world's cereal crops are deficient in zinc, leading to poor yields while zinc deficiency is the 5th leading risk factor for disease in developing countries. Zinc in soils is tightly bound to magnesium.

Copper (Cu) is especially plentiful in acidic, sandy soils and is an important enzyme activator found mostly in the chloroplasts of leaves.

Toxic elements

Pollutants are contaminants that have been introduced into the natural environment and cause instability, disorder, harm or discomfort to the ecosystem. Artificially high levels of all elements can have harmful or toxic effects. **Aluminium (Al)** is not used in significant amounts by plants. In soils, it immobilises phosphorus and generally increases the acidity and concentration of cations. As for most elements, aluminium becomes toxic to some plants above 1 ppm and to most plants above 15 ppm.

Lead (Pb) binds with organic matter in the soil and accumulates in certain organic tissues of plants. In high enough concentrations, it can cause brain damage in humans.

Other elements that are toxic to plants include arsenic (As), cadmium (Cd), sodium (Na) and even iron (if concentrations are high enough).

Provision of food, fibre and fuel

Perhaps the most readily appreciated soil function is in supporting the growth of agricultural and horticultural crops. The quest for food, fibre for clothing or construction and fuel for heating and cooking has been, and still is for many, of paramount importance to humanity. Soil is the mainstay of agriculture and forestry, forming the physical, chemical and biological medium in which plant growth occurs. Agriculture is the foundation that meets the immediate needs for almost 59% of the African population who live in rural areas and indeed, the soils of Africa do offer great potential for increased agricultural productivity. A staggering 98% of all daily calories consumed in Africa (i.e. kcal/capita/day) come from soil derived products [35].

The most productive soils are those that possess deep, permeable layers, an adequate supply of nutrients, and do not have significant periods of moisture stress. In reality, these correspond to the occurrences of Chernozems, Kastanozems, Phaeozems (temperate grassland soils that are not that widespread in Africa), Vertisols (see page 50 and facing page) and floodplain soils (Fluvisols). Normally these soils are deep with loamy to clayey textures and do not possess impermeable layers. They occur on land that is level to gently undulating, have a balanced nutrient supply and a water-holding capacity of more than 150 mm per metre. Crop yields are generally high and they can support a wide range of agricultural uses.

Agriculture can also be highly successful where seasonal rainfall can support crops, or where appropriate land management practices are needed to overcome some physical constraints. The tropics of Central and West Africa are regarded as having medium agricultural potential due to the presence of acid soils and soils with high phosphate buffering capacity. However, significant specialist assistance and the implementation of appropriate soil management technologies are needed to cultivate these soils.

Woodland and forests cover around 20% of Africa and are important sources of fuel and construction materials. This photograph shows an eucalyptus plantation on Ferralic Arenosols in Congo. Such plantations are replacing natural savannah ecosystems. From this plantation, most of the production, with an average turn-over of seven years, is exported to Europe for paper production. (HDF/IRD)

According to UN statistics, Sub-Saharan Africa (excluding South Africa) is the poorest developing region on the planet, with 29 out of 34 countries being amongst the poorest in the world [34]. With a significant part of the population being low-income farmers and population growth of around 4%, increasing demands on low production land is putting increased stress on soil resources. In parallel, the demand for cereals in Africa rose by around 200% between the early 1980s and 2003 [32].

Poor farmers who cultivate marginal lands face a high probability of crop failure. Adverse climatic conditions (e.g. aridity, drought) and physical soil properties which include surface crusting, impermeable layers, soil acidity, high salinity and alkalinity, wind and water erosion, are all contributing factors, exacerbate by changing climatic patterns.

However, as demand has been rising, there has been an alarming decline in food production in Africa over the past few decades. While there are many political and socio-economic reasons for this situation, major factors have been the decline in the quality of the soil resources and changes in land tenure and agricultural systems (no fallow, commercial production) in many African countries. Fertiliser use in Sub-Saharan Africa is extremely low, averaging at around 9 kg/ha compared to just over 200 kg/ha in industrialised countries, 150 kg/ha in East Asia, and 80 kg/ha in North Africa. This means that large areas of land are cultivated without the addition of fertilisers (generally limited to large commercial farms).

In recent years, the situation has been exacerbated by the rise in price of inorganic nutrients compared to the increase in returns from harvests. Since the 1960s, fertiliser prices paid by farmers have risen by over 600% while income from crops has only risen by half as much. The World Bank noted that between 2006 and 2008, the cost of phosphate fertilisers rose by a staggering 200% making it almost unavailable to farmers in Sub-Saharan Africa who, in order to deal with soil conditions that fix phosphate, need to apply large amounts to guarantee the necessary increase in per capita food production.

Irrigation, terracing and fertilisation of marginal soils can lead to successful crop production systems. This photograph from Ethiopia shows that even steep slopes can be cultivated. However, care is needed to avoid secondary issues such as erosion and contamination of water supplies by fertiliser and pesticide residues. (EVR)

The other major consideration is the loss of food-producing land to alternative uses such as urban and industrial developments, infrastructure projects and the cultivation of high-value or 'cash' crops (such as flowers in Kenya and Ethiopia). The magnitude of these losses are difficult to estimate for Africa as no reliable statistics exist. Cities such as Kampala and Nakuru have grown by 4-15% between 1990 and 2006 (see page 156).

If nutrient levels were to be enhanced and farmers trained in sustainable land management through substantive investment, an estimated 35% of arable land has the potential for sustainable agricultural production. With medium to high levels of nutrient inputs and with the associated services and facilities, the seeds for an African Green Revolution could be sown and Africa's food insecurity could be largely addressed. However, detailed information on the soil resource base is generally inadequate for most developmental purposes and, in most countries, detailed soil maps at farm-level are non-existent. When coupled with other socio-economic constraints such as land ownership, the lack of availability of capital for land management investments and the lack of soil considerations in policy and planning development, the reasons behind the lack of progress in poverty alleviation and food security become clear.

Food Security

In recent years, the term 'food security' has been widely used by politicians and decision makers to describe the availability of and access to food [38, 38a]. A society is considered to be food-secure when its citizens do not live in hunger or fear of starvation. The FAO estimates that the number of people without enough food to eat on a regular basis is over 800 million, and increasing. Over 25% of the world's undernourished people live in Africa. In Sub-Saharan Africa, since 2009, over 265 million people are malnourished and 30% of the population suffers from hunger [39]. Many factors influence this situation. Often not enough food is produced or imported to provide a satisfactory base for the diet. At other times, food distribution may be difficult due to poor infrastructure or conflicts. In the first case, efforts to enlarge the food supply are needed.

Increasing the productivity of arable soils can be achieved by increasing the number of crops grown each year or by increasing yields. However, both these approaches come with issues. Many parts of Africa suffer from soil nutrient depletion as the components which contribute to fertility are removed and not replaced and the conditions which support soil fertility are not maintained. This leads to poor crop yields. This is exacerbated in the tropics and sub-tropics where the nutrient content of soils is inherently low. Urbanisation and land take often consume productive soils forcing agriculture to move on to less productive, marginal land (most urban areas were originally located on fertile soils in order to ensure food security for their populations).

An additional, but often underestimated, element is food wastage. In 2011, a study produced for the FAO estimated that the total global food loss and waste amounted to one third of the edible parts of food produced for human consumption, amounting to about 1.3 billion tons per year [40]. In industrialised states more than 40% of losses occur at the postharvest and processing stages while in developing countries, more than 40% of losses occur at the retail and consumer levels. The total food waste by consumers in industrialized countries (222 million tons) is almost equal to the entire food production in sub-Saharan Africa (230 million tons) [40].

The JRC FOODSEC Action produces regional and annual bulletins each year describing the agricultural and pastoral situation for several African countries.

http://mars.jrc.ec.europa.eu/mars/About-us/FOODSEC/

What do we mean by fertile soils?

The previous texts have shown how healthy soils underpin agriculture and that the ecosystem functions that support this are the main nutrient cycles. However, most people are completely unaware of why a particular soil should be more productive than another and how plants access the nutrients that are locked up in the soil. The term 'soil fertility' refers to the inherent capacity of a soil to supply nutrients, minerals, water and air to the roots of plants in adequate amounts. Fertility should be viewed as a natural condition and depends on the main soil-forming factors and soil processes described in the preceding pages. Soil structure and organic matter levels are critical controls of soil health. The concept of productivity could be described as the ability of a soil to produce a crop. Artificial interventions to enhance fertility, such as the addition of fertilisers or drainage, systems, may result in increased productivity or crop yields but at the same time may also upset the natural soil balance (e.g. the rapid depletion of naturally available elements or the increased oxidation of organic matter).

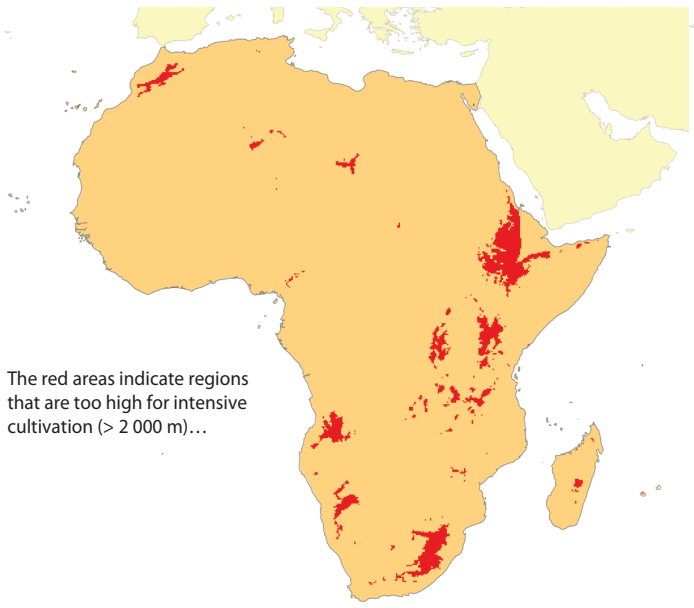
There is a general acceptance that plants require the presence of around fifteen elements in the soil to support healthy growth. These are broadly divided into macronutrients (carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, calcium, magnesium and potassium) which are required in relatively large amounts. Micronutrients or trace elements (iron, zinc, copper, boron, chlorine and molybdenum) are needed in much smaller quantities. This list is not exhaustive as plants also absorb other elements such as manganese, sodium, selenium (have no direct benefit to plants but are essential for healthy animals) and cobalt (critical for the natural fixation of nitrogen by leguminous plants). Carbon, hydrogen and oxygen are generally very abundant and supplied as carbon dioxide (CO_2) and water (H_2O). With the exception of Cl and N, the major source of the other elements is the weathering of parent material and the breakdown of minerals in the soil.

How do plants extract nutrients from the soil?

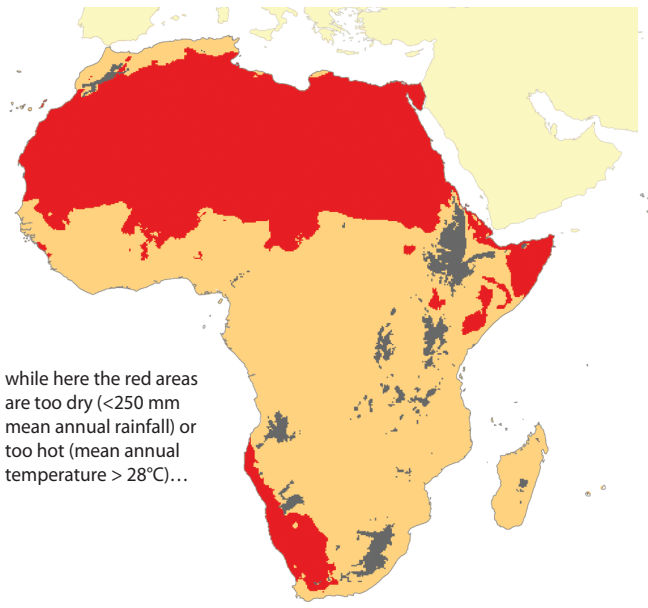
Plants take nutrients from the soil by a process known as cation exchange which is dependent on soil moisture and sunlight. When plants are photo-synthesising, very fine hairs on their roots pump hydrogen ions (H^+) into water within the soil. These hydrogen ions displace positively charged cations (i.e. nutrients) that are attached to negatively charged soil and organic matter particles. Once these cations are present in the soil water solution, potential energy differences between soil water and roots move nutrients from a higher solute concentration (soil) to a lower solute concentration (plant). Low levels of certain elements can cause symptoms of deficiency in plants, while at a higher level the same element may cause toxicity. Conversely, an abundance of one nutrient may cause a deficiency of another nutrient.

Maintaining soil fertility is an important step in creating sustainable agriculture, food security and economic returns. In natural ecosystems soil nutrients more or less remain stable. However, the harvesting of crops removes some of the nutrients from the cycle thus, over time, depleting the soil. (KH)

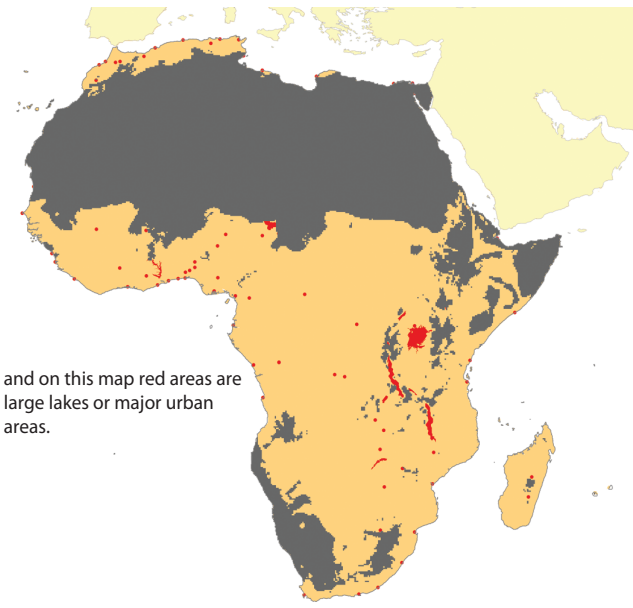
Soil constraints for agriculture in Africa



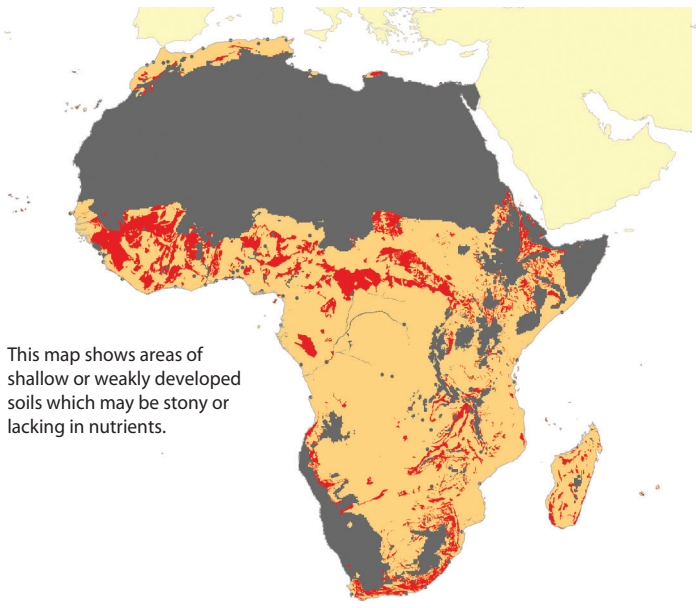
The red areas indicate regions that are too high for intensive cultivation (> 2 000 m)…



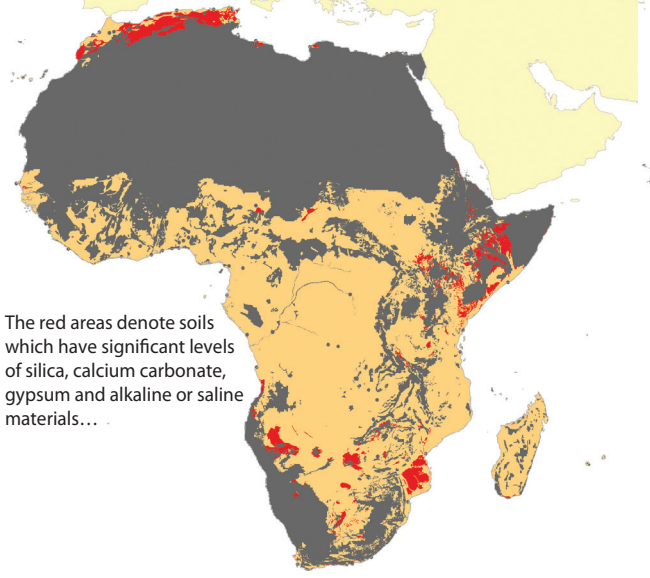
while here the red areas are too dry (<250 mm mean annual rainfall) or too hot (mean annual temperature > 28°C)…



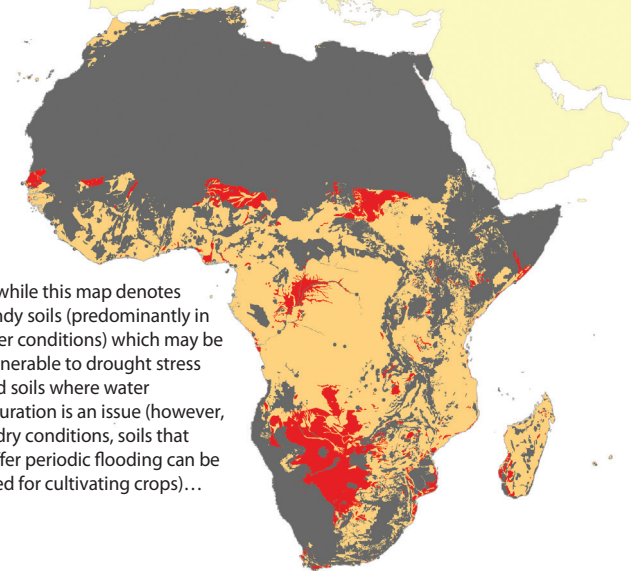
and on this map red areas are large lakes or major urban areas.



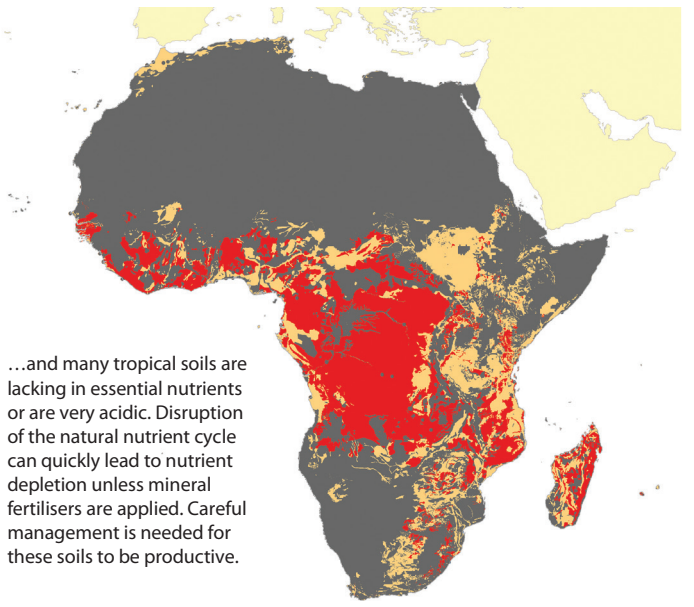
This map shows areas of shallow or weakly developed soils which may be stony or lacking in nutrients.



The red areas denote soils which have significant levels of silica, calcium carbonate, gypsum and alkaline or saline materials…



…while this map denotes sandy soils (predominantly in drier conditions) which may be vulnerable to drought stress and soils where water saturation is an issue (however, in dry conditions, soils that suffer periodic flooding can be used for cultivating crops)…



…and many tropical soils are lacking in essential nutrients or are very acidic. Disruption of the natural nutrient cycle can quickly lead to nutrient depletion unless mineral fertilisers are applied. Careful management is needed for these soils to be productive.

The naturally fertile soils of Africa?

So the soils that remain, the orange areas on the map **below**, covering around 8% of the continent, are relatively free of natural constraints for agriculture. However, this area still includes problematic soils (e.g. waterlogging may restrict some agricultural practices while soils such as Vertisols can be difficult to cultivate when too wet or too dry). It is clear that their distribution across the continent is uneven with large expanses seemly devoid of fertile soils! It should be stressed that the maps on this page present a very generalised view - human activity can have a positive impact on soil quality by allowing crops to be grown where conditions are not optimal, especially at local scales (see box below-left).

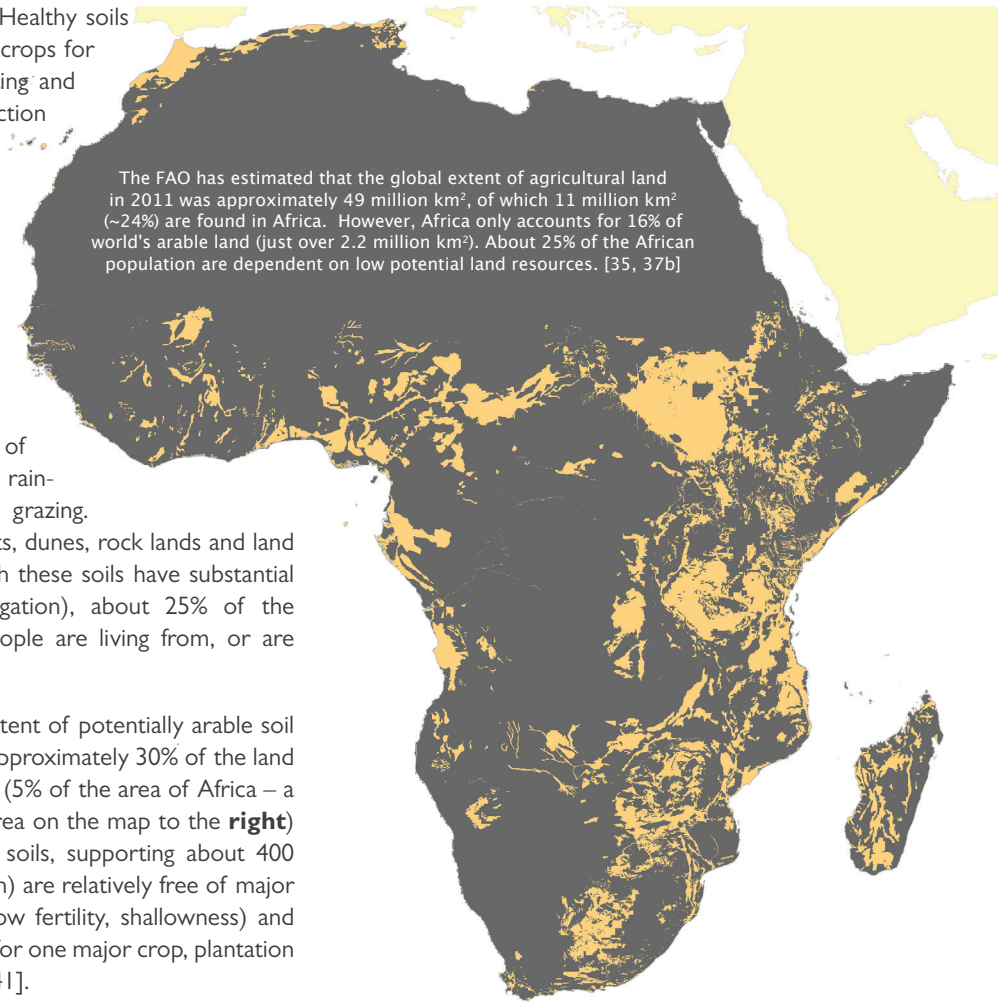
Soil is at the heart of food security. Healthy soils are needed to sustain life – to grow crops for food, feed for animals, fuel for heating and cooking and materials for construction and utensils.

Unfortunately, the conditions required for naturally fertile soils mean that the distribution of such land is limited across Africa. This page illustrates the environmental constraints to agricultural production.

Fifty-five percent of the surface area of Africa is unsuitable for any kind of rain-fed agriculture other than nomadic grazing. These are largely the deserts, salt flats, dunes, rock lands and land that is too steep to cultivate. Though these soils have substantial agricultural potential (e.g. with irrigation), about 25% of the population or about 250 million people are living from, or are dependent on, these resources.

The USDA has estimated that the extent of potentially arable soil in Africa is around 9 million km^2 (or approximately 30% of the land mass) of which 16% is of high quality (5% of the area of Africa – a value surprisingly similar to orange area on the map to the **right**) and 13% of medium quality. These soils, supporting about 400 million people (40% of the population) are relatively free of major soil constraints to agriculture (e.g. low fertility, shallowness) and rainfall is usually stable and adequate for one major crop, plantation agriculture, forests and aquaculture [41].

Sustainable management and effective conservation practices are essential to maintain soil fertility and thus ensure secure food supplies and reduce global poverty [37, 37a, 37b].

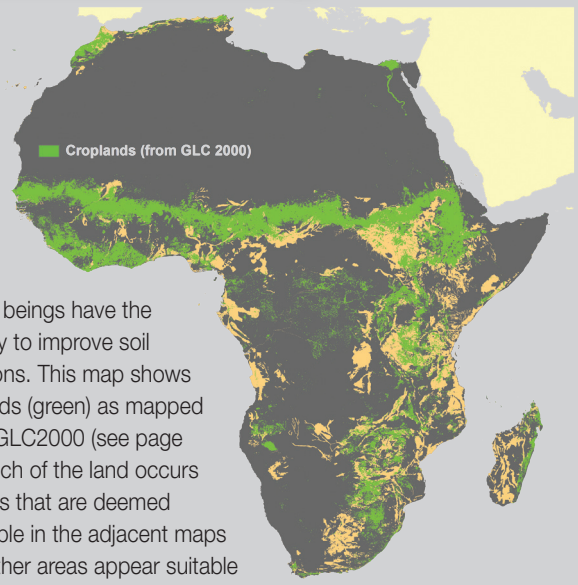


The FAO has estimated that the global extent of agricultural land in 2011 was approximately 49 million km^2, of which 11 million km^2 (~24%) are found in Africa. However, Africa only accounts for 16% of world's arable land (just over 2.2 million km^2). About 25% of the African population are dependent on low potential land resources. [35, 37b]

Maps based on data from the FAO Map of World Soil Resources 1:25 000 000 [23], WorldClim climate and elevation variables [12] and the Global Land Cover Map 2000 [16a].

Maps elaborated by JRC.

The human touch?



Human beings have the capacity to improve soil conditions. This map shows croplands (green) as mapped by the GLC2000 (see page 19). Much of the land occurs on areas that are deemed unsuitable in the adjacent maps while other areas appear suitable but are not cultivated. (JRC)

Traditional soil use and agriculture

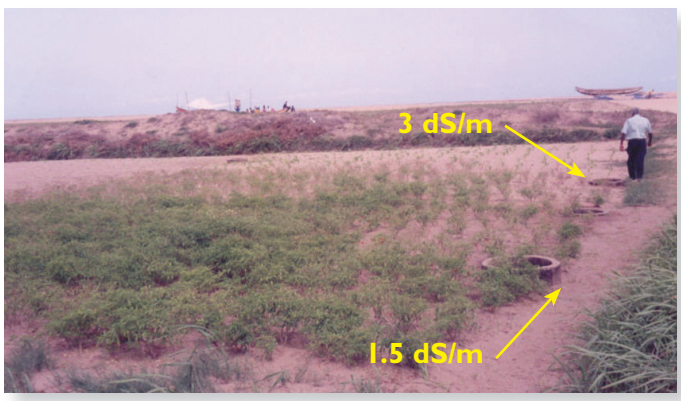
Threats to shallots cultivation in southeast Ghana

Close to the estuary of the River Volta, one can find an extraordinary, intensive horticulture system on beach sands. Despite its semi-arid climate, farmers on the Keta sand spit in southeast Ghana have developed a sustainable horticultural production system based on shallot cultivation on soils which have low nutrient content, low water holding capacity and a climate with a long dry period! However, the input of new technologies are threatening the very existence of this fragile system.

Shallot cultivation is a cash crop which is highly dependent on a substantial input of organic matter (manure) and water. Three growing seasons are supported. Traditionally, organic matter inputs came from poultry manure, fish remains and wood ash. The first growing season is totally rain-fed, the second is partly rain-fed while the last one, in the dry season, is totally dependent on irrigation water extracted manually from wells dung into a shallow aquifer held in the sand. Yields decrease with each cultivation (30% reduction between the first and the last) probably due to a slight increase in soil salinity as a result of the irrigation water. This system has been maintained for more than 100 years and has provided a stable income for local farmers.

Recently, the introduction of electric pumping systems have made sprinkler irrigation possible and allowed a larger area of the sand spit to be cultivated. However, this development is a severe threat to the sustainability of the farming system. The increased consumption of water appears to be greater than the recharge of the freshwater lens which, if not managed correctly, could become depleted and be replaced by salt water intrusion from the adjacent sea.

Due to the already marginal conditions, competition with other shallot-growing areas is intense and profit margins are low. Some farmers are already making a transition to a pepper-okra-tomato cultivation system which gives higher prices but requires more inputs of manure and water. Cow dung manure is now being transported to the area from a distance of around 100 km. However, the cow manure has led to weed infestations which need to be treated with herbicides. Given the porous nature of the sandy soil, there is a high risk of groundwater contamination from plant protection products. As a consequence, quotas on water extraction and limits on the use of manure may undermine the change of farming system nor is it certain whether it can even survive in its present form.



Above: Traditional agricultural methods which took note of local soil and climatic conditions in southeastern Ghana supported a sustainable farming system despite the low nutrient content and poor water holding capacity of the soils. (HBM)

Below: A dramatic example of the influence of salt on crop development. Salt levels in the well in the foreground are half those of the adjacent well. Crops irrigated with saline water (in the background) display less growth. (HBM)

Traditional techniques for the rehabilitation of degraded soils in the Sahel

The combined effects of climatic conditions, inherent poor soil quality and human activities have resulted in severe soil degradation across the Sahel. Soils display well-developed crusts while erosion by water and wind is substantial. Cultivated lands are particularly characterised by a gradual loss of structure, hardpan formation, reduced permeability, compaction and inadequate aeration which limit root development. Such soils are known as zipellé in Burkina Faso or hardé in Chad. Typical characteristics are shallow depth (< 50 cm), a pH of around 5, soil organic mater content of 1.2%, N < 0.6 g kg^{-1} and very low in nutrients (CEC is 0.11 $cmol^{+}$ kg^{-1}). However, the reintroduction of two traditional soil management practices has shown great potential to combat land degradation while improving the productivity of sealed and crusted bare soils, previously abandoned as wasteland.

The zai method (also called tassa in Niger or towalen in Mali), is a soil rehabilitation system that concentrates runoff water and organic matter in small pits (20-40 cm in diameter and 10-15 cm deep) dug manually during the dry season. A handful of animal manure or compost is added to each pit.

A young sorghum crop growing in Zai pits in Burkina Faso. (RZ)

The second method, originating from Niger, is the half-moon. This consists of a basin 2 m in diameter, dug with a hoe or a pick in order to break the crusted layer on the soil surface and to collect runoff water. The cultivated area for each half-moon is around 6 m^2. A barrowful (35 kg) of animal manure or compost is supplied to each half-moon.

Rain and runoff water collects in half-moon basins. Stone boundaries across the slope reduce runoff rates. (RZ)

Both practices are efficient in improving soil productivity. The application of organic matter enhances soil nutrient levels and improves crop nutrient uptake from soil reserves. The manure also attracts termites which improve soil structure through their nesting and foraging activities. This change in structure, together with the digging of the pit and breaking the crust, leads to increased water infiltration and drainage, lower runoff and reduced resistance to root penetration. The improved water status in the soil, increased decomposition of organic matter and nutrient release, result in substantial gains in sorghum grain yields of around 700-1 500 kg ha^{-1} compared to yield rates of 100 kg ha^{-1} in soils without any intervention.

Additionally, seeds included in the manure allow for the regeneration of shrubs and trees. Several studies have reported the re-establishment of herbaceous and woody species on formerly bare soil following two consecutive years of zaï in the central part of Burkina Faso (see page 148).

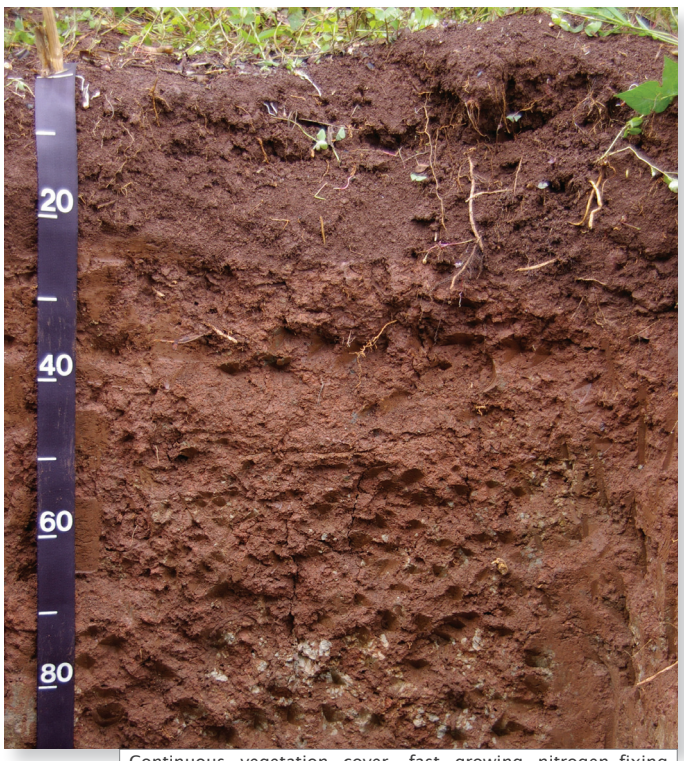
The Chagga Gardens: sustainable use of soils of the southern slopes of the Kilimanjaro

The Chagga people are the third largest ethnic group in Tanzania. They live on the southern and eastern slopes of Mount Kilimanjaro (and Mount Meru, as well as in the Moshi area) at an altitude of between 900 m and 1 900 m. The favourable climate, fertile volcanic soils and sustainable agricultural practices have supported the Chagga for thousands of years.

The Chagga are exponents of a practice known as forest gardening, a low-maintenance organic plant-based food production and agroforestry system. Forest gardening is believed to be the oldest form of land use in the world and is a great example of the benefits of poly-cultivation (i.e. the opposite of monoculture). Fruit and nut trees, shrubs, vines, herbs and perennial vegetables are inter-planted to give a multi-layered cropping system that replicates a woodland habitat. Root vegetables such as yams and sweet potatoes are grown in the soil, interspersed with eggplants, beans and maize. Coffee bushes provide a cash crop while banana and nut trees ensure a staple food source. Plant species (e.g. *Datura arborea*, *Rauwolfia caffra*) are grown to repel or eradicate various pests.

The sloping ground of Kilimanjaro is terraced to enable deep cultivation and reduce soil loss due to erosion. Manure from oxen and bird droppings are added to the soil as organic matter inputs. Each garden has a network of irrigation and drainage furrows allowing farmers to use runoff from the forest and other home gardens on higher slopes during dry periods.

Forest gardening is widespread in rural, suburban and urban areas of many African countries, particularly Malawi, Tanzania, Zambia and Zimbabwe. Such approaches play an essential role in establishing food security as most of the produce is used for subsistence. Women are usually the main actors in this system.



Continuous vegetation cover, fast growing nitrogen-fixing plants and inputs of compost and animal manure ensure that this Nitisol in the Chagga Gardens of Tanzania remains fertile. The high clay content of the soil is very evident below 20 cm (0–20 cm has been mixed by cultivation). (EM)

Banana trees interspersed with coffee bushes on the slopes of Kilimanjaro in northern Tanzania. Unlike other species, *Coffea arabica* prefers light shade which makes it ideal for forest gardening systems. Most of the coffee produced by the Chagga is exported to Europe. (EM)

Soil carbon cycle

The biological carbon cycle

One of the most important functions of soil is its role in the terrestrial carbon (C) cycle by facilitating the conversion of atmospheric carbon dioxide (CO_2) to living matter and then its breakdown and release to the environment. Biology plays an important role in the movement of carbon between the soil and atmosphere. Through photosynthesis, green plants use solar energy and water to turn atmospheric CO_2 into carbohydrates (i.e. sugars, starch and cellulose), the principle compounds that are necessary to build up biomass for plants or the bodies of animals. Most carbon leaves the biosphere through respiration and the decomposition of organic matter ($C_6H_{12}O_6$, e.g. litter fall, roots). Where oxygen (O_2) is present, aerobic respiration occurs, which frees the energy contained in the sugars and transforms carbohydrate 'fuel' back into carbon dioxide, which is released back to the atmosphere as follows:

$$C_6H_{12}O_6 + 6O_2 \text{ ---> } 6H_2O + 6CO_2 + \text{energy}$$

When oxygen is lacking, for example in soil that is saturated with water due to poor drainage, then microbial communities (e.g. Methanobacterium, Methanosaeta and Methanosarcina) catalyse the breakdown of organic matter (anaerobically). In these conditions, organic matter is broken down to produce methane (CH_4) and carbon dioxide:

$$C_6H_{12}O_6 \text{ --->} 3CH_4 + 3CO_2$$

The amount of carbon entering the terrestrial carbon cycle by photosynthesis and released back into the atmosphere by respiration each year is about 1 000 times greater than the amount of carbon that moves through the geological cycle on an annual basis. Carbon dioxide and methane are important greenhouse gases that affect the Earth's climate. This makes soil an important component in the study of climate change.

Soil organic matter and carbon

Organic matter is often described as the 'life-force' of the soil. It creates pores in the soil which help the roots of plants to develop and stores significant amounts of water thus increasing the soil's capacity to withstand drought conditions. Organic matter can attract the ions of essential nutrients and, as a result, reduce the risk of valuable plant food being leached away. The same process can occur with certain pollutants which limits the potential contamination of soil and groundwater. Finally, the biochemical structure of organic matter can help to buffer excessive acid or alkaline soil conditions.

The amount of soil organic matter is determined by a balance between biological inputs (e.g. plant residues), the rate of humus formation and its loss, which comprises decomposition of vegetation and humus mineralisation. Depending on the climate and land use, organic matter can remain stable in soil for long periods. However, the level of organic matter in soil can be manipulated through variations in input or output conditions. Several land management practices, such as the harvesting of crops or drainage, remove carbon from the soil. Minimal or no-till cultivation, mulching crop residues, crop rotation, and inter-cropping with perennials all enhance the formation and increased storage of organic matter in the soil. The drainage of peatlands leads to significant losses of organic matter and emissions of CO_2 to the atmosphere and should be avoided.

It is generally accepted that most soil organic matter contains between 40 to 60% C (by dry weight).

Soil organic carbon and soil functions

Low levels of organic carbon in the soil are generally detrimental to soil fertility and water retention capacity, and tend to increase vulnerability to soil compaction, which leads to increases in surface water run-off and erosion. Other effects of low organic carbon levels are a reduction in biodiversity and an increased susceptibility to acidification. Climatic conditions strongly influence both the trends and rates of accumulation and transformation of organic substances in the soil.

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Measuring carbon in soil

Although there are some promising new technologies, soil carbon usually cannot be measured directly in the field. Samples must be collected (see below) and sent to a laboratory for analysis. The most accurate method for measuring soil carbon is through dry combustion in an elemental analyser. These instruments heat a very small sample of dry pulverised soil to around 1 000°C and then measure the CO_2 levels that are released through the combustion process. If the sample contains carbonates or inorganic carbon, then the soil is pre-treated with hydrochloric acid to remove the inorganic compounds. Results are expressed as the percentage of carbon in the sample.

Traditional procedures for determing soil organic carbon are the loss on ignition (LOI) and Walkley-Black tests. However, both are less accurate than the elemental analyser process described above. LOI measures the loss of weight of organic matter in a dry soil sample after it has been heated in an oven to around 400°C for a few hours. The Walkley-Black method uses potassium dichromate to liberate the carbon in a sample. As both of these tests only measure organic carbon, neither can extract all the carbon that is present in a soil sample.

Calculating soil carbon stocks

The amount (or stock - t ha^{-1}) of soil organic carbon (SOC) can be calculated to a given depth using the following equation [45a]:

$SOC = C * BD * T * (1\text{-}VS/100) * T*10^2$, where:

- C is the organic carbon content for a specific soil type (% weight) for a given depth - determined by laboratory analysis;
- BD is the soil bulk density (g cm^{-3}) - a crucial factor which describes the weight of an undisturbed soil sample. Bulk density can range from 0.1 for light peats to 1.8 for very dense, compacted mineral soils;
- VS is the volume of coarse fragments (and/or ice) in the soil (% volume)a measurement recorded in the field;
- T is the thickness of the soil layer (e.g. 0.30 m).
- S is the extent of the soil type.

SOC is normally expressed in tonnes of carbon (tC), gigatonnes (Gt = 1 billion tonnes) or peta-grammes (Pg = 1 0^{15} g).

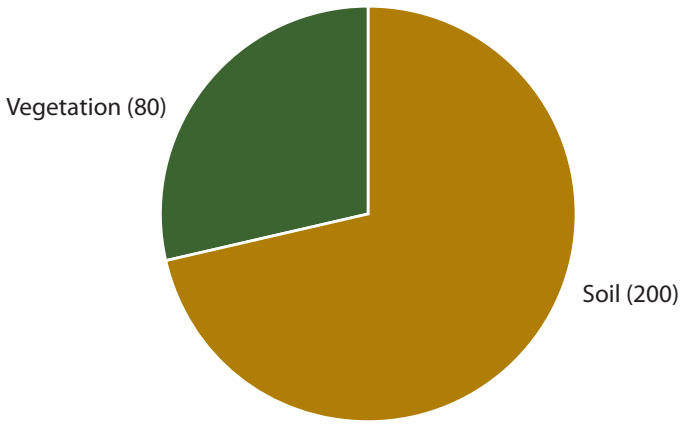
Problems in measuring carbon in soil

While the carbon content for a specific location can be calculated accurately using the methodology described above, the result is only applicable to the sampling location. The inherent variability of soil across the landscape means that the soil characteristics may be quite different a few metres away from a sampling site which means that the carbon content may also be different. Soil scientists often take several samples within a soil body to determine an average or 'typical' carbon content or density for a particular soil type.

Organic carbon in African soils

One of the most striking features of African soils is the huge range in values and the diversity in the distribution of soil organic carbon (see map on page 39). Values ranging from very low or negligible levels in the deserts of the Sahara, the Kalahari and the Horn of Africa to very high in the wetlands of Sudan (Sudd), DR Congo (Ngiri-Tumba-Maingombe), Congo (Sangha-Nouabalé-Ndoki), Rwanda, Burundi, Tanzania and the Barotse Flood Plain in Zambia [42-43]. The soils of the tropical zone contain slightly more carbon than the soils of the savannah regions.

The impact of land use change on carbon varies depending on type of change. The conversion of tropical forests into farmland reduces topsoil carbon content by 20 to 50% of the original levels through reduced production of detritus, increased erosion rates and increased decomposition of soil organic matter by oxidation. Deeper layers tend to be less affected. The conversion of forests to pasture appears not to change soil carbon dramatically and may even increase levels in some cases but may affect other issues (e.g. biodiversity, erosion). [44-45]

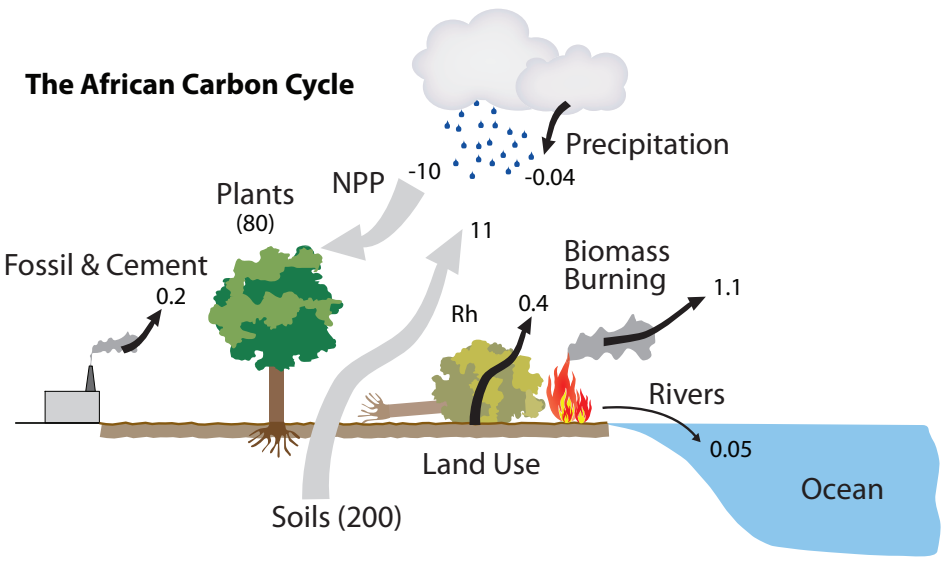


While exact figures do not exist, most studies indicate that the soils of Africa store about 2.5 times the amount of carbon contained in above-ground vegetation (values in 10^{15} g C). (JRC) [based on 43]

Global carbon balances

The largest global carbon reservoir is the deep ocean which contains close to 38 000 Gt C compared to around 2 200 Gt C on land, 750 Gt C in the atmosphere and 1 020 Gt C in the upper ocean (1 Gt is one billion tonnes).

Of the land pool, an estimated 1 600 Gt C are stored in the soil while vegetation holds around 500 Gt C.



A schematic representation of the African carbon cycle showing the main stores of carbon and the fluxes (exchanges) between them. The importance of the soil carbon reservoir is clearly apparent. In general terms, Africa emits slightly more carbon on an annual basis than it sequesters. Soil is by far the largest store, holding an estimated 200 Gt of carbon, with vegetation accounting for around 80 Gt C. With 11 Gt C, soils are also the largest emitter of C in Africa, primarily due to microbial or heterotrophic respiration (Rh) and decomposition of organic matter. However, this amount is almost offset by plant productivity (net primary productivity – NPP). On the other hand, carbon emissions due to land clearance and the burning of biomass are markedly higher than emissions due to the combustion of fossil fuels (e.g. oil and gas). While they affect large areas, emissions from savannah fires are offset by the subsequent regrowth.

While current data suggest only a small carbon imbalance across Africa, climatic fluctuations (especially drought) can lead to sizeable changes in net ecosystem productivity and increases in wildfires. In these situations, the land system of Africa becomes a major source of global carbon emissions.

Considering the current and increasing pressures on land across Africa (climate variability, land use change, population growth, industrialisation and urbanisation), carbon emissions are likely to undergo substantial changes over the coming years. (based on CW) [43]

All units are 10^{15} g of carbon.

Soil organic carbon in Africa: a perspective

Soil carbon and soil type

It is clear from the earlier text on soil-forming factors and soil processes that organic carbon content will vary according to the type of soil. Histosols in Africa (by definition soils rich in organic matter – see page 54) can contain close to 100 kg C m^{-2}, while Gypsisols (a desert soil containing high levels of gypsum and found only in very arid climates – see page 54) typically contain only around 1 kg C m^{-2}.

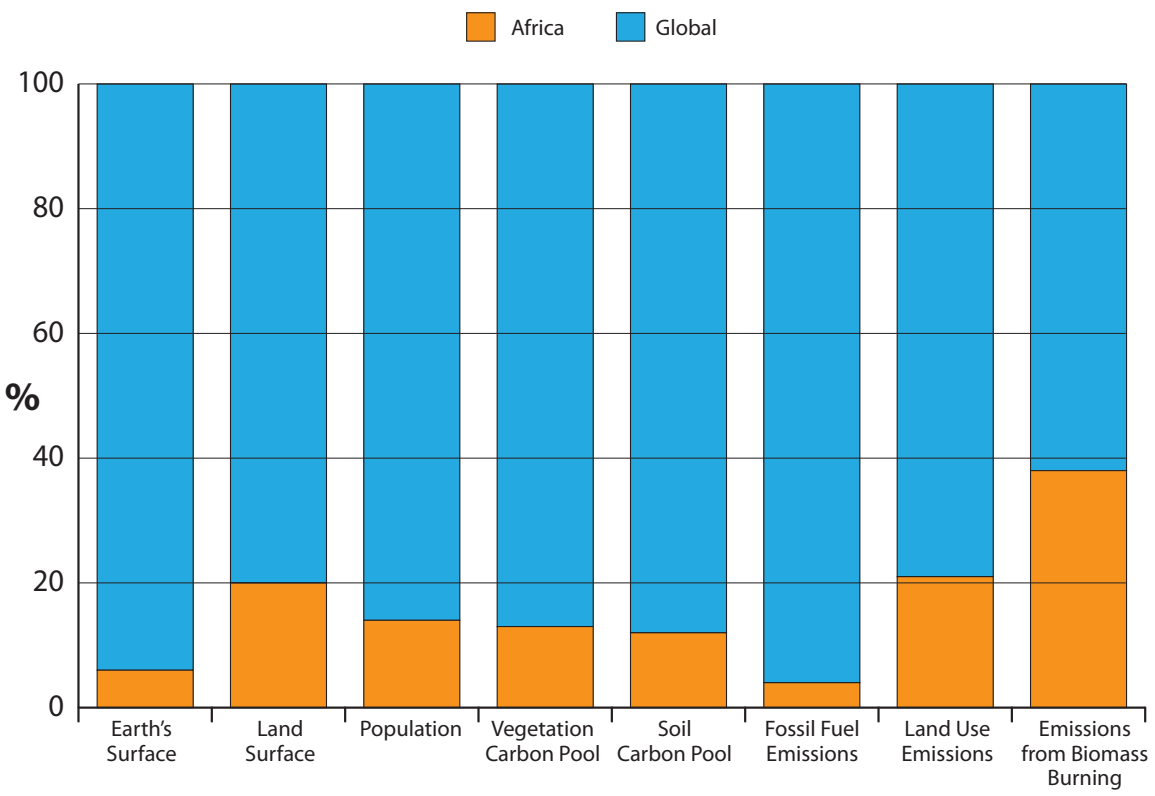
In addition, SOC varies with depth and soil type. In Leptosols (shallow soils over hard rock or gravel – see page 55) virtually all of the SOC is located in the 0–30 cm layer. In contrast, Histosols (organic soils also known as peat) can be several metres thick.

Soil carbon and ecosystems

The relationship between soil carbon content and ecosystems shows some interesting features. Using the Terrestrial Ecoregions of the World database of the World Wide Fund for Nature as a base, the soils with the highest mean SOC content, as expected, are found in the wet mangrove ecosystem with a mean carbon content of 6.61 kg m^{-2}. Similarly, there is no surprise that the deserts and dry shrublands ecosystem exhibits the lowest carbon content with only 1.53 kg m^{-2}, reflecting the limited biomass production and poorly developed soils of arid regions. Higher net primary production in tropical regions, coupled with deep soils, give very high carbon content to the soils of tropical and subtropical moist broadleaf forests (5.7 kg m^{-2}). Soils in tropical and subtropical dry broadleaf forests (5.0 kg m^{-2}) and flooded grasslands and savannahs (4.17 kg m^{-2}) also contain significant levels of SOC while levels are significantly lower in mediterranean forests, woodlands and scrub (2.83 kg m^{-2}) and montane grasslands and shrublands (3.47 kg m^{-2}) [46].

However, total SOC stocks also depend on the geographical extent of a soil. In this context, the graph below demonstrates that the most important stock of soil carbon to a depth of 1 m is stored in the tropical and subtropical grasslands, savannahs and shrubland ecosystems, holding around 80 000 Tg C*. Due to their small extent, the temperate conifer forests and mangrove ecosystems contain relatively low C stocks. Further investigation of the distribution of carbon within soil shows that in all ecosystems, SOC is concentrated in the topsoil. The slightly higher values in the subsoils of flooded grasslands and tropical moist broadleaved forests may reflect conditions that facilitate the leaching of carbon deeper into the soil (however, the reader should note that the values for the subsoil relate to more than twice the depth of the topsoil). These figures demonstrate that the topsoil is the most important SOC pool, yet it is also the most susceptible to manipulation by human activities and climatic variations which, together or singularly, can lead to the loss of soil carbon and degraded soils.

* Tg = a teragram, 10^{12} grams equivalent to 1 million (10^6) tonnes (megatonne) or 1 billion (10^9) kilograms



A global perspective of Africa with regard to carbon. For comparison, the soils of the northern circumpolar regions (i.e. above a latitude of 50° North) contain about 25% of the global terrestrial vegetation carbon and approximately 50% of the terrestrial soil carbon pool. It should be noted that data for African pools and sinks are very imprecise and that the uncertainties associated with these values can be very large. (JRC) [Emission data 43, 47]

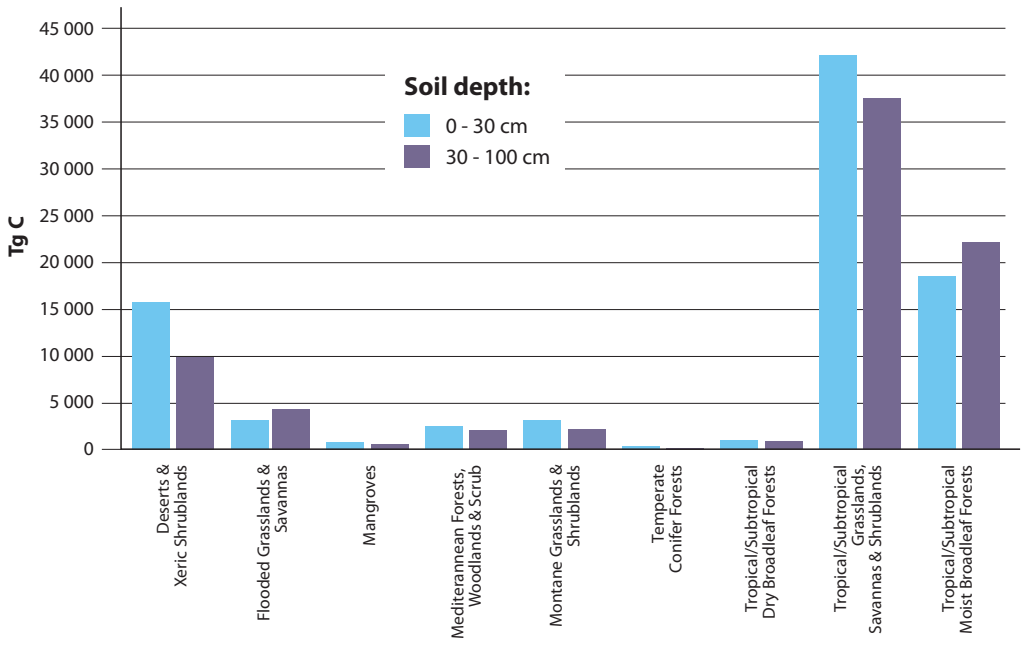
A profile of a Phaeozem from Tanzania – a soil that develops under natural grasslands in sub-tropical/sub-temperate climates. There is enough rainfall to support the vegetation and the organisms that drive the decomposition process. Soils, especially topsoils, that are rich in organic matter appear dark in colour and will show a gradual lightening with depth – very evident in this photograph. Dark-coloured soils absorb heat, warm up more rapidly and cool down less rapidly. Plants such as grasses contribute to soil organic matter through their extensive fibrous root mats and, to a lesser extent, litter fall on the surface. Over time, soil under grasslands, such as this Phaeozem or Kastanozems and Chernozems, can accumulate large amounts of soil organic matter. The conversion of natural grasslands to agricultural use causes considerable losses of organic matter. (SH)

The soils of Africa in the global carbon cycle

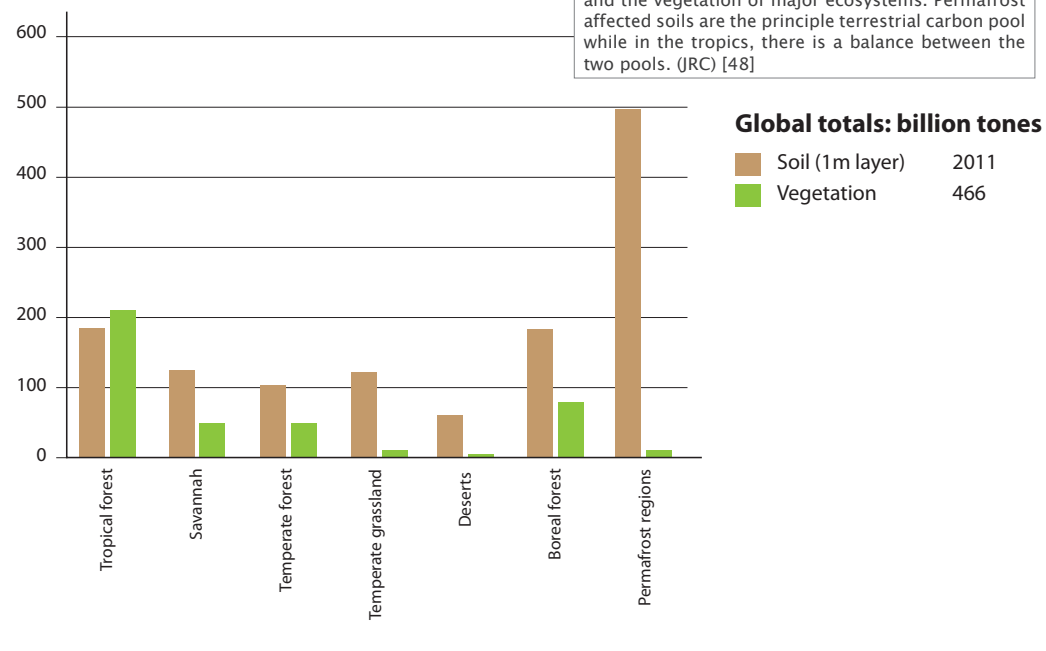
The graph above presents a global view of Africa from a carbon perspective. While occupying 20% of the Earth's land surface and being home to 14% of the world's population, Africa contributes only 4% of the global fossil fuel carbon emissions that are responsible for rising atmospheric carbon dioxide concentrations (0.2 Pg C yr^{-1}). This is a disproportionately small fraction but reflects the rural and under-developed nature of the African population. However, Africa generates more than one-fifth of the global emissions from land use (i.e. deforestation and land use change) and, staggeringly, nearly 40% of global emissions from burning biomass (i.e. deforestation, shifting cultivation, savannah fires, fuel wood, agricultural residues, etc.). Both the vegetation and the soils of Africa occupy a similar global proportion, about 13% and 10-12%, respectively. [47, 47a]

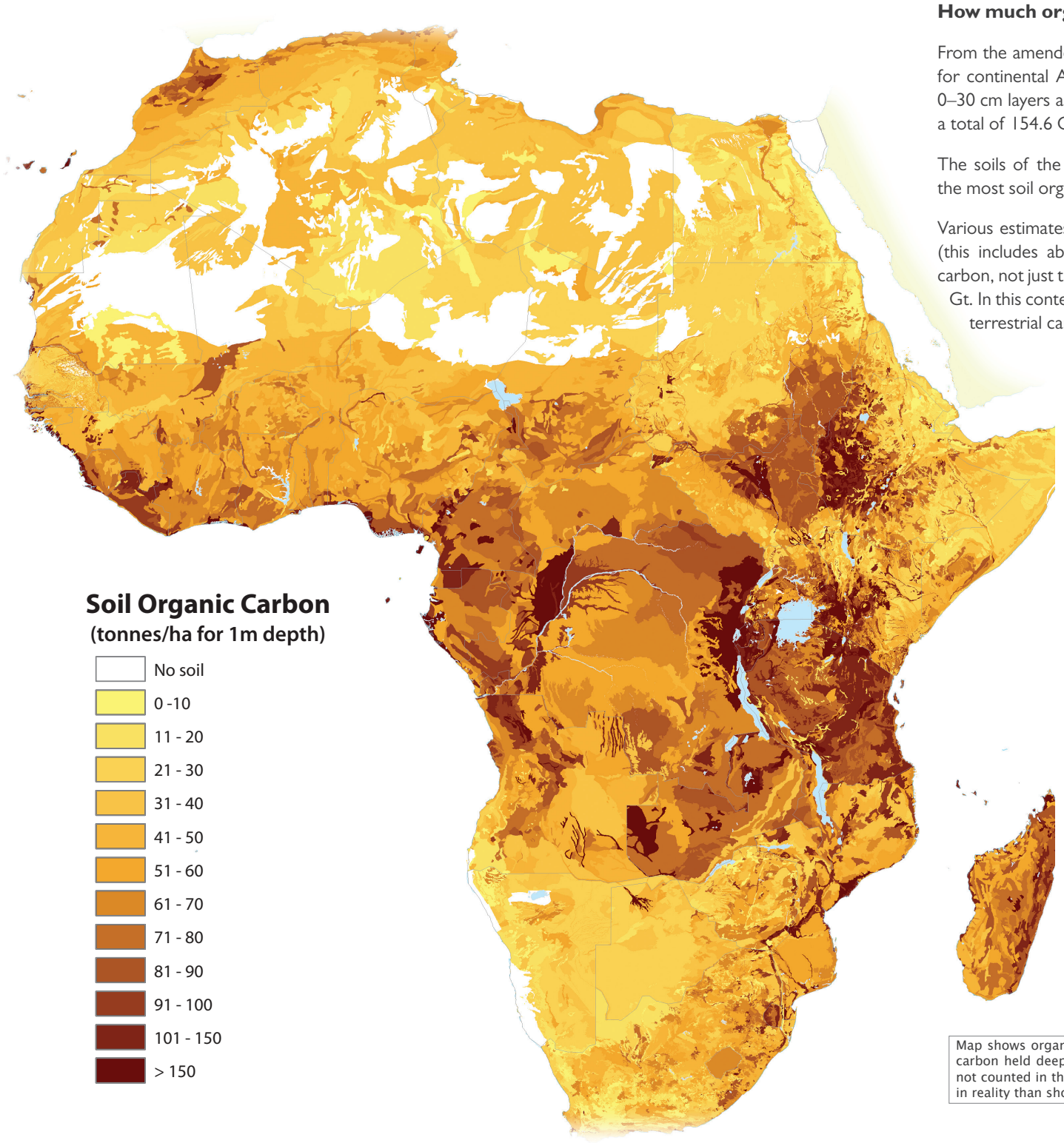
The graph below shows the amount of carbon stored in the soil (to a depth of 1 metre) and vegetation of the main ecosystems of the planet. The figure clearly illustrates the huge capacity of soil to store carbon compared to vegetation and emphasises the key role that soil plays in the terrestrial global carbon cycle. The only ecosystem approaching parity between carbon stores in vegetation and the soil is the tropical forest. This is due to the lush and continuously growing vegetation and the rapid recycling of litter and plant remains into the soil. However, the graph also shows clearly that the main reservoirs of global land-based carbon are the cold permafrost regions and ecosystems such as the boreal forests.

Topsoil and subsoil organic carbon stocks in major African ecosystems. (JRC) [46]



A comparison of organic carbon pools in the soil and the vegetation of major ecosystems. Permafrost affected soils are the principle terrestrial carbon pool while in the tropics, there is a balance between the two pools. (JRC) [48]





Map shows organic carbon in the uppermost 100 cm of soil. Organic carbon held deeper than 100 cm (e.g. deep peats, estuaries, etc) are not counted in this exercise. Consequently, there is more soil carbon in reality than shown by this map. (JRC/RHR) [49]

How much organic carbon is there in the soil of Africa?

From the amended version of the HWSD [49], soil carbon stocks for continental Africa have been calculated as 80.1 Gt C for the 0–30 cm layers and 74.5 Gt C for the depth 30–100 cm (this gives a total of 154.6 Gt C for 0–100 cm depth).

The soils of the Democratic Republic of Congo and Sudan hold the most soil organic carbon with 19.11 and 12.65 Gt respectively.

Various estimates place the total terrestrial carbon pool of Africa (this includes above ground vegetation and also all soil organic carbon, not just that in the upper 1 m) at between 250 000–280 000 Gt. In this context, soil holds between 55-70% of the total African terrestrial carbon pool.

The map on this page represents the distribution of soil organic carbon densities in Africa to a depth of 100 cm from the surface in tonnes C per hectare (t C ha^{-1}) with a resolution of 3 arc seconds. The calculations are based on data from an amended version of the Harmonized World Soil Database (see page 136).

The colours on the map correspond to the amount of organic carbon in the soil. Lighter tones indicate the lowest concentrations of organic carbon while darker tones indicate higher amounts. SOC varies according to temperature, moisture, local soil conditions and land use. Four main zones stand out: the very low arid regions, temperate grasslands, tropical forests and grasslands and wetlands. The maximum SOC densities were found in Rwanda (214.6 t C ha^{-1}) and Burundi (166.7 t C ha^{-1}) while the minimum SOC densities were found in arid Djibouti (15.1 t C ha^{-1}) and Mauritania (20.3 t C ha^{-1}). The average SOC content is 35.08 and 31.83 t ha^{-1} for the 0–30 cm and 30–100 cm soil layers, respectively. [49]

Most of the carbon stock of the continent is located in central Africa. Levels for much of northern and southern Africa are relatively low.

The reader should note that there are uncertainties in any estimate of soil carbon stocks at national and continental scales and the uncertainty of the information presented here is high. More confidence can be attached to information from regions with more detailed soil inventories (the Mediterranean parts of North Africa, South Africa and parts of Eastern Africa).

Significant additional effort would be required to improve the estimates and spatial resolution of the soil biophysical properties and the impact of human activities.

Abrupt boundaries in the map may reflect disparate soil datasets.

In the tropics, looks can be deceptive!

With no winters or frosts to kill insects or microorganisms, and constant heat and humidity to drive decomposition, organic carbon levels are generally low in most mineral forest soils of the tropics. Iron oxides (hematite) tend to dominate giving soils a reddish appearance. However, both of the soils shown in the photographs **below**, from Ghana, have as much organic carbon (about 14 kg C per m^2) as a temperate grassland in Denmark. In these cases, the organic matter has been stained red by the iron. (TB)

Soil and the hydrological cycle

Water is essential for the survival of almost all living organisms and soil plays a key role in the global hydrological cycle. Most of the rain falling in Africa is intercepted by vegetation or falls directly onto the soil surface. Once the leaves and branches have been moistened, any excess water drips from the canopy or runs down stems and trunks to the soil. Depending on factors such as soil moisture status, texture, organic matter content, soil structure, precipitation intensity and duration, rainwater may:

- soak into the soil body where it may be stored for plants to use;
- percolate downwards through the soil to recharge the water table or aquifers;
- flow horizontally or laterally through the soil to feed rivers, lakes or springs;
- be intercepted by roots growing through the soil.

The movement of water into the soil from the surface is known as infiltration, while the passage of water through the soil is referred to as percolation. Coarse textured soils such as sands and gravel usually have high infiltration rates. When precipitation rates exceed infiltration capacity (due to either prolongued or intense rainfall), or if the soil is full of water (saturated) or crusted (after dry conditions) or there is a subsurface impediment to drainage, water may run over the soil surface as runoff or overland flow, often directly into streams and rivers – this process is also a significant type of soil erosion (see page 155).

As water infiltrates into the soil, water in larger pore spaces and channels will move to lower levels under the force of gravity. In addition, capillary forces can bind water to soil and organic matter particles and even pull it through very small pore spaces, even against the force of gravity. If the volume of water entering the soil is small, then the moisture may only be attached to the surface of particles and the spaces will be empty. In hot climates, evaporation can move water towards the surface.

When a soil is saturated, all soil pores are filled with water and virtually all of the air in the soil has been displaced by water.

Depending on the soil characteristics, water may take several days to drain through the soil profile although some water can be absorbed by roots. Field capacity is defined as the level of soil moisture left in the soil after the removal or drainage of water from saturated conditions (48 hours after saturation).

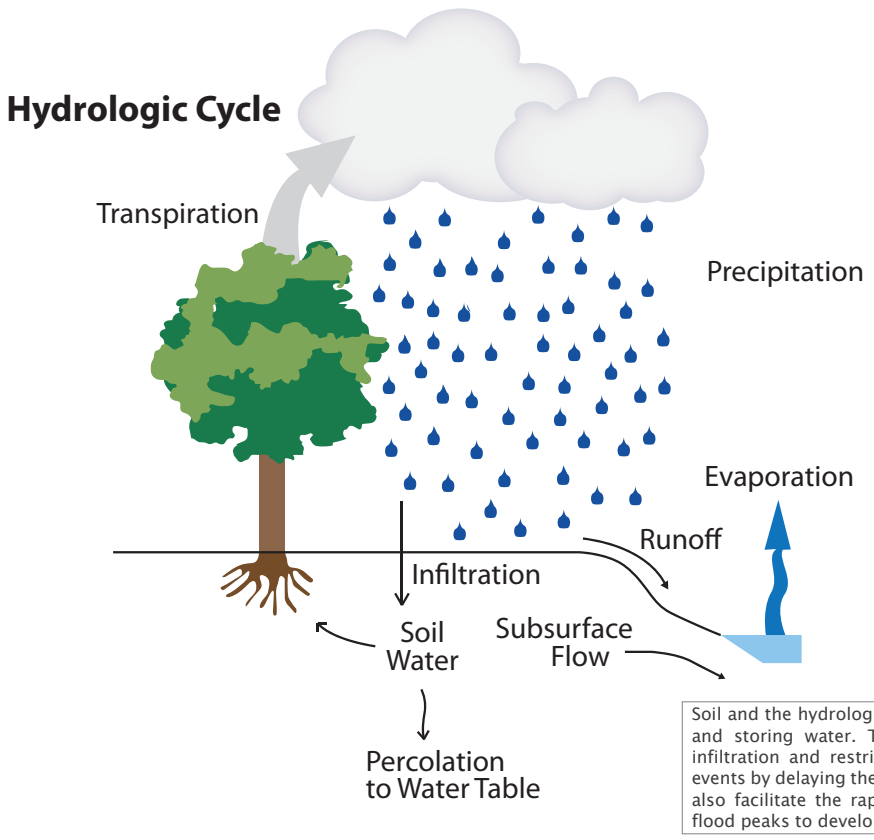
The wilting point is defined as the soil moisture content where most plant roots cannot exert enough force to remove water from small pores in the soil. Most crops will be damaged if the soil moisture content is allowed to reach the wilting point.

Understanding soil hydrological processes is important for cultivation, flood prevention and erosion control. Soils with very dry moisture regimes require irrigation to be used for crops. Soils in semi-arid moisture regimes can support rain-fed crops, but moisture will be limited during some of the growing season and some irrigation may be required. Soils in humid climates have sufficient moisture for crops without the need for irrigation. Very wet soils will require artificial drainage for most crop growing practices.

The general patterns of soil moisture across Africa are displayed on the map on page 18. Most of central and southeast Africa have moist soils all year round as rainfall is greater than evapo-transpiration rates. The soils of the savannah regions are generally dry in the summer months with a single, distinct wet season. A large part of the continent is desert, where soils are dry for significant periods. In the Mediterranean coastal zone and around the Cape of Good Hope, soils are generally moist in winter but dry in summer.

The Sahel

The Sahel is the climatic and biogeographic zone of transition between the southern extent of the Sahara desert and the less arid savannah. It stretches across the entire African continent between the Atlantic Ocean and the Red Sea. The word literally means "shore“ in Arabic as it describes the appearance of the vegetation as a coastline delimiting the barrenness of the desert. The Sahel includes parts of Senegal, southern Mauritania, Mali, Burkina Faso, southern Algeria, Niger, northern Nigeria, Chad, northern Cameroon, Sudan, Southern Sudan and Eritrea.



Soil and the hydrological cycle. Soil acts like a giant sponge absorbing and storing water. The sealing of soil by artificial surfaces limits infiltration and restricts the ability of soil to mitigate against flood events by delaying the arrival of water to river channels. Sealed surfaces also facilitate the rapid transport of water to river systems, causing flood peaks to develop sooner. (CSS)

These two profiles illustrate contrasting soil moisture conditions on hillslopes in the Weatherley catchment of the Eastern Cape Province of South Africa. The top profile is freely draining, well aerated and lying at the top of the slope. Excess water drains to the underlying rock and recharges the regional water tables. The lower profile shows a typical low-lying, saturated wetland soil where the water table is visible. (PLR)

How do plants take water from soil?

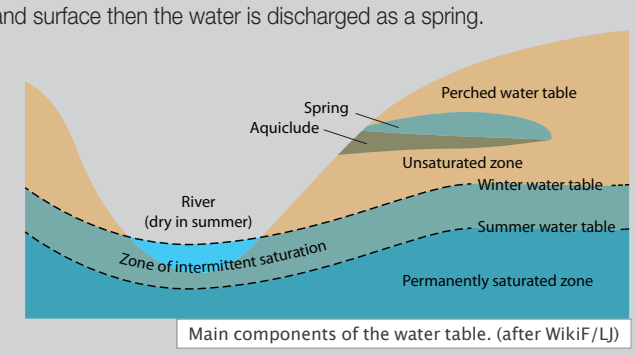
Plants can use only the water that is in direct contact with their roots. For most crops in a deep uniform soil, the root distribution is concentrated near the soil surface. Plants such as grasses, with a high root density per unit volume of soil, may be able to absorb all available soil water. Conversely, vegetables, with a low root density, may not be able to obtain as much water from an equal volume of the same soil. As a result, vegetables are generally more sensitive to water stress than high root density agronomic crops such as corn, wheat and sunflowers. Over the course of a growing season, plants generally extract more water from the upper part of their root zone than from the lower part.

Water table, springs and watering holes

An important feature of the African landscape, especially in climates with low rainfall or distinct rainy seasons, are watering holes. Such features are important in supporting natural wildlife and grazing animals such as cows or goats.

Elephants at a watering hole in South Africa. (MF)

Watering holes are depressions in the ground where water held by the soil comes to the surface. The upper limit or surface where the soil is saturated with water is known as the water table. The position of the water table reflects the surface relief but may vary due to topography, soil type and seasonal changes in precipitation or evapotranspiration. Springs, rivers, lakes and oases occur when the water table reaches the surface. Perched water tables occur above the regional water table when an impermeable barrier (aquiclude) prevents the downward flow of water through the ground. If a perched aquifer's flow intersects the land surface then the water is discharged as a spring.



Main components of the water table. (after WikiF/LJ)

Soil biodiversity

Soil is sometimes referred to as a biomantle, emphasising the fact that soil is a product, to a large extent, of biological activity. The majority of the vital soil functions described in the previous pages depend on the diversity of life that exists within it – soil biodiversity – ranging from genes and species to communities of organisms [50, 50a].

- A single teaspoon of fertile soil may contain thousands of species, millions of individuals and hundreds of metres of fungal networks.
- Scientists estimate that at least about one-quarter of species on planet Earth live in soils.

African soils contain an extraordinary range of taxa and species with varying body sizes, populations and activity. Some animals that lack size often make up for it in numbers. Soil may benefit animals in a variety of ways. It provides shelter, a breeding ground, waste dump, source of food (animal and vegetable), dietary supplement (geophagy) and means of hygiene (dust and mud baths). In their use of soil, animals can change its characteristics. The mixing of soil particles (bioturbation), decomposition of organic matter and nutrient cycling are heavily dependent on biological activity.

By burrowing and nesting, animals such as termites, ants, earthworms, moles, rodents, mongoose, birds and even large herbivores, mix and aerate soil layers. They create passages that aid the infiltration of rain and hasten the recycling and mineralisation of nutrients, both by direct digestion, and by disturbing litter. In fact, many creatures bring organic matter from the surface and deposit it deep in the soil. The consequences for soil porosity, aeration, water storage, drainage, bulk density, erodibility and nutrient status are profoundly important, both ecologically and economically. Indeed, thriving populations of invertebrates and microorganisms are regarded as a cornerstone of soil health.

In turn, soil fauna depend for their energy and nutrients on plants which in turn depend on soils in the first place. Both the aardvark and fungus-culturing termites (which make large earth mounds) could be regarded as 'ecosystem engineers.' For example, the aardvark is powerful enough to generate a surplus of deep burrows which in turn promotes warthog populations by providing protection from predators and allows these pigs to survive as both large herbivores and important soil excavators in their own right.

Similarly, fungus-culturing termites build and maintain large and sophisticated arrangements of chimneys and chambers to ensure oxygenation and humidity in their fungus cultures, which not only provides living space for many animals such as the dwarf mongoose (*Helogale parvula*) and the giant land lizard (*Varanus albigularis/exanthematicus*) but also modifies soil fertility to such a degree that some regard it as 'farming' by an insect.

One possible explanation for the extreme expression of soil fauna in Africa is a combination of switch effects and synergy. Subtle variations in the availability of critical catalytic nutrients can be amplified by ecological feedback loops and tipping points that culminate in categorical changes in the fauna.

Understanding soil biology relationships can have enormous practical significance. In the rehabilitation of land destroyed by strip mining, the most difficult problem is to find ways of alleviating soil compaction. Restoration is doomed to failure if attention is devoted to revegetation at the expense of finding ways to repopulate the soil with a self-sustaining array of animals - large and small. In agriculture, the current drive to pursue conservation farming methods requires that similar attention be given to achieving a healthy population of organisms capable of effecting bio-tillage.

While soil biota may be out of sight (and possibly out of mind?), taking steps to protect them may be doubly useful as efforts to protect soil communities are very likely to help conserve better-known endangered plants and animals that live above-ground. [50]

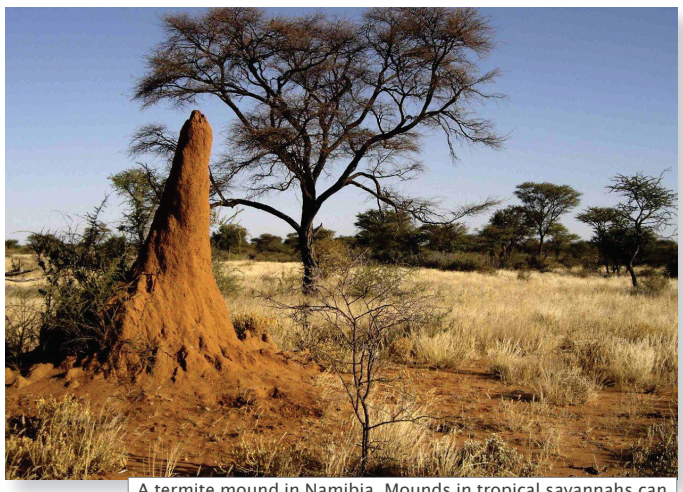
An aardvark (*Orycteropus afer*) in the Mapungubwe National Park, South Africa. The aardvark is a burrowing, nocturnal mammal that is native to Sub–Saharan Africa. They feed almost exclusively on ants and termites and can be regarded as the top of the soil food chain. Some researchers have estimated that one aardvark can consume up to 50 000 ants in one night. In addition to living in the soil, their old burrows are used by other mammals. (SC)

Termites and Soils

Termites are a group of soil-living, social insects, taxonomically known as *Termitoidae*, of the cockroach order Blattodea.

While there are similarities, termites are only distantly related to the ants. Many species of termites occur in Africa, ranging from the soil-feeding and mound building Cubitermes to the litter-feeding Macrotermes. As their diet consists of organic material mixed with clay minerals, termites play an important role in soil formation and nutrient recycling. They are soil miners and soil architects, building impressive mounds in all sizes and shapes with soil they extract from great depths. Termite mounds are a common sight in the landscapes of Africa.

- termites are a major source of income and protein for many rural households, where they are consumed during the rainy season;
- in savannah areas, the soils of termite mounds are used to increase soil fertility as levels of P, K, Ca, Mg and organic C are usually higher in the centre of mounds than in the adjacent soil;
- termite mounds are used for brick making as the soil tends be clay-rich. Termites build their mounds by bringing up clay particles from the subsoil to the surface and then bind them together by secreting a natural glue-like substance from their saliva;
- termite mounds are often inspected during geochemical prospecting for various metal ore deposits such as tin, silver, gold, uranium and diamonds. Termites can go to considerable depths to obtain moist soil to build their mounds and as such may bring up small samples of minerals.



A termite mound in Namibia. Mounds in tropical savannahs can be very large, some up to 9 m high. In drier savannahs, two to three metres is more typical. The shape of the mound can be indicative of the termite species (but not always!). (AM)

Above: The giant African millipede (*Archispirostreptus gigas*) can grow up to 40 cm in length and have more than 200 legs. It is widespread in lowland parts of East Africa, and rarely recorded above 1 000 m. While millipedes and other invertebrates are critical to many soil functions, our knowledge of soil biodiversity in tropical Africa is very limited. (BCT)

Below: a striking example of the relationships between above and below ground biodiversity. Organic matter (in the form of bird excrement) dropping from the nests of weaver birds in Namibia provides just enough nutrients to support initial soil development and microbial communities in an otherwise semi–arid environment. (EM)

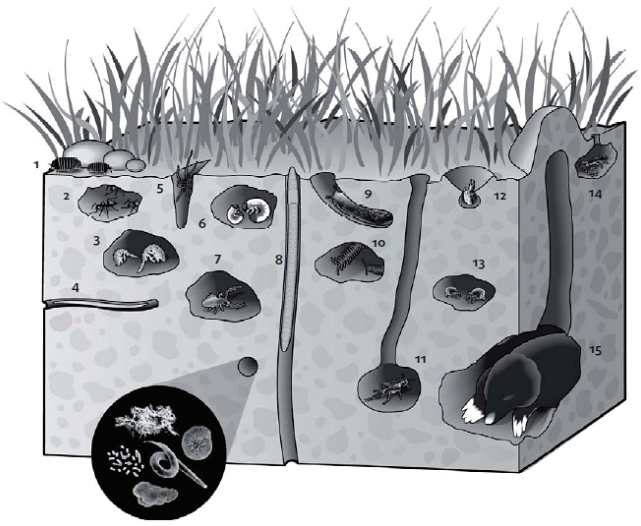
The Debe Hollows: a unique soil

The soils of the Kommetjie Veldt (Afrikaans for small cup; known as Malinda in Xhosa or Debe Hollows in English) are unique in Africa, if not globally. In an area of about 1 000 km^2 in the Eastern Cape Province of South Africa, the land surface is characterised by a surface micro-topography of mounds 60 cm to 80 cm high, with mixed soil horizons, subsoil mottling and lintwhite formation. Their origin is due to the activity of the giant African earthworm (*Microchaetus microchaetus*) which can grow to about 14 mm in diameter and over 6 m long! This is a clear example of a living organism being the dominant soil-forming factor.

Soil water conditions must be ideal for the earthworms to grow to this size. Mounds are raised above the water table and serve as their habitat during subsoil saturation. South-facing slopes generally have more earthworm activity as they are wetter and cooler. The casts of earthworms are more fertile than the surrounding soil, containing more phosphorus, calcium and much more exchangeable manganese (Mn). That implies that Mn is reduced in the earthworm gut and this process plays an important role in the formation of soil mottles and manganise-rich concretions. [51, 51a]

Debe Hollows near Dimbaza, Eastern Cape, South Africa. The hummocky landscape in the middle ground is due to the churning of the soil by the giant African earthworm. (TD)

A giant African earthworm *(Microchaetus microchaetus)* from the Eastern Cape Province, South Africa. (AM)



Workers in the factory of life come under the microscope: bacteria, nematoide, fungal mycelium, protozoans

1. Woodlice
2. Ants
3. Springtails
4. Under soil earthworm
5. Spider
6. Cockchafer larvae
7. Pseudoscorpion
8. Deep burrowing earthworm
9. Slug
10. Myriapods
11. Field cricket
12. Ant-lion larva
13. Mites
14. Common earwig
15. Mole

There's not only life on Earth, but in it as well. The diagram **above** shows some examples of life in the soil and their habitats. The amount of living matter contained in soil makes it the original renewable energy source. Some people refer to soil as the factory of life. (EC/LJ) [50]

Cultural heritage and trade

Preservation of cultural heritage and landscapes

Soil stores and protects much of our cultural heritage, including archaeological remains and landscapes. The soils of Africa are full of heritage [52]. Over long periods of time, indigenous communities have moved across the landscape, making use of its resources and by their activities modifying the environment. These communities have left signs and products of their activities across the continent, buried in the soil, sometimes in great numbers. There are many examples where objects preserved in soil have been used to understand history, often when no other evidence remains. The remains of dwellings can be identified from the outlines of ditches and postholes in soil through variations in texture and colour, charcoal from hearths can be dated while the remains of animal bones, settlement debris and plant remains can give an insight into past environments. A glimpse into society and beliefs can be obtained by investigating burial practices, grave artefacts and fragments of pottery or art. This last aspect is especially evident along the Nile Valley, in the Horn of Africa and along the North African coast.

Soil characteristics are critical in determining the preservation of an object. Being of organic origin, wood normally decays under combined biological and chemical attack when buried in the ground or submerged in water. However, it can survive for very prolonged periods in either a very dry or a completely waterlogged environment. In the same manner, organic matter decomposes much more rapidly in well-drained soils where well-preserved organic remains are usually scarce. In contrast, metal objects survive better in aerated conditions leading to the preservation of metal weapons, ornaments, jewellery and coins. Acid soils are rather aggressive in decomposing artefacts, especially iron. Pottery, ceramics and glass tend to survive in most soil conditions.

In addition, soil conditions often shape distinctive habitats or, together with specific land management practices, produce specific habitats and characteristic landscapes that are valued by society at large. For example, the wetlands of the Okavango and the open grassland and distinctive acacia tree of the Masai Mara are products of specific soil-climate interactions in the same manner as the tropical rain forests and oases in the deserts. Fertile soils give rise to agricultural landscapes such as the vineyards of South Africa or the olive groves of the Mediterranean. It should be remembered that the location of most urban sites were selected because they also provided a stable food supply to their resident populations.

It is important that soils with high or potential cultural heritage aspects are managed in a manner that preserves these features. Cultivation practices should be controlled, for example, by avoiding deep ploughing if archaeological remains are in the topsoil. Similarly, the risk of erosion, acidity/alkalinity levels and desiccation should be controlled if possible. Cultural 'erosion' of such traditional knowledge about soil is still responsible for the loss of a significant number of languages and their unique information, knowledge and conceptual systems about humans and nature, often acquired through experiential and insight learning.

An elephant in the Akagera National Park in eastern Rwanda. Tourism is a significant aspect of the economy of several African countries (e.g. Botswana, Kenya, Tanzania). The habitats that support the animal populations are heavily dependent on specific soil characteristics to support the vegetation and associated food chain. (AL)

Soil and culture: a traditional perspective

From a traditional perspective, land is considered as a sacred heritage, which needs care during its use and management. It is perceived as a lively environmental body, which represents the beginning and the end of life. Traditional communities see land as an asset and spiritual environment, which merits a lot of respect and attention as food and water provider. Land perception is part of a cosmogony and a cosmos vision developed by traditional communities such as the Dogon people in Mali. Its use is subject to rituals (for example, in the Sourou region in Burkina Faso and the mountainous areas of Lesotho).

Land is also an expression of power, strength and security for a given community. In most land tenure systems, common land represents open areas. However, freedom of land use fits within traditional systems of 'taboos' in conformity with unwritten rules.

Traditional or indigenous knowledge about land resources is "local knowledge that is unique to a given culture or society" and is based on careful observation and use of the societal resources. This local knowledge is the basis for the development of diverse ingenious natural resource management heritage systems throughout the continent.

Examples of cultural heritage and land management include:

- Floodplain recession management (e.g. Senegal, Niger and Sokoto rivers);
- Traditional Masai rangeland management systems in Kenya, providing scenic beauty and wildlife diversity with immense recreational value;
- Oases in deserts where spring water and irrigation sustain social services and an agro-ecosystem;
- The sophisticated land use system of the Konso (Ethiopia) which allows them to subsist in a mountainous area with fragile soils and erratic rainfall;
- Traditional sand dune management in the Sahel region that supports agricultural production through the use of a low soil disturbance tool (iler) and the improvement of soils with domestic waste and organic manure.

Archaeological excavations in Cameroon. Recent studies have led to the discovery of thousands of historical sites and archaeological remains hitherto unknown or inaccessible. Here, more than 400 arrow tips and iron spears dating from the eighteenth century have been unearthed in a Ferralsol near to the town of Kribi (RO/IRD)

Soils and trade

It is difficult to over emphasise the importance of soil for the economy of Africa as about two-thirds of Africans depend on agriculture or trade in agricultural products for their livelihoods. The fate of agricultural production is largely determined by the condition of the soils, therefore, soil directly affects economic growth, social improvement and trade in Africa. For instance, the famous wine producers of South Africa focus on identifying sites with soils developed from granite, table mountain sandstone and shale in order to produce grapes with the necessary character and complexity.

The impact of trade on the management of soils is varied but unfortunately often results in soil depletion and degradation. The demand for 'raw materials' (e.g. iron, diamonds, gold, phosphates, coal, uranium, etc.) is a major cause of soil losses in many African states, either from mining activities or contamination. Trade in agricultural products, - often a major feature of structural adjustment policies – has led to an increase in the area devoted to export crops. In many cases, the impacts have been significant and harmful to soil quality. A study in Mali, for example, found that the development of cotton as a cash export crop substantially increased the cultivated area and affected soils through a markedly reduced fallow period. The profitability of cotton, cocoa, coffee, tea and other crops led farmers to expand cultivation onto marginal land, resulting in increased land degradation and soil erosion. On the other hand, export crops may sometimes be more soil-friendly than the domestic crops they replace. In parts of eastern and western Africa, tree crops such as coffee and cocoa have helped to prevent erosion by stabilising soils. Horticulture provides a high-value export and is claimed to have limited effects on soil quality, although concerns have recently been raised about the health of workers and the environmental effects of the inappropriate use of pesticides.

The resulting depletion of nutrients from soils has caused agriculture production to stagnate or decline in many African countries. In some cases, notably in the East African highlands, the rate of depletion is so high that even drastic measures, such as doubling the application of fertiliser or manure or halving erosion losses, would not be enough to offset nutrient deficits. If nutrient depletion and land degradation continue at current rates, one has to wonder how farmers in African countries will be able to produce enough crops to trade and to provide food for ever-larger populations. Unless African governments take the lead in confronting the problems of nutrient depletion, deteriorating agricultural productivity will seriously undermine the foundations of trade in Africa.

The dumping of industrial wastes is another hazard for African soils. From statistical indications, the protocol of the Basel Convention has failed to protect African soils and its people against the crime of illegal hazardous dumping by some unscrupulous industrial operations. For example, in 2006, 500 tonnes of toxic wastes were dumped in the soils of the Côte D'Ivoire; in 1992, 10 million tones of toxic waste were disposed of in Somalia; in 1989, 15 000 tonnes of pharmaceutical waste were dumped in Guinea-Bissau; many other events have not been recorded.

Examples of preservation of cultural heritage by soil. **Top left**: Olive trees being cultivated in bunded enclosures in an ephemeral channel in Tunisia. Olive cultivation has been carried out in North Africa for several thousand years and is an important cultural aspect of the region. The bunds harvest runoff and irrigation water during the dry season. In addition, fine particles of nutrient-rich eroded soil are captured by these micro-dams thus enhancing the fertility of the land. (TG); **Middle left**: the Pyramids of Meroe in Sudan, an ancient city on the east bank of the Nile approximately 200 km north-east of Khartoum. Built approximately 2 500 -3 000 years ago, writing tablets, statutes and pottery have been preserved in the dry sandy soils (FD); **Bottom left**: soil conditions and land management practices often shape distinctive habitats or landscapes such as this terracing system in the highlands of Malawi. (MAP)

Soil as a source of raw materials

In Africa, soil has been used as a raw material for making, producing and manufacturing various goods and services for thousands of years. In many places, these practices continue to this day. The main uses include:

Construction

Various types of houses are built by using soil as a construction material. Soil is used for roofing and thatching houses in arid and semi-arid areas of Africa where other thatching material is unavailable. Houses with soil or green roofs are heat and cold absorbers and make the dwellings more comfortable to live in.

Clay is used to make bricks of different sizes, colours and shapes. Clay roofing has been used as roofing and thatching material for a very long time. Bricks made of clay are used for walls in modern and as well as ancient buildings. The Great Mosque of Djenné (Mali) is the largest mud brick or adobe building in the world and is considered by many to be one of the architectural wonders of the world (see page 11). Brick-walled houses are very strong and again absorb heat and cold. Brick-walled houses are also durable, provided that timely maintenance is carried out. Some of the soil types used for different housing include plinthite as bricks for building houses, loamy to clay soils for plastering straw houses while sand is used for mixing with cement for rendering, mortar and concrete making. Most dwellings in rural areas are plastered with soils mixed with crop straw to make it resistant to cracking.

Soils also provide major building material in road construction. Pisolithic gravel is used widely for roads and air strips. Rocky soil is used as final fill in roads, in most cases the outer cover of dam walls is made from sandy loam soils while the cores of dam walls are often made from Vertisols or other soils containing swelling clays.

Finally, many roads in rural Africa are unsurfaced with vehicles being driven on the soil surface. In wet conditions, traffic can cause the surface to deteriorate, making the road impassable.

Utensils

Many rural inhabitants throughout Africa use clay, especially kaolinitie, to make a variety of pots, cups, kettles and pans. In fact, earthenware is one of the oldest materials produced by humans. While less strong, less durable and more porous than stoneware, earthenware is also less expensive to produce and much easier to work. Due to its higher porosity, earthenware containers must usually be glazed or baked in order to be watertight. Soils with very high kaolinite clay contents are thus seen as a valuable local resource. Many kinds of food and drink are prepared using such utensils while earthenware jars are used to store grain for brewing beer. While red earthenware made from red clays is very familiar, other colours can be found depending on the chemistry of the clay. Some communities make drinking glasses from sandy soil while sand-filled containers are used for cooling food or drinks. Bags filled with sand are often used to slow the thawing of frozen items.

Household furniture

In many African rural areas, beds, seats, benches and cupboards are constructed of soils. Crop residues and/or hay are mixed with soil and water in a large pit to make it strong and increase its plasticity. The more plastic the mud the stronger it becomes. The objects are then shaped by hand or in moulds as required.

Ornaments and ritual/spiritual objects

Soil is used to make ornamental or decorative objects. Cosmetics for painting faces are usually soil-based. Soil-made items are used for celebrating traditional beliefs and also serve as objects of worship.

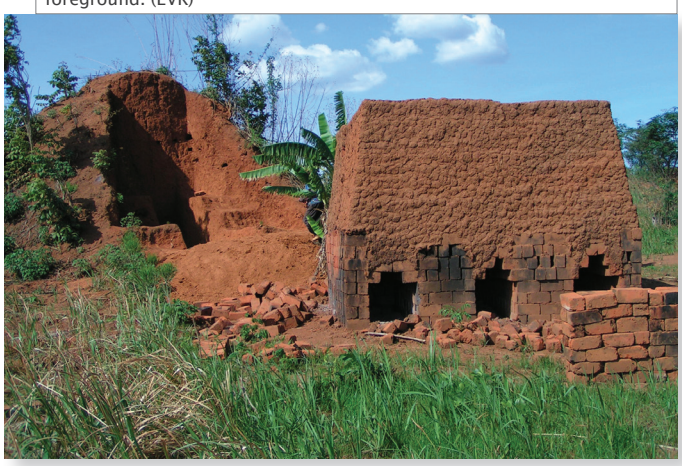
Recreation

Topsoil is used for levelling and filling gardens and lawns while sport turf is grown on selected soil types. Coarse sand is used for building golf greens and sand 'hazards'. In Kenya and South Africa, Vertisols are used as “bully” in the construction of cricket pitches while Ferralsols or their equivalents are used for clay tennis courts.

Medicinal and food/nutrients

In some areas people eat clay soils as a medicine for treating diarrhoea and use them for treating skin diseases or ulcers. In some traditions (such as Uganda), pregnant women use clay from termite mounds as a source of minerals. Animals such as birds use sand to enhance digestion of food in their gizzards. Bentonite is used as a nutrient. Soil is also a source of salt for animals. Many antibiotics are based on soil fungi (e.g. *Penicillium notatum*).

Above: Houses bricks being made from a silt-rich soil (Planosol) in Ethiopia. The worker is simply digging out the topsoil and placing it in a mold. Houses made out of mud bricks with roofs made from woven branches can be built quickly and cheaply and exist in practically all cultures. (EVR); **Below**: An oven in D.R. Congo, built from and used to fire bricks made from clay-rich soil extracted from an adjacent termite mound (partially excavated in the background). Finished bricks are stacked in the foreground. (EVR)



Soil health

The underlying principles of “soil health” are that soil is not just a growing medium, rather it is a living, dynamic and ever-so-subtely changing environment. Analagous to human health, a healthy soil can be considered as :

- being in a balanced state of well-being in terms of biological, chemical and physical properties;
- not being diseased (i.e. not degraded, nor degrading), nor causing negative off-site impacts;
- functioning interactively with each of its qualities to reach its full potential and resist degradation;
- providing a full range of functions (especially nutrient, carbon and water cycling) and in such a way that it maintains this capacity into the future.

The term soil health is used to express the ability of a soil to:

- sustain plant and animal productivity and diversity;
- maintain or enhance water and air quality;
- support human health and habitation.

Different soils have different levels of health conditions depending on the inherited qualities and on the environmental settings. Soil health can be measured in terms of individual ecosystem services provided relative to a particular site. Specific aspects used to evaluate soil health include CO_2 release, humus levels, microbial activity and available calcium.

Factors adversely affecting soil health include issues such as deforestation, absence of soil cover, overgrazing, monocropping, inappropriate tillage, soil nutrient mining and pollution.

Good practices to maintain and/or improve soil health include permanent soil cover (conservation agriculture), integrated plant - animal production, crop rotation/association, controlled grazing, controlled carbon levels (relatively close to the limits set by soil type and climate), integrated nutrient management, maintenance of biological productivity (relatively close to the limits set by the soil environment), contour tillage and terracing to reduce erosion and a limitation/reduction on the level of contaminants.

A small banana farm in Cameroon with underplanting of secondary crops that benefit both the soil and the local community – an example of good practices for sustaining soil health. Such land management practices reduce soil degradation rates, increase the accumulation of soil carbon, maintain soil moisture, improve soil structure and provide a better habitat for the soil microorganisms. Healthy soils provide better environmental services, and benefit both agricultural and ecological systems. Other examples include the Konso controlled grazing system in Ethiopia, traditional integrated agro-ecosystem management in hilly areas of Kenya and the land protection system in Burkina Faso. (EM)

Soil assessment – Land evaluation

Land evaluation

Decisions on land use have always been part of the evolution of human society. In the past, land use changes often came about by gradual evolution, as the result of many separate decisions taken by individuals. In the more crowded and complex world of today, the use of the land is frequently dictated by government policies or economic factors. In Africa, many land use changes are concerned with putting environmental resources to new kinds of productive use or for developing previously unused (often marginal) lands. To ensure the suitability of any proposed change, there is a need for an effective and holistic evaluation or assessment process. Such actions are particularly important in the context of current debates on the competition between biofuel and food crops or with nations acquiring land outside of their borders to assure food security or stable food prices.

The goal of land evaluation is to guide rational decisions on land use in such a way that the natural resources are put to the most beneficial use for man, while at the same time conserving those fundamental ecosystem functions for the future. Such evaluations must be based on a good understanding of both the natural environment and of the type of land use envisaged. There have been many examples of damage to natural resources and of unsuccessful land use enterprises through a failure to account for the mutual relationships between land and the uses to which it is put. Land evaluation should bring about such an understanding and present planners with options regarding the most promising kinds of land use.

An important consideration is that land evaluation is concerned with an assessment of land performance for a specified purpose. For example, the suitability for a crop such as cassava can be quite different to that for potatoes. The Food and Agriculture Organization of the United Nations (FAO) has developed a Framework for Land Evaluation which has been widely used throughout Africa [53]. The FAO approach involves understanding and interpreting the interactions between climate, soils, vegetation, topography and land use. To be of value in planning, land use considerations must be limited to those which are relevant within the physical, economic and social context of the area considered.

Soil characteristics and qualities in land evaluation

When land is mapped for resource exploitation, the areal units defined by the surveyor are normally described in terms of land characteristics (i.e. an attribute that can be measured or estimated). Examples include slope angle, rainfall, soil texture, available water capacity and biomass of the vegetation.

If land characteristics are employed directly in an evaluation, problems can arise from the interaction between characteristics. For example, the hazard of soil erosion is determined not only by the angle of the slope but also by its length, vegetation cover, soil structure, rainfall intensity and other characteristics. Because of these interactions, it is recommended that the comparison of land with land use should be carried out in terms of composite indicators of land qualities.

In this context, a land quality indicator is a complex attribute of land which acts in a distinct manner in its influence on the suitability of land for a specific kind of use. Land qualities may be expressed in a positive or negative way. Examples include moisture availability, erosion resistance, flooding hazard, nutritional value of pastures and accessibility. Where data are available, aggregate land qualities may also be employed (e.g. crop yields, mean annual increments of timber species).

The soil assessment part of such an approach involves transforming soil characteristics into soil quality indicators before matching them with crop requirements.

Soil qualities and related soil characteristics

Soil qualities are related to the agricultural use of the soil and more specifically to specific crop requirements and tolerances. To illustrate the relationship, the following table outlines the soil characteristics needed to define the seven soil quality indices that are required to define land suitability for maize cultivation.

Soil qualities		Soil characteristics
SQ1	Nutrient availability	Soil texture, soil organic carbon, soil pH, total exchangeable bases
SQ2	Nutrient retention capacity	Soil organic carbon, soil texture, base saturation, cation exchange capacity of soil and of clay fraction
SQ3	Rooting conditions	Soil textures, bulk density, coarse fragments, vertic soil properties and soil phases affecting root penetration and soil depth and soil volume
SQ4	Oxygen availability to roots	Soil drainage and soil phases affecting soil drainage
SQ5	Excess salts	Soil salinity, soil sodicity and soil phases influencing salt conditions
SQ6	Toxicity	Calcium carbonate and gypsum
SQ7	Workability (constraining field management)	Soil texture, effective soil depth/ volume, and soil phases constraining soil management (soil depth, rock outcrop, stoniness, gravel/ concretions and hardpans)

Assessing the suitability for maize cultivation in Africa

The following text describes a typical land evaluation exercise to assess the suitability of maize cultivation. Seven key soil qualities have been identified as being critical for maize production: nutrient availability, nutrient retention capacity, rooting conditions, oxygen availability to roots, excess salts, toxicities, and workability.

- Nutrient availability (SQ1)

This soil quality is decisive for successful low level and intermediate input farming. Therefore, diagnostics related to nutrient availability are manifold. Important soil characteristics of the topsoil (0-30 cm) are: soil texture, structure, organic carbon, pH and total exchangeable bases (TEB). For the subsoil (30-100 cm), the most important characteristics are: texture, structure, pH and TEB.

- Nutrient retention capacity (SQ2)

Nutrient retention capacity is of particular importance for the effectiveness of fertiliser applications and is therefore of special relevance for intermediate and high input level cropping conditions. Nutrient retention capacity refers to the capacity of the soil to retain added nutrients against losses caused by leaching. Plant nutrients are held in the soil on the exchange sites provided by the clay fraction, organic matter and the clay-humus complex. Losses vary with the intensity of leaching which is determined by the rate of drainage of soil moisture through the soil profile. Soil texture affects nutrient retention capacity in two ways, through its effects on available exchange sites on the clay minerals and by soil permeability.

The soil characteristics used for topsoil are organic carbon, texture, base saturation, cation exchange capacity of soil, pH and cation exchange capacity of the clay fraction. Soil pH serves as an indicator for aluminium toxicity and for micro-nutrient deficiencies.

- Rooting conditions (SQ3)

Rooting conditions address various relationships between soil conditions of the rooting zone and crop growth. They include effective soil depth (cm) and effective soil volume (vol. %) and are related to the presence of factors that restrict the effective rooting depth or decreases the effective volume of soil that is accessible to roots. As soil depth/volume limitations affect root penetration and may constrain yield formation (roots and tubers), the following factors are considered in the evaluation:

1. adequacy of foothold (i.e. sufficient soil depth for anchoring the crop);
2. available soil volume and penetrability of the soil for roots to extract nutrients;
3. space for root and tuber crops for expansion and economic yield in the soil; and
4. absence of shrinking and swelling properties affecting root and tuber crops.

Relevant soil properties to be considered are soil depth, soil texture/structure, the presence of swelling clays, soil temperature and the presence of coarse fragments (stones) or surface crusts.

- Oxygen availability (SQ4)

Oxygen availability in soils is largely defined by the drainage characteristics of soils. The determination of soil drainage classes is based on soil type, soil texture, slope, movement of the groundwater table and the occurrence of waterlogging, periodic flooding or iron pans in the soil.

- Excess salts (SQ5)

Accumulation of salts may cause salinity. An excess of free salts (soil salinity) is measured as electric conductivity (in dS/m) or as saturation of the exchange complex with sodium ions, which is referred to as sodicity or sodium alkalinity and is measured as exchangeable sodium percentage (ESP).

Salinity affects crops by inhibiting the uptake of water. Moderate salinity affects growth and reduces yields; high salinity levels may kill the crop. Sodicity causes sodium toxicity and affects soil structure leading to a massive or coarse columnar structure with low permeability.

- Toxicities (SQ6)

Low pH leads to acidity related toxicities (e.g. aluminium, iron, manganese toxicities) and deficiencies (e.g. phosphorus, molybdenum). Conversely, calcareous soils generally exhibit micronutrient deficiencies of iron, manganese and zinc and in some cases toxicity of molybdenum. Gypsum strongly limits available soil moisture. Tolerance of crops to calcium carbonate and gypsum varies widely.

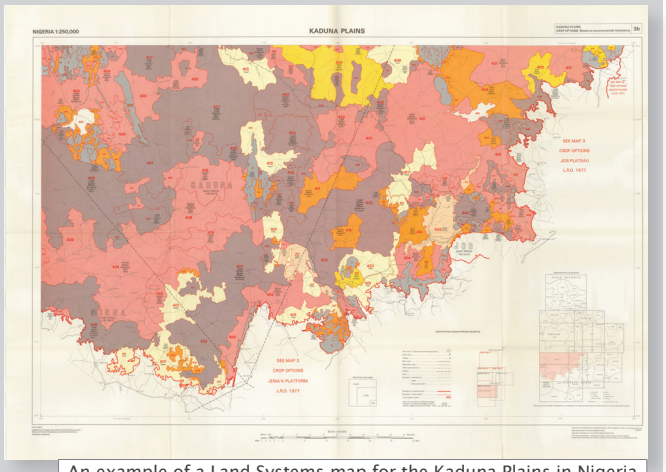
Low pH and high calcium carbonate and gypsum levels are mutually exclusive. Acidity related toxicities such as aluminium toxicities and micro-nutrient deficiencies are accounted for respectively in SQ1 and in SQ2. Therefore, this indicator only includes calcium carbonate and gypsum related toxicities.

The Land Systems Approach

One challenge facing early natural resource surveys was the physical size of the areas being considered. Methods were sought to allow a rapid appraisal of land in order to identify areas of promise for future developments. What became known as the Land Systems approach emerged from the early use of black and white aerial photography by the Division of Land Use in Australia, the National Institute of Road Research in South Africa and MEXE, an experimental unit of the British Army.

The Land Systems approach was particularly suited to multi-disciplinary teams investigating a broad range of landscape facets. Separate land systems were defined where recurring patterns of uniform environmental conditions were identified: therefore, a land system could be expected to have broadly similar topographic, soil-based, vegetative and climatic, conditions. These distinctions were kept at a high level and so were appropriate for delineation from aerial photography, thus providing a flexible framework for rapid field survey. The Land Systems approach was then utilised for a range of high level applications, such as the provision of crop options for maize, millet, sorghum, groundnut, cotton, yam and rain fed rice. [54,54a]

The Land Systems approach was used worldwide, and especially in Africa. The WOSSAC archive in the UK (see page 139) holds a range of examples of Land System maps.



An example of a Land Systems map for the Kaduna Plains in Nigeria from 1978, itself part of a wider Central Nigerian project (CNP) undertaken by the British Land Resources Division of the Overseas Development Administration. This mapping included six northern states of Nigeria: numbered land systems were recorded based on assessment of landscape elements including geology, landform, relief, slope, drainage, outcrops, ironpan presence, soil and vegetative cover. (WOSSAC)

http://www.wossac.com/search/wossac_detail.cfm?ID=250

Soil assessment – Soil evaluation

- Workability (SQ7)

Workability or ease of tillage depends on several interrelated soil characteristics such as texture, structure, organic matter content, soil consistency/bulk density, the occurrence of gravel or stones in the profile or at the soil surface and the presence of rock outcrops or continuous hard rock at shallow depth. Some soils are easy to work independently of moisture conditions, other soils are only manageable at an adequate moisture status, especially for manual cultivation or light machinery. Constraints related to soil texture and structure affect low and intermediate input farming systems, while the constraints related to irregular soil depth, volume of stones and irregular soil depth affect mechanised land preparation and harvesting operations. Workability constraints are therefore handled differently for low/intermediate and high input agricultural systems.

The workability soil quality includes physical hindrance to cultivation and limitations to cultivation imposed by texture/clay mineralogy.

Agro-ecological zoning and land evaluation for maize cultivation

In order to make an inventory and evaluate the biophysical land resource, the FAO has developed the system of agro-ecological zones (AEZ) [55, 55a, 55b]. The FAO-AEZ classification is based on key characteristics of the climate, soils and topography. For climate, the number of days during the year that rain-fed soil moisture is available when temperature conditions allow crop growth is calculated. This period is referred to as the reference length of growing period (LGP) and is derived from a water balance model. For this exercise, the soil quality indices described above were calculated from the Harmonized World Soil Database (HWSD - see page 136) while the topography and slope information were derived from the SRTM database (see page 15).

- Climate classes

  Desert/Arid: <60 days LGP

  Dry semi-arid: 60-120 days LGP

  Moist semi-arid: 120-180 days LGP

  Sub-humid: 180-270 days LGP

  Humid: >270 days LGP

- Soil classes (HWSD FAO' 90)

  Hydromorphic soils: Gleysols, Histosols, gleyic units

  Excellent soils: Cambisols, Luvisols, Nitisols, Chernozems, Kastanozems, Phaeozems, Greyzems, Fluvisols (>2% slope).

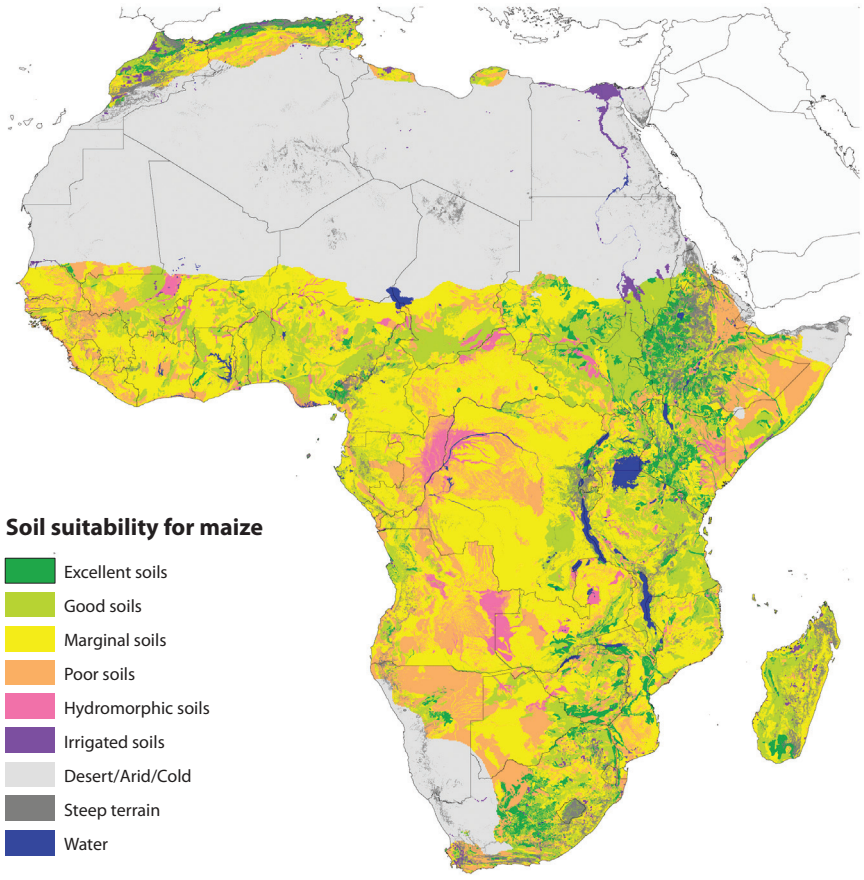
  Good soils: Vertisols, Regosols, Andosols, Podzoluvisols.

  Marginal soils: Ferralsols, Arenosols, Lixisols, Podzols, Plinthosols, Planosols, Acrisols, Gleysols, Arenosols, Podzols (>2% slope).

  Poor soils: Alisols, Calcisols, Gypsisols, Solonchaks, Solonetz, Leptosols, Histosols, Anthrosols (>2% slope), miscellaneous units, Soils with lithic, stony, petrocalcic, petroferric or petrogypsic, saline, sodic, rudic, salic, takyric and yermic phases.

Calculation of land suitability index

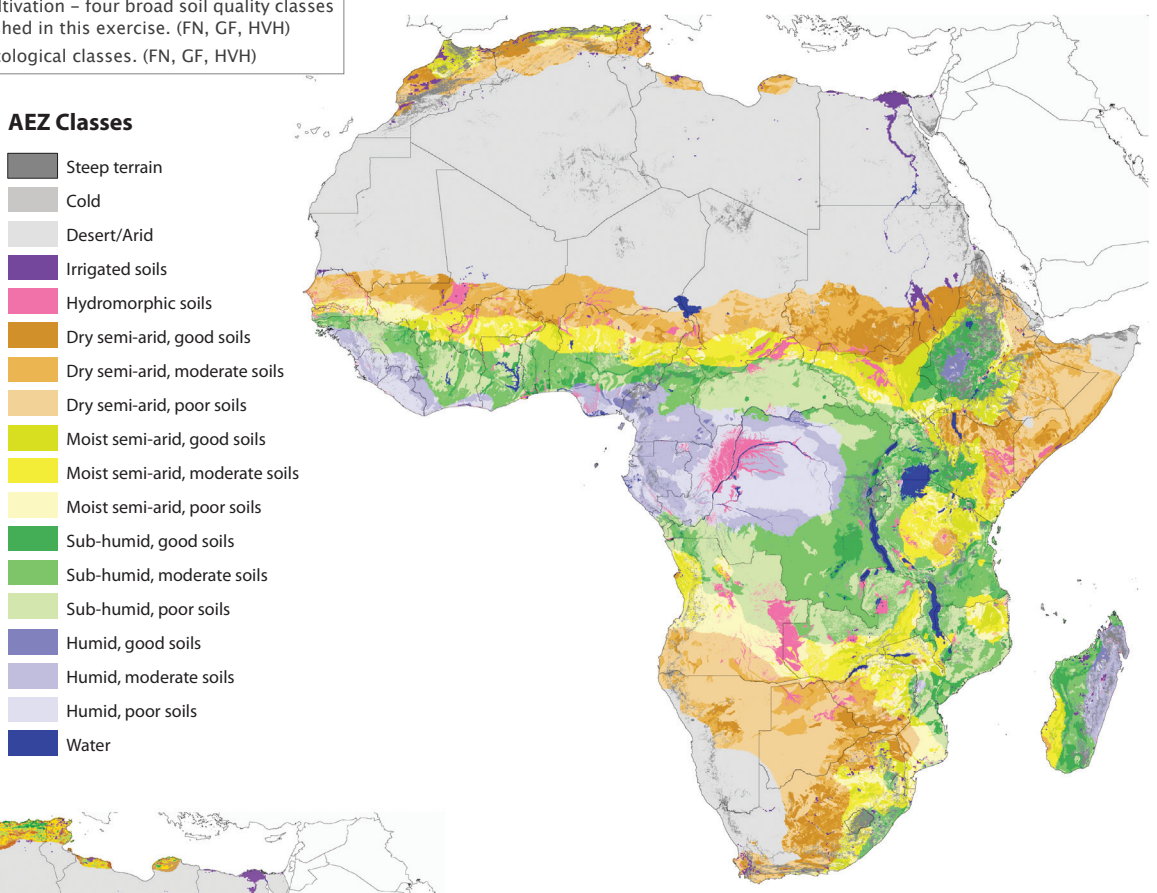
The specific requirements for maize production were compared against the agro-ecological parameters for each cell in the AEZ map. Land was scored as being very suitable, suitable, marginally suitable and not suitable. The final output map (on the right) clearly defines the most suitable regions in Africa for maize cultivation. It is important to note that this is not a map of actual production and that less suitable areas could become suitable on the basis of changes in land management practices, the introduction of farming technologies and climate change. In fact, one of the strengths of this approach is that by varying parameters such as soil moisture and length of the growing season, the impact of climate change on the distribution of specific crops can be assessed. Such outputs are vital in discussions on food security.

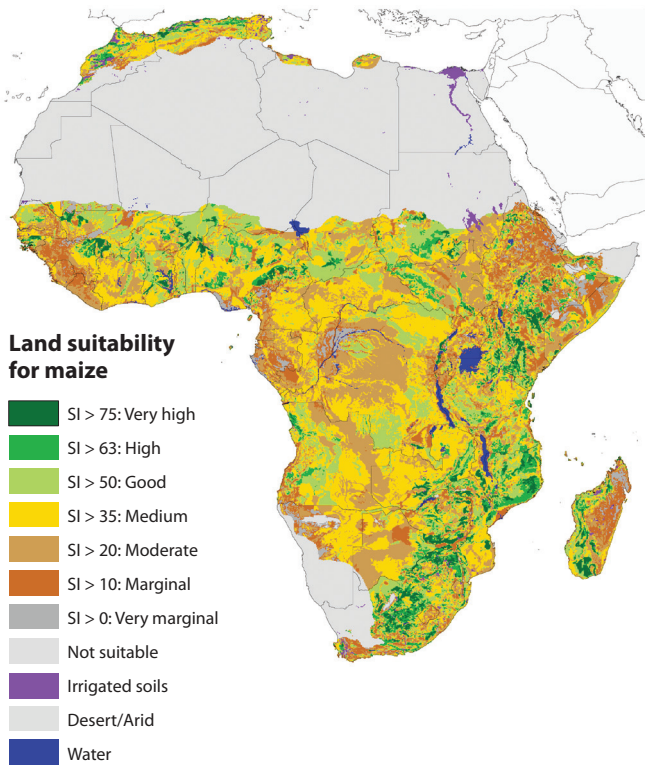


Young maize or corn (*Zea mays*) plants. Maize is Africa's primary source of food. Leafy stalks produce ears which contain seeds or kernels that are used as a vegetable or starch in cooking or animal feed. (AJ)

Above: Map showing soil suitability classes for low input maize cultivation – four broad soil quality classes were distinguished in this exercise. (FN, GF, HVH)

Right: Agro-ecological classes. (FN, GF, HVH)





Land suitability map for maize in Africa at low input. It is clear that large parts of Africa are unsuited to this type of agriculture. Optimum cultivation is predominantly in south-eastern Africa, in parts of the Sahel and on the more humid regions of the North Africa. (FN, GF, HVH)

The East African Groundnut scheme

A fundamental experience which contributed to the use of soil and land evaluation surveys was the failure in the late 1940s of the ambitious East African Groundnut* Scheme (see Ferralsols section on page 53). This embarrassing experience, in what was then Tanganyika, failed to produce any meaningful quantities of groundnuts and was to influence the planning of all subsequent commercial agricultural schemes in Africa [56].

Sites considered to be suitable for groundnuts were identified in 1946. But problems such as unreliable rainfall and, most importantly, the largely infertile and stony soils which were difficult to cultivate with machinery, led to the collapse of this ambitious endeavour in 1949. The failure of this scheme initiated the requirement for rigorous land assessments before embarking on any future agricultural scheme into the thinking of development planners and boosted the status of soil surveys and land evaluation in the decades that followed.

*Despite its name, the peanut (or groundnut - *Arachis hypogaea*), is actually a legume (i.e. a bean). Peanuts grow best in light, sandy loam soil and require five months of warm weather together with an annual rainfall of 500-1 000 mm (or the equivalent in irrigation).

The soils of Africa

A Planosol from Morocco. The sharp boundary between the light, silty topsoil (above 40 cm) and the darker, clayey subsoil (below 40 cm) is clearly evident. This change in texture is a relict of past sedimentation processes. (EM)

A young soil around 40 cm deep showing only limited evidence of soil-forming processes. The soil body is very stony. The underlying bedrock is being weathered into large blocks. To the right of the tape, exfoliation (also known as onion skin weathering) is causing the rock to detach along concentric planes. (EM)

A Vertisol from North Africa. This heavy, clay-rich soil is very productive when cultivated. However, the presence of swelling clay minerals make the soil sticky when wet and hard when dry. Deep cracks (up to 1 m in length in the photograph) and a lack of clearly defined horizons are characteristic of this soil type. (EM)

Kaolinite clay occurs in abundance in soils that have formed from the chemical weathering of rocks in hot, moist climates, for example in tropical rainforest areas. Comparing soils along a gradient towards progressively cooler or drier climates, the proportion of kaolinite decreases, while the proportion of other clay minerals such as illite (in cooler climates) or smectite (in drier climates) increases. Such climate-related differences in clay mineral content are often used to infer changes in climates in the geological past, where ancient soils have been buried and preserved. This profile is from Kenya. (EM)

Soil Classification: Naming and grouping soils together

From the previous pages of this atlas, one can understand how soil can develop different characteristics with depth and in different geographical areas. Apart from glaciers, water and urban areas, soil covers the Earth's surface as a continuum (even bare rock surfaces can have soil material at microscopic level). The gradual changes of soil characteristics across the landscape make the comparison of different soil types difficult. In addition, soil is highly complex, much more so than water or air, and lacks the hierarchical order of many biological systems (e.g. orders, families, genera or singular: genus). To overcome this problem pedologists (scientists who study soil) have developed various ways to characterise, identify, label and group soil bodies according to certain rules. This important task is known as soil classification, one of the advanced branches of basic and applied soil sciences.

Classification is the procedure by which soil is arranged into groups, categories or, as the word implies, classes, relevant to a specific purpose. The purpose of any classification is to organise our knowledge in such a manner that the properties of objects may be remembered and their relationships may be understood most easily for a specific objective. The process involves formation of classes by grouping the objects on the basis of their common properties. Classification helps us deal with complexity. There are too many objects to consider individually. If we can find some common properties or behaviour between them, we can make meaningful classes to help us organise our knowledge and simplify our decision making.

Early soil classifications were based on individual characteristics such as the texture of the topsoil (e.g. loam, clay or sand) or the parent material (e.g. alluvial soil, gravelly soil, etc.). During the late 1880s, the Russian geologist Dokuchaev, now regarded as the father of soil science, was the first to suggest a more scientific classification based on the combination of soil characteristics in relation to their formation. This approach, known as the genetic principle, remains the guide for most present day national soil classification. This principle allows features resulting from soil-forming processes to be distinguished from those whose origin is geological.

Different approaches to soil classification

During the twentieth century many new soil classification systems were developed around the world as a result of a growing interest in soil conservation and alternative land uses from agriculture. These systems focused on various basic and applied aspects which could be grouped into two categories: natural and technical.

Natural classifications group soil types by some intrinsic properties, behaviour, or origin without reference to any particular use. Examples include:

- Group by ecologically important characteristics such as soils of savannah or tropical rainforest. Such groups may be geographically-compact but can have diverse properties and functions;
- Group by origin where a common development, depending on the interpretation of soil-forming factors and soil genesis, is presumed. This type of classification is called genetic. The soil is considered as a natural body with its own history and ecology.

Technical classifications group soil types by some properties or functions that relate directly to a proposed purpose. Examples include:

- Hydrological: groups soil types according to water regimes such as drainage classes;
- Agricultural suitability: groups soil types according to their ability to support specific crops or agricultural activities;
- Land use capability: groups soil types according to their land management capacities;
- Fertility: groups soil types according to the availability of essential nutrients;
- Engineering: groups soil types according to their bearing strength and behaviour under different moisture conditions.

Soil science, unlike many other scientific disciplines (e.g. botany), does not have a single, universally used, classification system (see text on current trends below). This is because soil is far too complex for a single classification to be applicable globally. Therefore, many countries have developed their own specific approaches to classifying soils based on national concepts or practical needs, often using local names for soil types based on the identification of typical examples. This approach complicates the comparison of soil types between different parts of the world as names often do not translate well between taxonomic systems. The FAO Legend for the Soil Map of the World was an attempt to address the need for a globally accepted soil classification system. While several countries have used the FAO legend for national mapping purposes, many difficulties were encountered.

Current trends

A number of soil classification systems have developed that use quantitative criteria involving field assessed soil characteristics and/or laboratory analysis to identify and refine hierarchical classes. Such approaches have been used in many countries to revise national classification schemes. The availability of quantitative soil parameters eases the comparison of national classification systems because specific characteristics can be examined rather than broad concepts.

Revision of the United States Department of Agriculture's (USDA) Soil Taxonomy classification scheme [57] and the development of the World Reference Base for Soil Resources (pages 48-59) from the FAO Legend of the Soil Map of the World were important responses to this more analytical approach.

In 1998, the 16th Congress of the International Union of Soil Science in Montpellier, France, adopted the World Reference Base for Soil Resources as the official terminology to name and classify soils - the system used in this publication.

Towards a Universal Soil Classification System?

Most national soil classification systems were developed for a specific purpose, often quite different from the questions being posed today. Soils suitable for agricultural purposes, especially cultivation, usually received more attention in the past. In addition, national conditions often gave rise to particular perspectives and where the broad or global view of soils was normally not considered. This often led to massive confusion and disagreements between soil scientists. However, the current broader view of soil functions and understanding the role of soil in global environmental processes require a better understanding and description of all soils (in particular, anthropogenic soil, cold soils, soils of the tropical regions). In addition, most classification schemes were elaborated before the recent boom of observation technologies, data storage and computer processing capability.

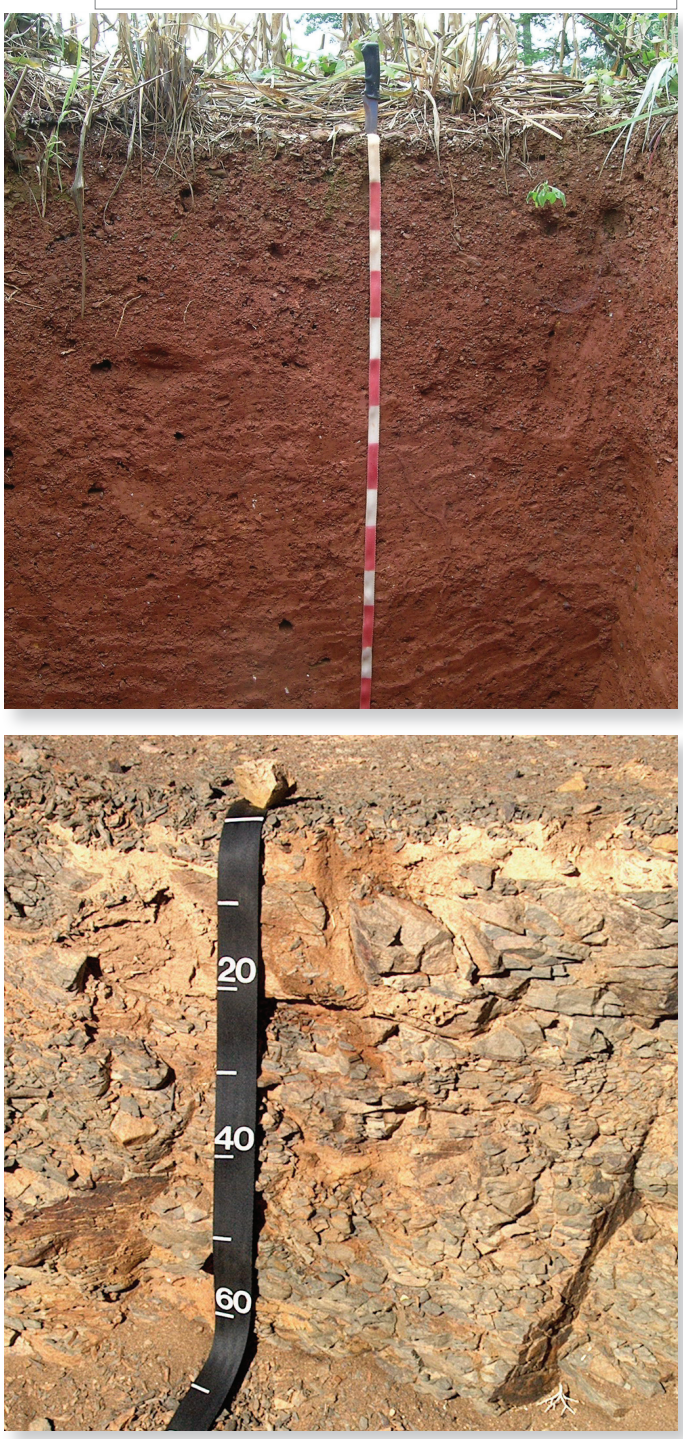
At a meeting in Godollo (Hungary) in 2009 to celebrate the 100th anniversary of the 1st International Conference of Agrogeology (widely regarded as the first ever international soil science conference), participants called on the International Union of Soil Sciences (IUSS) to address the problem of our lack of a common language within the soil science community, particularly in relation to the taxonomy of soils.

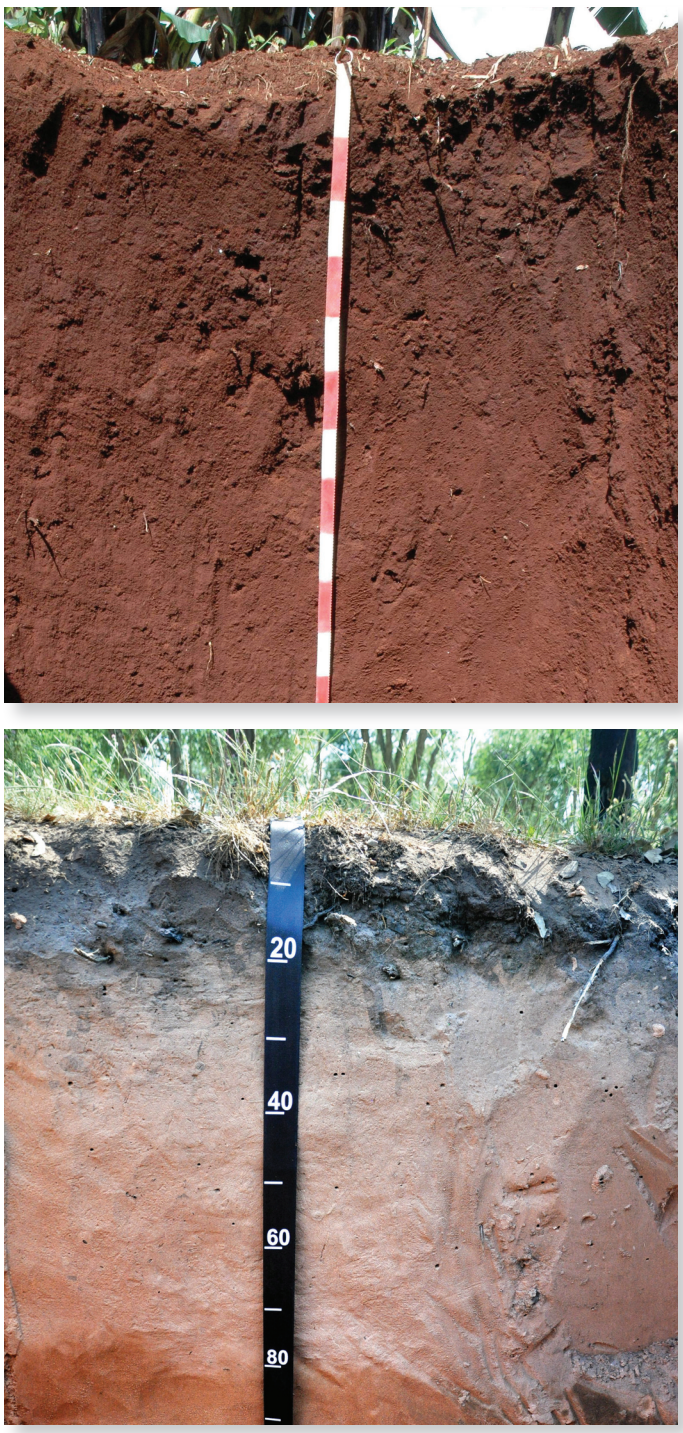
Consequently, during the 2010 World Congress of Soil Sciences in Brisbane, Australia, the IUSS Council unanimously accepted the "Godollo Resolution" and established a Working Group to coordinate investigations and development of common standards, methods and terminology in soil observations and investigations towards a new universal soil classification system. In this context, the term 'universal' implies that a system is commonly accepted and commonly applicable.

Further details on the development of the Universal Soil Classification System can be found at the USDA Natural Resources Conservation Service web site through the following link:

http://soils.usda.gov/technical/classification/Univ_Soil_Classification_System/

The pictures below show the variability of soil. The upper pair of images show characteristic red tropical soils from Ghana and Kenya. Despite the huge distance between their locations, they display similar characteristics and responses which would imply that they should be grouped together. The lower pair of images show a thin soil developing over hard bedrock (**lower left**) and a soil developing in a vegetated sand dune. Both are immature or young soils in a desert environment. However, the nature of their parent material and the amount of organic matter puts these two soils into separate classes. **Clockwise from below**: Acrisol, Ghana; Nitisol, Kenya; Arenosol, Morocco; Leptosol, Namibia. (EM)





Development of soil classification in Africa

"Soil is the source of all life. Yet we know more about soils of Mars than about soils of Africa,"

Pedro Sanchez, Director of the Earth Institute's Tropical Agriculture and the Rural Environment Program (2010)

At the end of the 19th century and during the first half of the 20th century, the soils of Africa were investigated by European soil scientists according to their understanding of temperate soils at that moment. At this time, the Dokuchaev principle of zonality, associating the location and characteristics of soils with climate and vegetation zones, still played an important role in soil classification and mapping. In the early 1890s, studies in South Africa grouped soils according to the zonality concept. This was reinforced by the presence of large tracts of uniform soil, such as the red Kalahari sands, the black clays and the highly weathered soils of the eastern escarpment. In 1900, a very important soil survey was concluded by French colonial institutions in Madagascar which collected 500 soil samples on the "red island" to be analysed in Paris. Information on ochrous or red earths, yellow earths, purplish earths and sandy earths, together with an agricultural map of the island, were presented at the international exposition in Paris in 1900.

Even in these very early studies, the red soils of Africa were considered to be special. Several surveys noted the occurrence of such soils, as is shown in the use of the term 'Red Earths' in early British literature. After the identification of laterites in India in 1807, the red soils of Africa became equated with laterites and the term Lateritic soil became popular probably leading to the early misconception that all red soils are laterites (see page 26). Lateritic soils were observed in Madagascar in 1902.

However, the zonal soil concept that so influenced classifications in Russia and America did not conform to the ancient land surfaces of Africa as the continent has been subjected to considerable climatic fluctuations. Some of the old stable landscapes on which soils were formed date back to the mid-Tertiary period. Although weathering crusts were not scraped away by glaciers and ice caps as they were in Europe and North America, Africa underwent several pluvial (wet climate) and inter-pluvial cycles of erosion and sedimentation. Stone-layers in strongly weathered soils are generally the result of geological erosion and deposition and suggest that the soils are formed on transported deposits. Hence, strongly weathered and deep regoliths are the products of successive geomorphological cycles and are the result of geogenesis rather than pedogenesis.

The development of soil classification systems has gone on hand in hand with developments in survey methodology. In 1904 the soil series was introduced by the US Soil Survey as a basic mapping unit. The series originally included all soil types developed on the same parent material, but the concept changed from being a geological unit to a mainly climatically-developed unit, and ultimately, to an independent natural unit defined on the basis of its own properties. The present concept of the soil series is of soils that are essentially alike in all major profile characteristics. This concept has been adopted for soil mapping in most parts of Africa.

The earliest known soil map of Africa at a scale 1:25 million was published by C.F. Marbut in 1923 [58]. This map is based on the analyses of less than thirty soil profiles scattered over the entire continent. The intention was to show the probable location and trend of the great soil belts of Africa based on climatic, lithological or phytogeographical factors. Between 1930-1945, this map was supplemented by several notable small-scale surveys undertaken on limited budgets and with few staff (e.g. Z.Y. Shokalskaya in 1944). Of note were a reconnaissance survey of the Belgian Congo and a map of the central part of Nyasaland (Malawi).

The Provisional Soil Map of East Africa by G. Milne (1935-1936), developed using the concept of the soil catena, is regarded by many as the outstanding survey of this period (see page 15). The value of the catena concept to soil survey is that it permits the prediction of soil distribution based on landscape position. This is particularly useful in reconnaissance surveys where the extrapolation of repeating landscape units over large areas is required. An ecological approach to soil mapping was adopted for Northern Rhodesia (1937, 1943, 1948) which exploited the relationship between vegetation and associated soils. In Rhodesia a soil classification based on geological materials was proposed at the end of the 1940s, because of the marked differences in soils that were associated with changes in parent material. A descriptive legend based on this system, including references to mean annual rainfall, temperature, altitude, and the dominant vegetation, was subsequently used for the Provisional Soil Map of Southern Rhodesia (Zimbabwe).

A mosaic of the eight seperate sheets that make up the soil map of Africa of Jules D'Hoore (1963–1964). The originals are stored in the library of ISRIC. While soil names may have changed and boundaries refined, the basic information portrayed by the map is still very reliable. (JRC) [59]

Digital versions of the individual sheets and a readable legend can be downloaded from the EUDASM archive:

http://eusoils.jrc.ec.europa.eu/esdb_archive/eudasm/africa/

The term "Podzolic" made its first appearance in 1938 with regard to soils of tropical regions on account of the occurrence of light coloured surface horizons linked to a subsurface accumulation of clay. With the introduction of the concept of Podzolic soils, many of the red soils were moved into this group as the textural change began to be considered to be more significant than the colour. The different meanings given to the terms Laterite, Lateritic and Podzolic resulted in a high degree of confusion regarding the classification of tropical and sub-tropical soils.

After 1945 there was a growing demand for a comprehensive soil taxonomy that would help evaluate soils in developing countries, especially with regard to their potential for food production. A resurgence of soil studies in the tropics saw the emergence of new terms. In 1947, the term Latosol was introduced to bring together some of the highly weathered soils. Many kinds of Latosols were soon recognised, differentiated by the reddish-yellow, red or dark red colour of the B horizon. The 1950s saw an increase in the number of studies on African soils as a result of European countries, especially Belgium, France and Portugal, establishing a pedological section within large research stations in their African colonies. The increased interest in soil survey resulted automatically in a special interest in soil classification. One of the early problems was the confusion created by the use of the term 'Laterite', covering a red soil, a red material that hardens or a hard iron-rich material. On the basis of an exploratory study in the Congo, the term 'Lateritic soils' was replaced at first by a more narrowly defined 'Latosol', characterised by a high degree of aggregate stability and a dominance of low activity clays and oxides of iron and aluminium. During this period, the term 'Ferralitic soils' appeared in French (1954) and Portuguese (1954) literature to group some of the red soils.

In 1954, the 5th International Congress of Soil Science was held in Leopoldville (Kinshasa), the first to be held in a tropical environment. The classification of soils in the tropics was amply discussed with special attention given to the use of the term 'Ferrallitic soils' as a substitute for 'Lateritic soils'. The name 'Latosol' was felt to be less suitable on account of its very broad scope and its reminiscence of the term 'Laterite'. At the 6th International Congress in Paris in 1956, a French system of soil classification was presented in which the red soils of the humid tropics were labelled as 'Sols Ferrallitiques' and 'Sols Ferrugineux Tropicaux'. In 1958 the terms Oxysols and Ochrasols were used in West Africa.

In 1960 the US Soil Survey produced the first operational version of Soil Taxonomy (see page 47) which brought a new impetus to soil classification. The new system attracted much international interest among less developed countries, which were often not in a position to assess its merits.

In order to ensure a more precise definition and a subdivision of the Latosols in the Congo, the term 'Kaolisols' was coined in 1961 to denote inter-tropical soils with the dominance of kaolinite in the clay fraction mixed with important quantities of free oxides. Kaolisols included Ferralsols and Ferrisols. Much emphasis was laid by Belgian soil scientists on characteristics that were easily recognisable in the field (e.g. the presence of pseudosands in Ferralsols or shiny clay skins in Ferrisols). Many of these criteria were later incorporated in international classification systems, such as Soil Taxonomy (Oxisols) and WRB (Ferralsols), and in the FAO Legend (Ferralsols).

Within the English-speaking parts of tropical Africa, the approach used in Ghana and in parts of Nigeria is perhaps the best known. The Ghana system (1962) is a natural classification based on rainfall and parent material. Freely-drained soils in the humid zone were divided in to Latosols if derived from parent material of intermediate to felsic composition and Basisols that developed from basic parent materials. Other British Commonwealth territories used various *ad hoc* local classifications.

In the former Belgian Congo, the INEAC (Institut National de l'Etude Agronomique au Congo) system (1961) emphasised successive stages of weathering. The Portuguese developed a classification for deep, relatively well drained profiles through a 'sialitico - fersialitico – ferralitico' sequence. Soil colour was an important feature of many groupings. For the general soil map of Angola (1:1 million), such groupings were used as taxonomic units, with complexes of groupings as cartographic units. The French pedologists of ORSTOM (Office de la Recherche Scientifique et Technique d'Outre-Mer) were also involved in the development and revision of soil classification systems throughout former French colonies, especially in Algeria and Morocco. A revision of the Ferrallitic soil classification was published in 1966, followed by the first French classification. The ORSTOM system put much emphasis on climatic zonation rather than lithogenic influences. It is a natural, hierarchical system, based on the evolution of the profile as a whole.

Please read [52, 54a, 54b, 60] for further information on the history of soil survey in Africa.

Towards a common system

The establishment of national soil survey classifications resulted in a confusing situation as no one system was universally accepted. Two developments served as a basis for international exchange of pedological and agronomic information. They include the FAO 'Soil Map of the World (scale 1: 5 000 000) which started in 1961 and the Soil Map of Africa (also at a scale 1: 5 000 000 - see facing page) published in 1964 in the framework of a joint project by the Inter-African Pedological Service and the CCTA (Commission de Coopération Technique en Afrique) [59].

The CCTA classification reflected a major effort of correlation between the various systems in use in different African countries. It is an outstanding synthesis and was particularly valuable in bringing the ORSTOM and INEAC approaches to the attention of anglophone countries in Africa. This approach was used in a number of regions, including Northern Rhodesia (Zambia), Southern Rhodesia (Zimbabwe), Nyasaland (Malawi) and by the British Land Resources Development Centre. The development and application of this system stimulated cooperation and the international exchange of pedological information and ideas.

Although initially developed as a legend for a specific map and not a soil classification system per se, the FAO Legend (1974) found quick acceptance as an international soil correlation system [61]. It has been used on FAO soil surveys in Africa and as a basis for the national soil classification in many African countries (e.g. Kenya). The revised Legend (1988) introduced amendments based on experience gained while using the legend in Botswana, Egypt, Kenya, Sierra Leone and Zambia. The revised Legend was used as the basis for the national map of Botswana.

Through their National Soil Institutions, most countries have updated their soil information since the publication of the FAO Soil Map of the World. In fact, several African countries have now produced national soil maps that in scale and level of information can easily compete with those from the industrialised world. Botswana, Kenya, Rwanda, Ghana, Tunisia are but a few examples of countries that have gone to great lengths to carry out a full inventory of their soils.

In the 1960s, attempts were made in South Africa to apply Soil Taxonomy to South African conditions. Many of the principles, particularly the use of diagnostic horizons, were subsequently used in devising a new two-tier system that culminated in the publication of "Soil Classification: A Binomial System for South Africa" in 1977. A revised version, "Soil Classification: A Taxonomic System for South Africa", was published in 1991. A similar keyed classification of soil series was produced for Zambia in the 1980s but it is far more flexible, allowing for expansion and modification as experience grows and new series are defined.

Since 1982, the International Society of Soil Science had been active in the development of an internationally acceptable soil classification system. In 1992, the Working Group Reference Base (RB) proposed the FAO Revised Legend as a base, rather than developing a fully new soil classification system, and to give it more scientific depth and coherence. The first version of the World Reference Base (WRB) was endorsed in 1998, in a historical motion, as the official soil correlation system of the International Union of Soil Science (see page 50).

Indigenous soil classifications

For millennia, farmers in Africa have, through experience, developed a detailed nomenclature of different types of soils. This knowledge, accumulated over time, constitutes fundamental socio-cultural and economic values of each local community. For example, the old name of Egypt was Kemet, meaning alluvial dark and fertile soils and the word 'deshret' in ancient Egyptian was the name of desertic red soils.

Indigenous knowledge of soils was regarded by the scientific community as a simplistic collection of human experiences and primary attitude towards understanding natural resources. However, in the 1960s, scientists began to perceive the pertinence of indigenous soil knowledge on land development strategies. Understanding farmers' knowledge on soil and land management strategies appeared to be of utmost interest for developing improved technologies for sustainable soil fertility management at local level. For example, the local specificity and indigenous knowledge should be taken into account to ensure the successful implementation and adoption of new technologies.

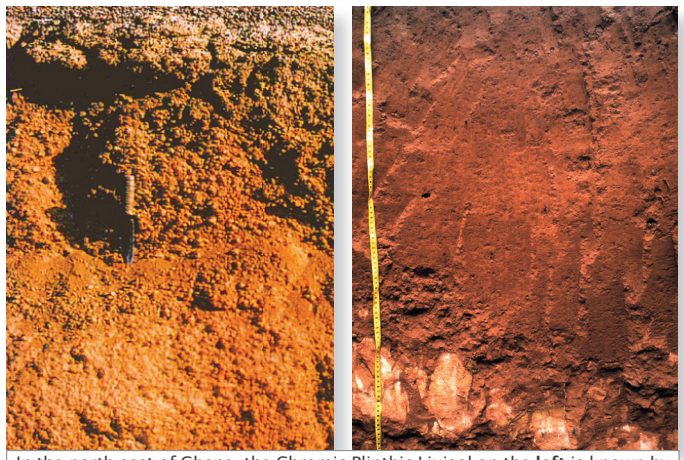
Nowadays, increasing interest in traditional soil knowledge has led to the development of ethnopedology, a hybrid discipline between natural sciences and social sciences. However, local perception of soil quality shows an interest in sociology because this denotes the relationship between farmers and the land. Moreover, the diversity of soil quality representations in a given area implies the diversity of production systems.

Ethnopedology studies in Africa have revealed that indigenous soil classifications are based primarily on soil productive capacity. The main factors controlling the taxonomy fall into two groups: (i) environmental factors such landform (topography), vegetation and fauna; and (ii) topsoil morphological properties such as colour, depth, texture, density, stoniness and water movement. Some derived secondary factors include land slope, soil workability, stickiness and hardness. Examples include:

- The topsoil colour reflects soil fertility level. Dark soils are considered more fertile than other colours (red, white, etc.);
- The soil texture gives information about soil workability and soil water retention capacity;
- "Bissiga" in Mooré language (Burkina Faso) means sandy soil, usually used for millet and vegetable crops;
- "Bolé" denotes clayey soils, suitable for sorghum and other crops that need more moisture. In terms of soil management, soils with coarse texture are easier to work with the hoe. They have a high infiltration rate but a low water holding capacity;
- The landform is used to locate soil in the topographic position in the landscape and to estimate the level of erosion risks based on the slope;
- In the Mooré language, the upper part of a slope is called "zegedga" which denotes where erosion risks are high;
- In the Yemba language (Dschang, west Cameroon), soils of well-drained plains, called "tsa'a pepeuo" are considered to be very fertile and are used for intensive agriculture. Poorly-drained soils of inland valleys, "tsa'a ngui", are only used for off-season crop production or grazing.

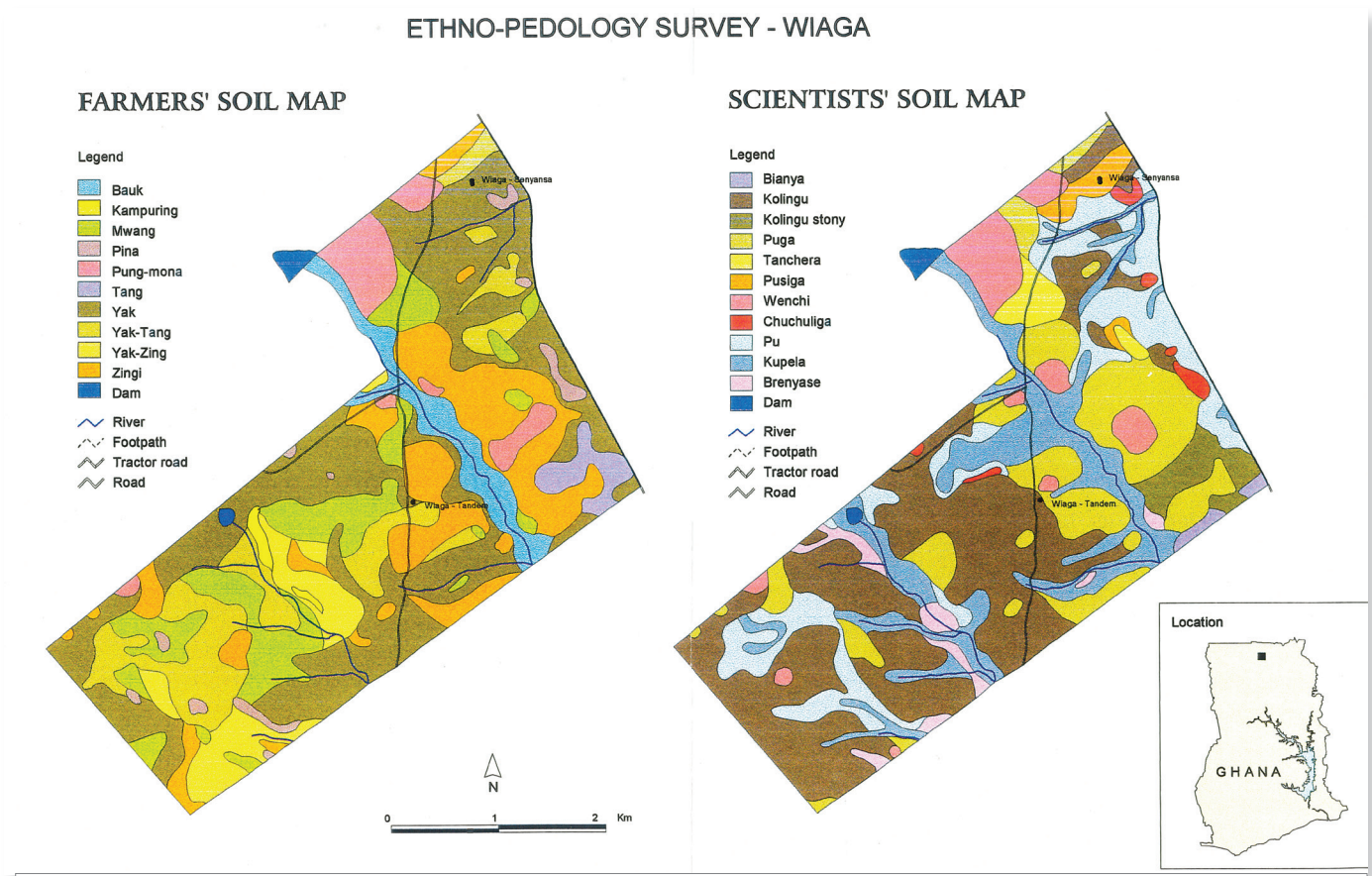
The vegetation can also be used to differentiate soils according to the original vegetation cover (forest soils, savannah soils). Plant species can also be used as soil fertility or infertility indicators.

Although these factors are used in most local soil classification, local management of soil fertility varies with individual capacities, local perception of constraints and other opportunities. Indigenous soil classification systems in Africa are increasingly being used by land managers and further research is needed to ensure better correlation of these indigenous systems and the conventional classification systems.



In the north east of Ghana, the Chromic Plinthic Lixisol on the **left** is known by the local Mamprusis people as *Kokua sabli*. These words denote the presence of iron-manganese nodules, the dark colour of the soil and a general low fertility, especially in drought conditions. The Chromic Lixisol on the **right** is known as *Bihigu sabli*, which denotes a dark colour and sandy textured soil found in the uplands. (both ISRIC) [62]

Local farmers tend to use their experience to evaluate and delineate soil types. They rely on topsoil colour and crop performance to assess nutrient levels, while texture is used to determine soil moisture relationships. (PDI)



A comparison between a soil map made by local farmers on the basis of their knowledge of local soil characteristics (left) and a more 'classically' produced map made by soil scientists (right). In some cases, there is a close correspondence while in other parts, there is a clear difference in diagnostic criteria. For example, in some areas farmers only consider texture as the basis for differentiation while soil surveyors consider physiography, drainage and depth. (ISRIC) [62]

The World Reference Base For Soil Resources

Origins

In the 1970s and '80s, the FAO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) prepared a legend for the 1:5 million soil map of the world, broadly based on the main soil-forming factors. This map was used by many UN sponsored projects and, over time, many countries modified and adopted the legend to fit their particular needs [61]. Consequently, many of the soil units used in the FAO system are known in many countries and have similar meanings.

The World Reference Base for Soil Resources (WRB) was developed under the auspices of the International Union of Soil Science, by building on the foundations of the FAO legend, to create a common basis for correlating the soil resources of different countries [63]. Objective criteria derived from both field inspections and laboratory analysis of the soil are used to systematically classify different soil types into a Reference Group with specific characteristics denoted through the use of prefixes and suffixes (see page 51).

The WRB is not meant to replace national soil classification systems but rather designed to serve as a common language through which national soil classification systems can be compared and correlated.

The World Reference Base for Soil Resources

The WRB places all types of soil within thirty-two major soil groups (see adjacent column) with a series of uniquely defined qualifiers for specific soil characteristics (see page 51).

For describing and defining different types of soil, the WRB exploits the following nomenclature:

- soil characteristics comprising single observable or measured parameters;
- soil properties, a combination of characteristics indicating soil-forming processes;
- soil horizons, representing three-dimensional bodies characterised by one or more soil properties.

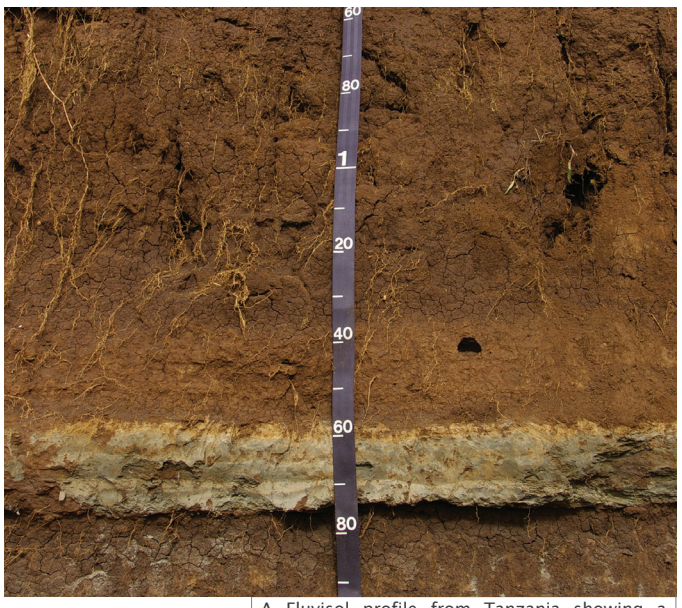
Soil horizons and properties are used to describe and define soil classes on the basis of 'diagnostic' criteria. This means reaching a certain degree of expression, as determined visually, by prominence, measurability, importance and relevance for soil formation, soil use and quantitative criteria. To be diagnostic, soil horizons also require a minimum thickness.

Reference soil groups in WRB are defined by the presence of diagnostic horizons. The soil in the picture has no diagnostic surface horizon. It has a bleached, light coloured albic horizon, from which the clay and some of the iron oxides have been translocated and accumulated in the underlying argic horizon. Below the argic horizon there is a red mottled horizon that cements upon drying to form a hard pan called plinthite. Because of the presence of the argic horizon and its low base saturation, the soil belongs to the Acrisols group. (EM)

WRB Reference Soil Groups

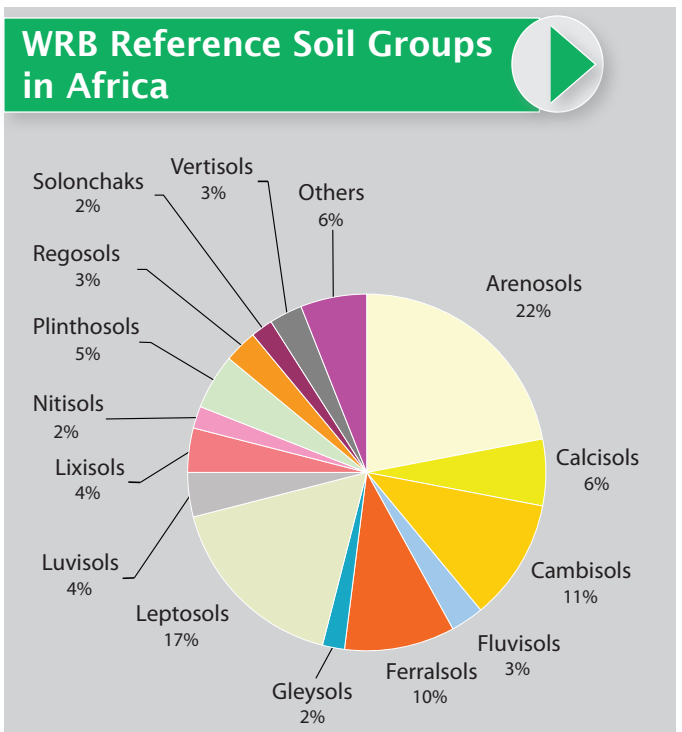
The thirty-two WRB Reference Soil Groups (RSG) are allocated on the basis of dominant identifiers which are usually the factors or processes that most clearly condition the formation of the soil. The sequence of the groups is according to the following principles:

1. Firstly, organic soil (**Histosols**) is defined to separate it from mineral soil.
2. The second major distinction is to recognise human activity as a soil-forming factor. Hence the position of the **Anthrosols** and **Technosols** after the **Histosols**; a benefit to the early definition of **Technosols** is the removal of soil that could be toxic and should not be touched.
3. Next are soil types with a severe limitation to rooting (**Cryosols** and **Leptosols**). **Cryosols** combine all mineral soil types that are affected by permafrost (a layer of soil that is continuously frozen for two or more consecutive years). **Leptosols** are mainly found in the mountainous areas and comprise shallow soils over hard rock and extremely stony soils with little fine earth.
4. Then comes a group of RSG that are or have been strongly influenced by water: **Vertisols**, **Fluvisols**, **Solonetz**, **Solonchaks** and **Gleysols**. **Vertisols** are churning, heavy clay soils with a high proportion of swelling clays. Deep and wide cracks form from the surface downward when they dry out and close when wet. **Fluvisols** occur in river valleys and comprise soil in recent alluvial, lacustrine or marine deposits and display a characteristic layering of sediments. **Solonchaks** have a high concentration of soluble salts at some time in the year and are largely confined to arid and semi-arid climate zones or coastal regions. **Solonetz** are strongly alkaline soils (pH > 8.5) and have a dense, strongly structured, clayey subsurface horizon that has a high proportion of adsorbed sodium and/or magnesium ions. **Gleysols** are soils with a high groundwater table. The distinctive oxidation-reduction pattern of brownish zones on the outer side of structural elements and along pores versus a grey, blue or green matrix, indicative of groundwater influence, set **Gleysols** apart from other wet soils.
5. The following group contains soils where iron (Fe) and/or aluminium (Al) chemistry plays a major role in their formation: **Andosols**, **Podzols**, **Plinthosols**, **Nitisols** and **Ferralsols** (the latter three are mostly found in the tropics). **Andosols** are soils developed in volcanic ejecta. They are characterised by a unique aluminium-silica chemistry as a result of rapid weathering of the volcanic minerals. **Podzols** have a typical ash-grey upper subsurface horizon, bleached by the loss of organic matter and iron oxides, on top of a dark accumulation horizon of humus and Fe compounds. Distribution in Africa is limited to temperate zones and small pockets in the tropics. **Plinthosols** contain plinthite, an iron-rich, humus-poor mixture of kaolinitic clay, quartz and other constituents that hardens irreversibly on exposure to repeated wetting and drying, **Nitisols** are deep, well-drained, red, tropical soils with diffuse horizon boundaries and a subsurface horizon containing shiny, flat-edged or nut-shaped polyhedric elements. **Ferralsols** are the classical deeply weathered, red or yellow soils of the humid tropics. They have diffuse horizon boundaries, and a high aluminium content.
6. Next comes a group of soil types with perched water: **Planosols** and **Stagnosols**. **Planosols** have a light-coloured, coarse-textured surface horizon that shows signs of periodic water stagnation and abruptly overlies a dense, slowly permeable subsoil with significantly more clay than the surface horizon. Found on flat lands, they are typically seasonally waterlogged. **Stagnosols** display a characteristic oxidation-reduction mottling pattern due to processes caused by periodically stagnating surface water.
7. The next grouping comprises soils that occur predominantly in dry grassland regions (e.g. savannahs) that have well developed humus-rich topsoils and a high base saturation: **Chernozems** have a thick, dark, humus-rich surface horizon. **Kastanozems**, found in drier conditions, also display a humus-rich surface horizon but it is thinner and not as dark as that of the **Chernozems**. Due to more humid conditions, **Phaeozems** are leached more intensively so that the dark, humus-rich surface horizon contains less bases.
8. The next group comprises soil from drier regions with accumulation of gypsum (**Gypsisols**), silica (**Durisols**) or calcium carbonate (**Calcisols**).
9. Then comes a group with a clay-rich or argic subsoil horizon. They can be grouped as having a) low base status, with high-activity clays (**Alisols**) or low-activity clay (**Acrisols**) or b) high base status, with high-activity clay (**Luvisols**) or low-activity clay (**Lixisols**). **Albeluvisols** (with tongues of topsoil protruding into the subsoil) are not found in Africa.
10. The last group contains relatively very homogenous sands and young soils that have limited or poor profile development: **Umbrisols**, **Arenosols**, **Cambisols** and **Regosols**. **Umbrisols** are associated mainly with acidic parent material and areas with an excess of precipitation. Under these conditions deep, dark-coloured and acid surface layers develop which are known as umbric horizons, from which the soil derives its name. **Arenosols** are undifferentiated soils in sandy deposits such as wind-blown sands of deserts. **Cambisols** have a subsurface horizon that only shows some initial development such as a change in colour and/or soil structure. **Regosols** comprise undifferentiated fine and medium textured soils.



A Fluvisol profile from Tanzania showing a characteristic layering of sediments. (EM)

WRB Reference Soil Groups in Africa

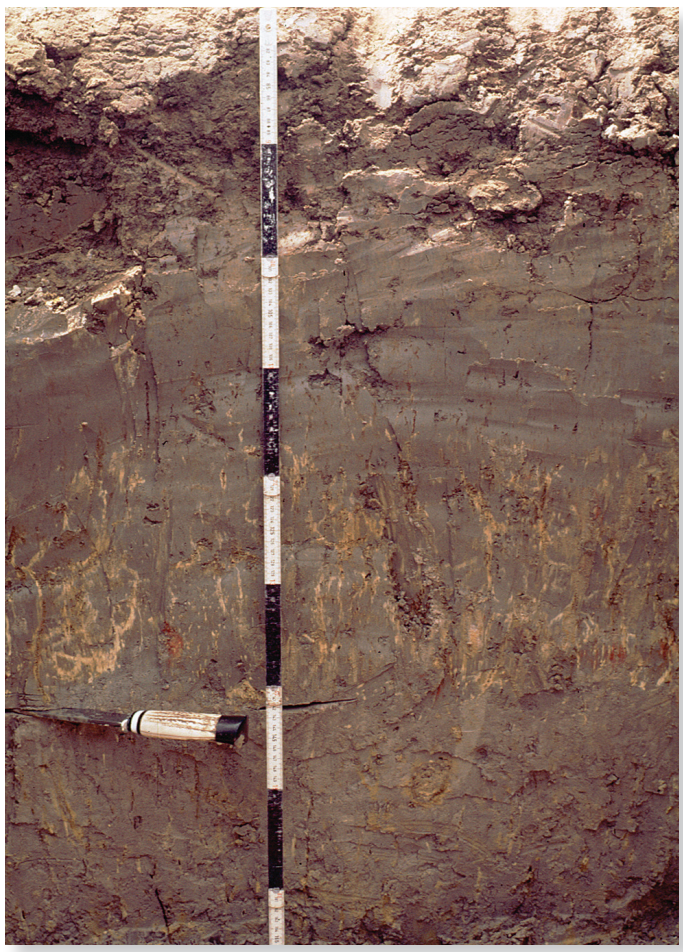


The chart shows the share of the major WRB Reference Soil Groups for Africa. Reference Groups occupying 1% or less have been combined as 'Other'. The total area comprises some 30 million km² or about 20% of the global soil cover. (AJ)

The continent of Africa contains all but one of the WRB Reference Soil Groups and illustrates a great soil diversity (see page 61). It is important to notice that over 60% of the soil types represent hot, arid or immature soil assemblages: Arenosols (22%), Leptosols (17%), Cambisols (11%), Calcisols (6%), Regosols (2%) and Solonchaks/Solonetz (2%). A further 20% or so are soils of a tropical or sub-tropical character: Ferralsols (10%), Plinthosols (5%), Lixisols (4%) and Nitisols (2%). A considerable area (6%) is occupied by a further 16 reference groups that cover an area of less that 1% of the African land mass. This fact illustrates that a considerable number of soil types are associated with local soil-forming factors such as volcanic activity, accumulations of gypsum or silica, waterlogging, etc. What is interesting is that unlike the other continents, Africa does not exhibit large expanses of prairie or steppe-type soils (i.e. Kastanozems, Chernozems and Phaeozems).

How to identify a soil according to the WRB?

Let's take a closer look at this soil profile from the delta of the Senegal River in northern Senegal.



The soil is this photograph (JD) clearly shows a structured surface layer, overlying a structureless subsoil. The layer between 20 and 40 cm depth shows some reddish-brown mottles and vague stratification on the right hand side of the photograph. Between 40 and 60 cm yellowish-orange spots are evident, indicative of the formation of the mineral jarosite (a basic hydrous sulphate of potassium and iron, characteristic of acid sulphate soil environments). Below 60 cm, the soil is uniformly grey in colour. The soil is clayey throughout and laboratory analysis indicates a pH of about 3 (very acid) in the jarosite layer.

The above combination of characteristics means that this soil classifies as a Fluvisol, which must exhibit Fluvic material starting within 25 cm of the soil surface or starting immediately below a plough layer of any depth and continuing to a depth of 50 cm or more. Moreover, the jarosite layer fulfils the criteria of a thionic horizon and the colour of the subsoil is indicative for a gleyic colour pattern and reducing conditions.

The next step is to identify the possible qualifiers for Fluvisols:

Prefix	Suffix
Subaquatic	Thionic
Tidalic	Anthric
Limnic	Gypsiric
Folic	Calcaric
Histic	Tephric
Technic	Petrogleyic
Salic	Gelic
Gleyic	Oxyaquic
Stagnic	Humic
Mollic	Sodic
Gypsic	Dystric
Calcic	Eutric
Umbric	Greyic
Haplic	Takyric
	Yermic
	Aridic
	Skeletic
	Arenic
	Siltic
	Clayic
	Drainic

Following the rules set by the WRB, the full name of the soil is an **Endogleyic Fluvisol** (**Hyperthionic**, **Clayic**). The specifier Endo- is added to Gleyic because the gleyic colour pattern starts below 50 cm. Hyper- is added to Thionic to indicate the very low pH.

WRB qualifiers

This section explains the terms used in the legend of the soil maps in this atlas. The description of the qualifiers below avoids technical language as much as possible to facilitate the reader's understanding of specific soil terminology.

Albic: a light-coloured subsurface horizon from which clay and free iron oxides have been removed, or in which the oxides have been segregated to the extent that the colour of the horizon is determined by the colour of the sand and silt particles rather than by coatings on these particles.

Arenic: having a loamy fine sand or coarser layer, at least 30 cm thick, within 100 cm of surface.

Argic: a subsurface horizon with distinctly higher clay content than the overlying horizon.

Brunic: having a layer starting within 50 cm of the soil surface, at least 15 cm thick, which meets certain alteration criteria of the cambic horizon but lacks the cambic texture criteria.

Calcaric: having 2% or more calcium carbonate between 20 and 50 cm depth.

Calcic: having a layer, 15 cm or more thick, with 15% or more secondary carbonate present only in the form of fine particles dispersed in the matrix or as discontinuous concentrations.

Cambic: having a subsurface horizon starting within 50 cm depth showing evidence of alteration with respect to the underlying material.

Carbic: having a layer with illuvial amorphous substances composed of organic matter and aluminium that does not become redder on ignition.

Chromic: having a reddish coloured subsurface layer, 30 cm or more thick.

Duric: a subsurface horizon showing weakly cemented nodules or concretions cemented by silica (SiO_2).

Dystric: having a base saturation of less than 50% in the major part between 20 and 100 cm depth.

Eutric: having a base saturation of 50% or more in the major part between 20 and 100 cm depth.

Ferralic: a horizon within 100 cm of the soil surface where the clay fraction is dominated by low-activity clays and the silt and sand fractions by highly resistant minerals, such as (hydr)oxides of Fe, Al, Mn and titanium (Ti).

Ferric: a horizon within 100 cm of the soil surface where segregation of Fe and/or Mn has taken place to such an extent that discrete nodules have formed and the internodular matrix is largely depleted of Fe.

Fibric: having, after rubbing, two-thirds or more of the organic material consisting of recognisable plant tissue within 100 cm depth.

Gleyic: having influence of groundwater within 50 cm depth.

Haplic: having no applicable other qualifier.

Hypoluvic: Having an increase in clay content of 3% or more within 100 cm of the soil surface (Arenosols only).

Lithic: having continuous rock within 10 cm depth.

Lixic: Having an argic horizon that has a low nutrient holding capacity in some part to a maximum depth of 50 cm below its upper limit.

Luvic: having a subsurface horizon with higher clay content than the overlying horizon, a moderate to high nutrient holding capacity and a base saturation of 50% or more between 50 and 100 cm depth.

Mesotrophic: having base saturation of <75% at a depth of 20 cm from soil surface.

Mollic: having a thick, dark surface horizon rich in humus and a neutral soil reaction.

Nudilithic: having continuous rock at the surface.

Pellic: having in the upper 30 cm of the soil a dark colour with a Munsell value when moist of 3.5 or less and a chroma of 1.5 or less (Vertisols only).

Petric: having a strongly cemented or indurated layer starting within 100 cm of the soil surface.

Pisoplinthic: having a horizon starting within 100 cm of the soil surface containing nodules that are strongly cemented with Fe and/or Mn.

Plinthic: a subsurface horizon that consists of Fe-rich, humus-poor mixture of kaolinitic clay with quartz and other constituents, that hardens irreversibly on exposure to repeated wetting and drying.

Protic: showing no soil horizon development.

Rendzic: having a thick, dark surface horizon rich in humus and a neutral soil reaction, that contains or overlies material with a calcium carbonate equivalent of 40% or more.

Rhodic: Having within 150 cm of the soil surface a reddish subsurface layer, 30 cm or more thick, with a Munsell hue that is redder than 5 YR, a value of less than 3.5 when moist and when dry, a value that is no more than one unit higher than when moist.

Salic: having a horizon rich in salt within 100 cm depth.

Sapric: having, after rubbing, less than one-sixth of the organic material consisting of recognisable plant tissue within 100 cm depth.

Silandic: Having one or more layers, cumulatively 30 cm or more thick, with andic properties (Andosols only).

Skeletic: having > 40% (by volume) gravel or other coarse fragments over a depth of 100 cm from the surface.

Sodic: having 15% or more exchangeable sodium plus magnesium within 50 cm depth.

Solodic: having a layer, 15 cm or more thick within 100 cm depth, with a strong columnar or coarse prismatic structure that does not have 15% or more exchangeable sodium plus magnesium.

Stagnic: having stagnation of surface water within 50 cm depth.

Thionic: having a horizon rich in sulphur or a layer with sulphides, 15 cm or more thick within 100 cm depth.

Takyric: having a heavy-textured surface horizon comprising a surface crust and a platy structured lower part.

Tidalic: flooded by tidal water but not covered at average low tide.

Umbric: having a thick, dark surface horizon rich in humus and an acid soil reaction.

Vertic: having a clay-rich subsurface horizon with evidence of movement of soil masses within 100 cm depth.

Vitric: having layer(s), 30 cm or more thick, with a limited to moderate amount of allophane, imogolite or organo-metalic complexes resulting from the weathering of volcanic ash.

Xanthic: having a ferralic horizon that has in a sub-horizon, 30 cm or more thick within 150 cm of the soil surface, a Munsell hue of 7.5 YR or yellower and a value, when moist, of 4 or more and a chroma, when moist, of 5 or more.

Yermic: having a surface horizon of rock fragments embedded in a loamy layer, may be covered by thin wind-blown sand.

Further information on the WRB system can be found in the WRB 2006 Technical Manual [63], which can be downloaded from the WRB page on the FAO website [63a]. (FAO)

Major soil types of Africa

Reader's Tip!

This section presents the major types of soil that can be found in Africa as defined by the Reference Soil Groups of the World Reference Base (WRB) scheme. The following pages aim to help the reader understand the key characteristics of each soil type, their associated landscapes and their broad distribution pattern across Africa.

The soils are presented in two groups: those which have significant areal extent (referred to as the major soil types) and those with a more restricted occurrence across the continent (referred to as the minor soil types). In both cases, the soils are listed alphabetically.

Each block provides a clear definition and simple description of the soil. In addition, the reader is shown a typical profile that illustrates the soil's key characteristics and a typical landscape, land cover or land use that is associated with that soil. For the major soil types, a map indicates the regions where a particular type of soil is dominant. Due to the very small scale of these maps, the less extensive minor soil types cannot be shown.

The colour used in the box surrounding the soil name is the same as the legend of page 64 and for the overview and regional maps shown in pages 68 – 127. In this way, when you see a specific colour on the map (e.g. red), you can locate the same colour in this section to discover the basic characteristics of the soil in question (i.e. red corresponds to Andosols).

It's important to remember that a particular type of soil is not limited to the areas shown on the map and that on a local scale, other soil characteristics may be more significant.

Soil and water conservation structures in Tigray, Ethiopia. Thousands of kilometres of stone bunds were built by hand in a spectacular effort to protect shallow soils (Calcaric Regosols in this example) from further erosion. (KV)

Acrisols

Strongly acid soils with a clay-enriched subsoil and low nutrient-holding capacity (from Latin *acer*, acid)

Acrisols are acidic soils dominated by kaolinte and display a clay accumulation horizon in the subsoil. They are quite common in Africa and are mainly found in the wetter parts of the tropics and subtropics. They are normally associated with acidic bedrock and are deficient in nutrients, thus requiring substantial applications of fertiliser to produce satisfactory crop yields.

Left: Manual land preparation on the central plateau of Madagascar at the onset of the rains – note the dark red soil colour. (OS)

Below: Deep red Acrisol in eastern Madagascar with a thin, dark-coloured, surface layer enriched with humus. Clay particles have been lost from the lighter coloured layer by leaching or faunal activity (probably termites). The round, light-coloured areas are old roots and channels of burrowing animals filled with material from above. (OS)

The map shows where Acrisols are dominant. They cover around 3% of Africa.

Soil Taxonomy classifies most of these soils as Ultisols.

Alisols

Very acid soils with a clay-enriched subsoil and high nutrient-holding capacity (from Latin *alumen*, alum)

Alisols have a higher clay content in the subsoil than in the topsoil as a result of clay migration. Alisols have a low base saturation at certain depths and high-activity clays (e.g. vermiculite, illite and montmorillonite) are present in the clay-rich horizon. The acidity is caused by the weathering of minerals which release a large amount of aluminium - often at levels that are toxic to most crops. They occur predominantly in humid tropical, humid subtropical and warm temperate regions.

Left: Undulating landscape over sandstone in Natal, South Africa. The vegetation is semi-natural grassland grazed by goats and sheep. (ISRIC);

Below: Deep, red Alisol from Natal, South Africa. The soil has a dark, humus-enriched surface layer. The acid nature of the soil inhibits deep rooting. The bright red and yellow spots at about 1 m depth indicate a layer of iron accumulation which must remain moist to prevent hardening. (ISRIC); The map shows where Alisols are dominant. They cover around 1% of Africa.

Soil Taxonomy classifies most of these soils as Ultisols.

Andosols

Young soil developed in volcanic deposits (from Japanese *an*, black and *do*, soil)

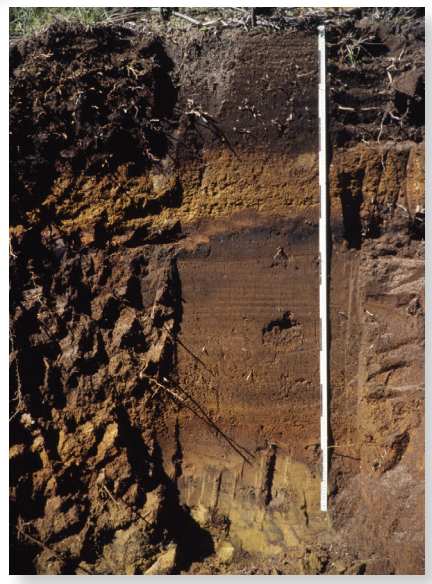
Andosols develop from materials ejected from volcanoes (e.g. ash, pumice, cinder) which weather to produce specific clay minerals. In more humid climates, many Andosols develop a thick, dark topsoil as a result of the fixing of organic substances by aluminium that is released from the weathering of the clay minerals. Andosols are found along the Rift Valley in Eastern Africa, around Mount Cameroon,and in Madagascar. They have a high potential for agricultural production, but many suffer from strong phosphorus fixation due to high levels of active iron and aluminium.

Left: Andosols are found on the slopes of volcanoes or in areas that have received ash, pumice or cinders from an eruption. The picture shows volcanic cones of the Virunga Mountains on the border between Rwanda, the DR Congo and Uganda. There are many active and extinct volcanoes along the African Rift Valley. (SDD)

Below: This profile shows clear layering as a result of intermittent eruptions of Mount Kenya. The upper 50 cm represent the youngest soil. An older soil occurs below in which the original, dark-coloured surface layer is still visible. (ISRIC)

The map shows where Andosols are dominant. They cover less than 1% of Africa.

Soil Taxonomy classifies most of these soils as Andisols.



Arenosols

Easily erodable sandy soil with low water- and nutrient-holding capacity (from Latin, *arena*, meaning sand).

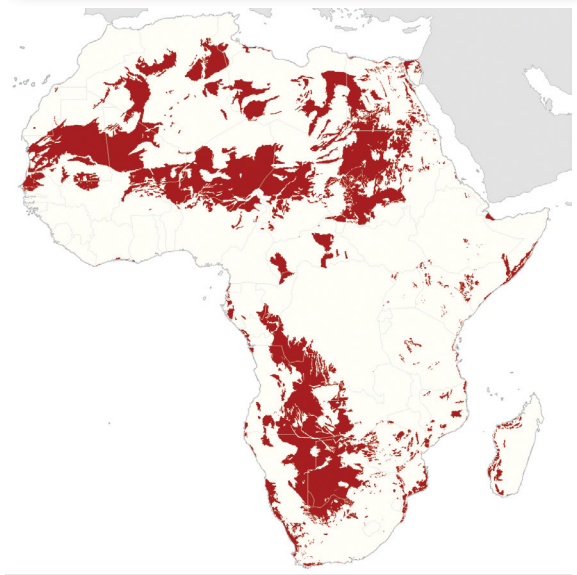
Arensols develop as a result of the in situ weathering of quartz-rich parent material or in recently deposited sands (e.g. dunes in deserts and beaches). They are among the most extensive soil types in the world and are the dominant soil in Africa. The Kalahari Sands is the largest body of sand on Earth. Soil formation is often limited by a low weathering rate. If vegetation has not developed, they can be prone to wind erosion. Once vegetated, the accumulation of organic matter, clay bands or the formation of humus-aluminium complexes can occur.

Left: Attempts to stablise migrating sand dunes in southern Tunisia using date-frond fences. Left unchecked, dune systems can engulf villages and fields. (TG)

Below: Deep, sandy soil with thin, clay-rich bands in South Africa. Clay migrates through the soil with percolating water and is deposited in bands where the wetting front stops. The presence of these bands enhances the water-holding capacity just enough for crops to survive short dry spells. The holes are burrows. (ISRIC)

The map shows where Arenosols are dominant. They cover around 22% of Africa.

Soil Taxonomy classifies most of these soils as Psamments.



Calcisols

Soil with significant accumulation of calcium carbonates, generally found in dry areas (from Latin *calcarius*, lime-rich)

Calcisols occur in many parts of Africa, especially where the climate is dry enough to allow the accumulation of calcium carbonate in the soil. They form through the leaching of carbonates from the upper part of the soil which precipitate when the subsoil becomes oversaturated, from carbonate-rich water moving through the soil or by the evaporation of water which leaves behind dissolved carbonates. Precipitated calcium carbonate can fill the pores in the soil, thereby acting as a cementing agent, and can form a solid hard pan (calcrete) that is impenetrable to plant roots.

Left: Extensive grazing is one of the few options on dry Calcisols. (EM)

Below: a typical Calcisol landscape in Namibia. The carbonate enrichment is such that a hard calcrete layer has developed 20 cm below the surface. (EM)

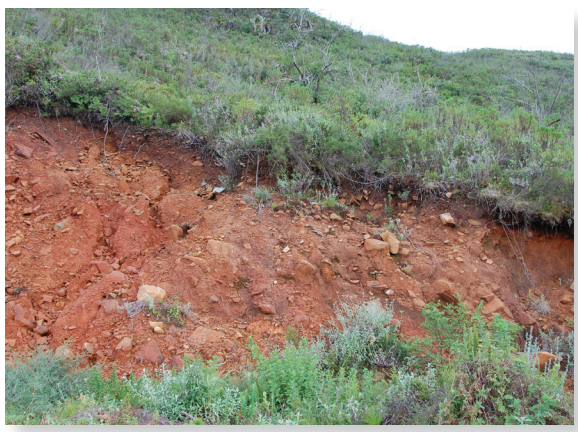
The map shows where Calcisols are dominant. They cover around 6% of Africa.

Soil Taxonomy classifies most of these soils as Calcids.

Cambisols

Soil that is only moderately developed on account of limited age (from Latin *cambiare*, to change)

These are young soils. Generally lacking distinct horizons, Cambisols exhibit only slight evidence of soil-forming processes usually through variations in colour, the formation of structure or presence of clay minerals. They are extensive throughout Africa and can have varied characteristics depending on the nature of the parent material, climate and terrain.

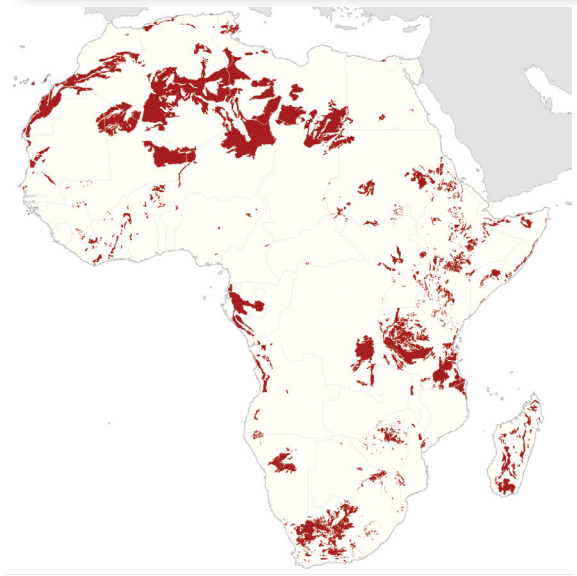


Left: Chromic Cambisol at Tsetsera Sussundenga district in Mozambique. Incipient soil formation has resulted in a distinctive red colour due to high levels of iron oxide. (SDD)

Below: A profile of a deep Cambisol in Rwanda. Roots of plants extend deep into the subsoil to obtain nutrients from freshly weathering minerals. (ISRIC)

The map shows where Cambisols are dominant. They cover around 11% of Africa.

Soil Taxonomy classifies most of these soils as Inceptisols.



Ferralsols

Strongly weathered soils with low nutrient-holding capacity (from Latin *ferrum*, iron and *alumen*, alum)

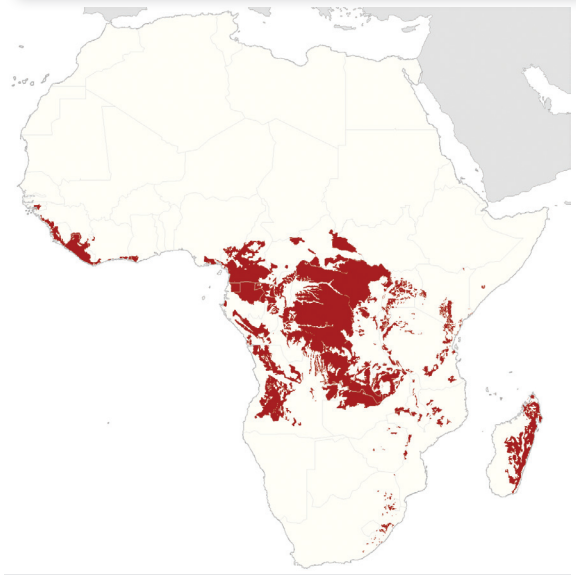
Ferralsols are widespread in Central, Eastern and Southern Africa. Mostly associated with high rainfall areas and very old (Tertiary) land surfaces, they are strongly leached soils that have lost nearly all of their weatherable minerals over time. As a result, they are dominated by stable products such as aluminium oxides, iron oxides and kaolinite which give Ferralsols their strong red and yellow colours. Levels of calcium and magnesium are very low. The binding of particles by iron oxides gives an apparent sandy or silty feeling (pseudosand).

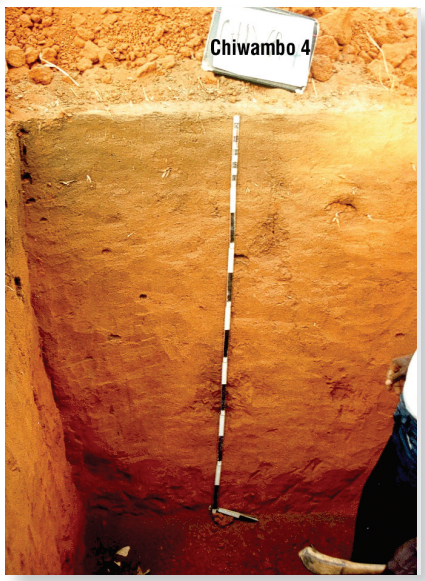
Left: In very acid soils, such as on this Arenic Ferralsol on the Makonde Plateau, Tanzania, plants such as pineapple (*Ananas comosus*) are a good choice as an intercrop with cashew (*Anacardium occidentale*). (JD)

Below: An Acric Ferralsol from the Mtwara District of Tanzania (the centre of the disastrous Tanganyika groundnut scheme – see page 45). Noticeable is the characteristic lack of layering in the profile as a result of biological mixing and the low organic matter content of the topsoil. (SDD)

The map shows where Ferralsols are dominant. They cover around 10% of Africa.

Soil Taxonomy classifies most of these soils as Oxisols.





Fluvisols

Young soil in floodplains, lakes, deltas or marine deposits (from Latin *fluvius*, river)

Fluvisols occur in all periodically flooded areas such as flood plains, river fans, valleys, tidal marshes and mangroves throughout Africa. Fluvisols show a layering of sediments with pedogenic horizons as a result of deposition by water. Their characteristics and fertility depend on the nature and sequence of the sediments and length of periods of soil formation after or between flood events. High water velocities or turbulent action gives rise to gravelly or sandy soils. Low velocities or standing water give rise to fine-textured soils, often mixed with significant amounts of organic debris.

Left: Fluvisol along the bank of the Zambezi River in Zimbabwe. The layered structure of the soil, caused by the deposition of new material during floods, is evident. (OS)

Below: Distinctive horizontal strata of a Fluvisol in the bank of the Manafwa River, Uganda. Banana plants thrive in the fertile, loamy soils which receive biannually fresh sediment originating from landslides on Mount Elgon (see page 158). (JD)

The map shows where Fluvisols are dominant and clearly denotes the major river network. They cover around 3% of Africa.

Soil Taxonomy classifies most of these soils as Fluvents.

Gleysols

Soils saturated by groundwater for long periods (from Russian *gley*, 'mucky mass')

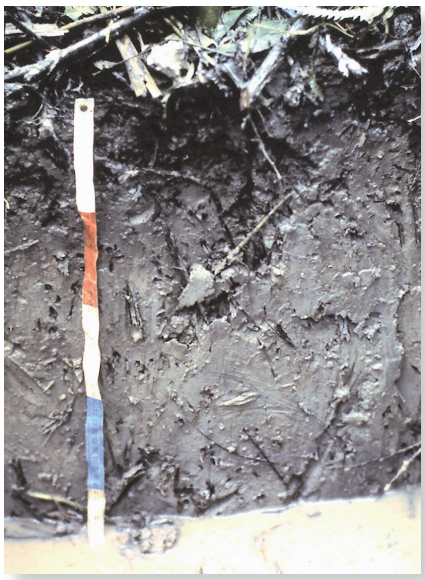
Gleysols occur in low-lying areas or depressions where the groundwater comes close to the surface and the soil is saturated with water for long periods of time. Gleysols display characteristic reddish, brownish or yellowish colours in the upper part of the soil where oxygen is present, in combination with greyish/bluish colours deeper in the soil where oxygen is absent (reduced). Often Gleysols are found with wetland vegetation (e.g. grass, reeds, sedges). Because of their wetness, Gleysols show little soil development apart from accumulation of organic matter in the surface layer and rust mottling.

Left: Typical Gleysol landscape with standing water between the Kafue and Zambezi Rivers in central Zambia. (OS)

Below: Completely reduced Gleysol from the Niger River delta, Nigeria. (OS)

The map shows where Gleysols are dominant. They cover around 2% of Africa.

Soil Taxonomy classifies most of these soils as aquic suborders.



Gypsisols

Soil with significant accumulation of gypsum, generally found in dry areas (from Greek *gypsos*, gypsum)

Gypsisols are soils with substantial (secondary) accumulation of gypsum ($CaSO_4.2H_2O$). They are found in the driest parts of the arid climate zone, and in Africa the are predominantly found in the northern Sahara. Many Gypsisols occur in depressions and reflect former lake beds that have dried up through evaporation. The processes for gypsum precipitation are similar to Calcisols (see previous page). Gypsum that forms a solid hard pan is referred to as gypcrete. Natural vegetation is sparse and dominated by xerophytic shrubs or ephemeral grasses.

Left: Gypsisols under a semi-arid climate around the Chott Djerid in Tunisia. Hardened gypcrete is common in this region. (AJ)

Below: A Gypsisol profile from Makanya in Tanzania (southwest of Mt. Kilimanjaro). Above the knife, the soil has a non-cemented horizon containing significant amounts of secondary accumulation of gypsum. Below the knife, a harder (more indurated), petrogypsic horizon is evident. (JD)

The map shows where Gypsisols are dominant. They cover nearly 2% of Africa.

Soil Taxonomy classifies most of these soils as Gypsids.

Histosols

Soils with a large amount of organic material generally developed under excess water or cold conditions (from Greek *histos*, tissue)

Histosols, also known as peat, contain a high amount of organic matter, usually more than 20%, and have a high water content. Their bulk density is very low and when drained, they suffer from irreversible shrinkage and surface subsidence. Histosols are rather rare in Africa, occurring mostly in wetlands, isolated pockets in low-lying areas or depressions and in coastal regions where organic debris accumulates. Their distribution is limited by the rapid decomposition of organic material in tropical regions due to the permanently high temperatures.

Left: Histosols are typical of wetlands. This small depression is in the vast rainforest of the Ivindo National Park in Gabon. (BM)

Below: A Histosol on the slopes of Mount Bisoke – extinct volcano in the Virunga Mountains of Rwanda. In the Virungas, peat is found in swampy conditions at high altitudes. (SDD)

While Histosols may be significant locally, their distribution accounts for less than 1% of Africa.

Soil Taxonomy classifies these soils as Histosols.

Leptosols

Shallow soil over hard rock or gravelly material (from Greek *leptos*, thin).

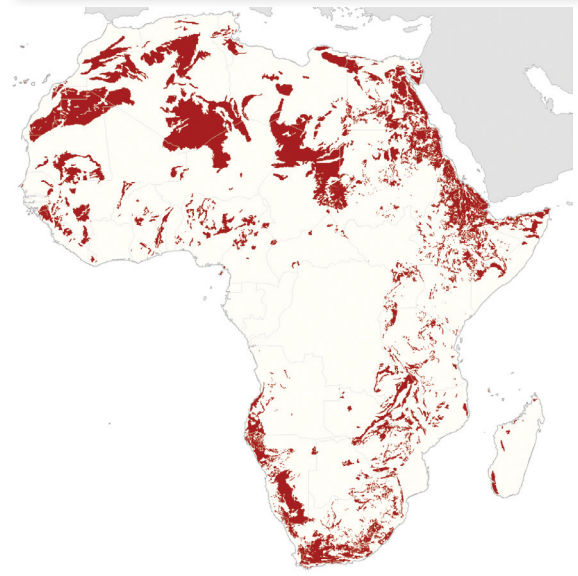
Leptosols are shallow soils over hard rock, very gravelly material or highly calcareous deposits. Because of limited pedogenic development, Leptosols have a weak soil structure. Leptosols occur all over Africa, especially in mountainous and desert regions where hard rock is exposed or comes close to the surface and the physical disintegration of rocks due to freeze/thaw or heating/cooling cycles are the main soil-forming processes. In WRB, bare rocks exposes at the surface (possibly displaying only microscopic soil formation) are referred to as Nudilithic Leptosols.

Left: Rock outcrops are typical of Leptosol landscapes. Trees must be shallow rooting or develop where the soil is a little deeper and where impeded drainage can lead to higher water retention. (EM)

Below: Leptosol from Ethiopia – a cover of debris some 20 cm thick overlies a dolerite. Soil development is slow. Only limited extensive grazing is possible. (JD)

The map shows where Leptosols are dominant. They cover around 17% of Africa.

Soil Taxonomy classifies most of these soils as Entisols.



Lixisols

Slightly acid soils with a clay-enriched subsoil and low nutrient-holding capacity (from Latin *lixivia*, washed-out substances)

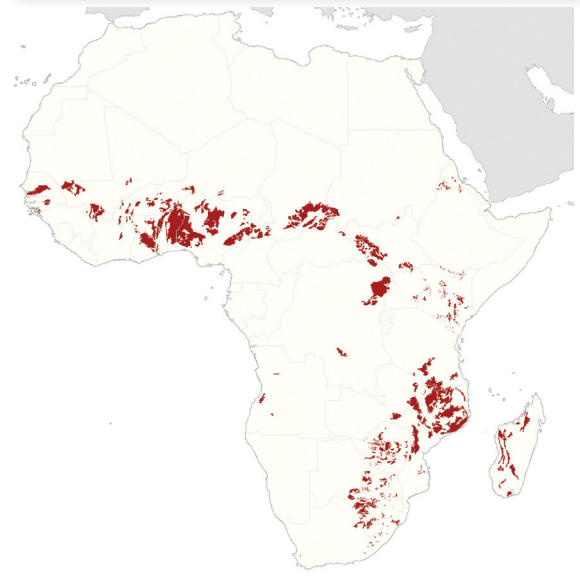
Lixisols are slightly acid soils that show a distinct increase in clay content with depth. The clay is predominantly kaolinite with limited capacity to hold nutrients. Occurring mainly in the dry savannah region with low biomass production, Lixisols do not hold much organic matter and lack a well developed soil structure. High-intensity rainfall will destroy any soil structure present making Lixisols prone to erosion. If the soil is not protected, a crust may develop which prevents rain entering the soil. Overland flow will then erode the topsoil which is the most fertile part. Wind erosion may be an issue as loose soil particles at the surface can easily be blown away.

Left: A cultivated Lixisol from Tanzania. Note the use of sorghum stalks as a mulch to protect the soil from erosion. (OS)

Below: A characteristically red Lixisol from Tanzania. (EM)

The map shows where Lixisols are dominant. They cover around 4% of Africa.

Soil Taxonomy classifies most of these soils as Alfisols.



Luvisols

Slightly acid soils with a clay-enriched subsoil and high nutrient-holding capacity (from Latin *luere*, to wash).

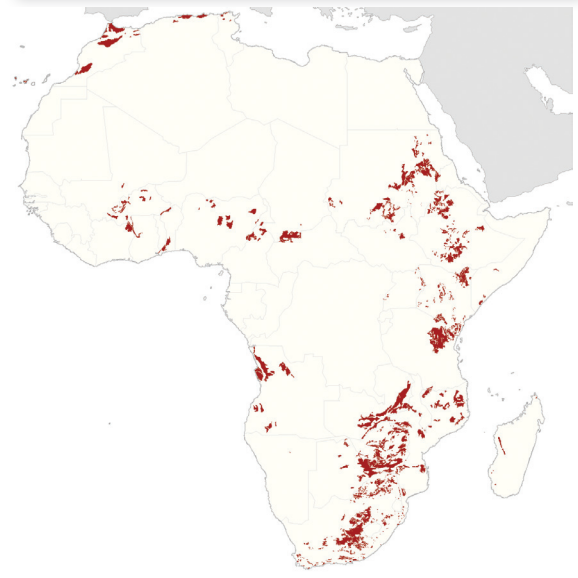
Luvisols have a distinct increase in clay content with depth as a result of clay movement from the upper part of the soil to the lower part. The clay is usually a mixture of kaolinite, illite and montmorillonite, giving the soil a high nutrient-holding capacity. In general, Luvisols have a well-developed soil structure, which contributes to a good water-holding capacity. Luvisols in Africa are mainly found in the Mediterranean region and in the southern and eastern parts of Africa on relatively young surfaces.

Left: Drip-irrigated cultivation on Luvisols in Morocco. Note the virtual absence of a darker coloured surface layer, indicating that this soil is poor in organic matter. (OS)

Below: Red Luvisol from Botswana – note the deep rooting and the much better developed soil structure compared to the Lixisosl. (ISRIC)

The map shows where Luvisols are dominant. They cover around 4% of Africa.

Soil Taxonomy classifies most of these soils as Alfisols.



Nitisols

Deep red soils with a well developed, nut-shaped structure (from Latin *nitidus*, shiny)

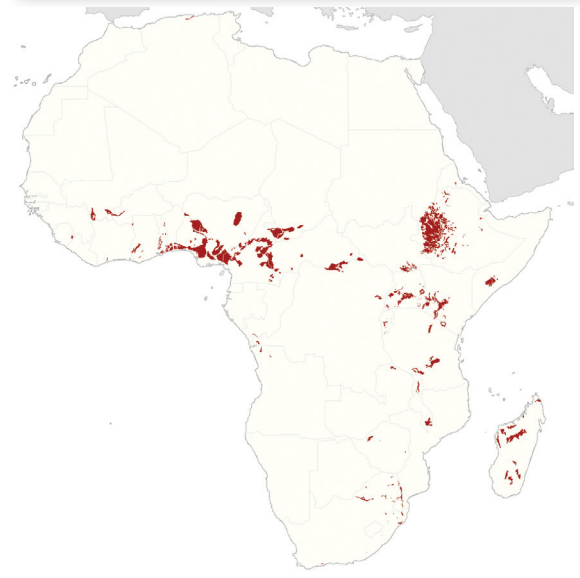
Nitisols develop mainly from basic iron-rich rocks such as basalt. Their main characteristics are a dark red colour and a well-developed structure that is nutty in appearance with shiny surfaces. The active iron content (i.e. amorphous iron oxides and hydroxides) is high, which enforces strong bonding of soil particles and the formation of the nut-shaped aggregates. The shiny surfaces are a mixture of clay and iron coatings. Most Nitisols are dominated by kaolinite clay. While common in eastern Africa, they also occur in many other parts of Africa.

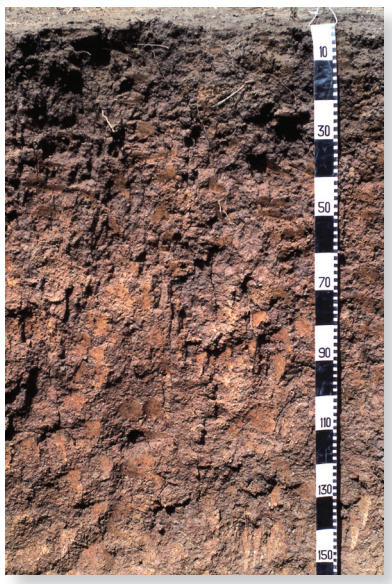
Left: Nitisols are much sought after because of their high productivity despite a high phosphate-fixing capacity. Coffee crop on Nitisols in the highlands of Kenya. (ISRIC)

Below: Nitisols are mainly developed in highly weathered products of basic igneous parent rock. This Nitisol from Benin shows a well-developed structure. Rooting is limited to the upper part of the soil due to strong acidity and high aluminium toxicity in the subsoil. (OS)

The map shows where Nitisols are dominant. They cover around 2% of Africa.

Soil Taxonomy classifies most of these soils as Oxisols.





Phaeozems

Slightly acid soils with a thick, dark-coloured surface layer (from the Greek *phaios*, dusk and Russian, *zemlja*, earth or land)

Phaeozems are characterised by their, thick, dark-coloured, surface layer which is rich in organic matter and well-supplied with nutrients. Their development requires a reasonable amount of precipitation and a lush vegetation, preferably grasses. This characteristic distinguishes them from Chernozems, which they border where conditions are wetter, and Kastanozems where conditions are drier. Outside Africa, they are typical prairie soils. Most Phaeozems in Africa occur in the highlands, but their distribution is quite limited.

Left: Strip cultivation along contours on Phaeozems in South Africa to prevent erosion. (ISRIC)

Below: Phaeozem on exfoliating dolerite in Natal, South Africa. (ISRIC)

The map shows where Phaeozems are dominant. They cover less than 1% of Africa.

Soil Taxonomy classifies most of these soils as Mollisols.

Planosols

Poorly structured surface layer abruptly overlying a slowly permeable layer (from Latin *planus*, flat)

The most important characteristic of Planosols is the very slow permeability of the subsoil which causes water entering the soil to stagnate above this layer. The transition to the slowly permeable layer is very sharp - clay content at least doubles or significantly increases. As a result of the frequent waterlogging in the topsoil, iron and manganese are dissolved and precipitated as reddish-brown or black concretions on both sides of the abrupt boundary. The removal of iron in the topsoil causes the structure to collapse. Therefore, most Planosols have a structureless topsoil.

Left: Bricks made from material from the bleached horizon of Planosols in southwestern Ethiopia. (EVR)

Below: Planosol from Ethiopia. The abrupt textural change at 40 cm depth is clearly visible. The surface layer is almost structureless and has a thin (5 cm) organic layer. (EVR)

The map shows where Planosols are dominant. They cover just over 1% of Africa.

Soil Taxonomy classifies most of these soils as Albaqualfs and Albaquults.

Plinthosols

Soils with accumulation of iron that hardens irreversibly when exposed to air and sunlight (from Greek *plinthos*, brick)

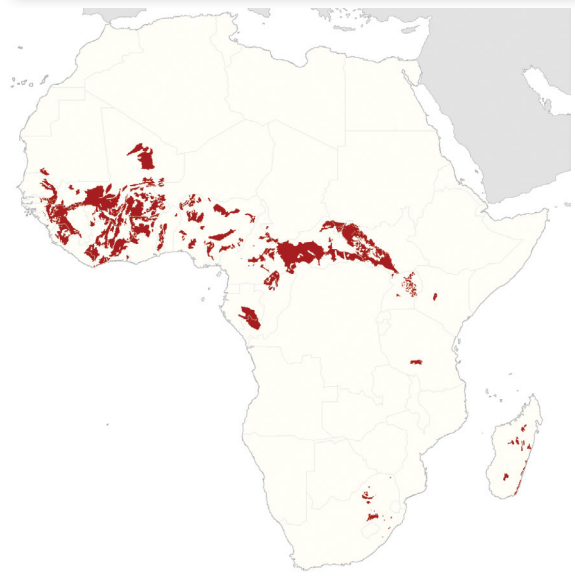
Plinthosols display an accumulation of iron (and manganese) in the subsoil as large mottles or concretions. This iron-rich layer develops mostly under the influence of fluctuating groundwater. While buried, the layer (called plinthite) is soft and can be cut by a knife. However, once exposed to air and sunlight, it hardens irreversibly and is often known as ironstone). When brought to the surface by erosion, the hard ironstone layer forms a cap that protects the area from further erosion. Non-protected areas continue to erode and what originally were the lower parts became the highest parts in the landscape. This phenomenon is known as landscape inversion.

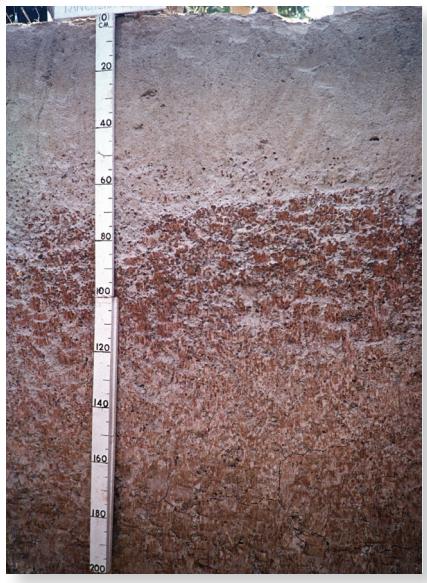
Left: Tableland landscape in northern Burkina Faso defined by an old ironstone cap. Over time the ironstone cap and protected slopes are degraded to give a catena of Petric Plinthosols, Pisoplinthic Plinthosols and Eutric Plinthosols, with Regosols in the upper part of the slope. (MB/IRD)

Below: Plinthosol in Ghana. The iron-rich layer starts at 70 cm depth and occurs here as interconnected mottles. (ISRIC)

The map shows where Plinthosols are dominant. They cover around 5% of Africa.

Soil Taxonomy classifies most of these soils with the Plinth- prefix of Ultisols and Oxysols.





Regosols

Weakly developed soils in unconsolidated material (from Greek *rhegos*, blanket)

Regosols are weakly developed mineral soils in unconsolidated medium and fine-textured material - more coarse-textured soils are Arenosols (in the case of sand) or Leptosols (in the case of gravel). Regosols show only slight signs of soil development - some accumulation of organic matter producing a somewhat darker topsoil is often the only evidence of soil formation. Limiting factors for soil development range from low temperatures, prolonged dryness, characteristics of the parent material or erosion. Regosols are extensive in eroding lands such as mountains or deserts where soil formation is generally absent.

Left: Landscape with Regosols in the Middle Atlas of Morocco – gullies that have developed by the overland flow of rainwater and bare areas due to sheet erosion are clearly visible – rock outcrops are often common. (AR)

Below: Regosol on weathering tilted schist in the Anti Atlas mountains of Central Morocco. The loosened mixture of gravels and fine earth is heavily affected by slope processes, giving little chance for soil formation. (OS)

The map shows where Regosols are dominant. They cover around 3% of Africa.

Soil Taxonomy classifies most of these soils as Entisols.

Solonchaks

Soils with accumulation of salt (from Russian *sol*, salt)

Solonchaks are strongly saline with high concentrations of soluble salts. They are mostly associated with arid regions and with areas where saline groundwater comes close to the surface or where evapo-transpiration rates are considerably higher than precipitation, at least during a large part of the year. Salts dissolved in soil moisture remain behind after the evaporation of the water and accumulate on or just below the surface. Their characteristics and limitations to plant growth depend on the amount, depth and composition of the salts.

Left: A salt flat with Halophyte vegetation in Namibia. Recent water has evaporated leaving a distinctive 'puffed' up surface that collapses if walked upon. (EM)

Below: A Solonchak from southern Morocco. The white surface layer with a thickness of about 50 cm is very rich in soluble salt derived from slightly saline groundwater at a depth of 5 m which comes to the surface by capillary rise. (AR)

The map shows where Solonchaks are dominant. They cover around 1% of Africa.

Soil Taxonomy classifies most of these soils as Salids.

Solonetz

Soil with a clay accumulation horizon, rich in sodium (from the Russian, *sol*, meaning salt and *etz*, meaning strongly expressed).

Solonetz are strongly alkaline soils. They display with a dense, clay-rich subsoil containing a high amount of exchangeable sodium and a distinctive columnar structure. Sodium has the ability to disperse clay particles and organic matter in the topsoil, which are subsequently washed deeper into the soil. Large pores are filled with clay and structural elements capped with organic coatings. Solonetz are normally associated with flat lands in climates with hot, dry summers or with former coastal deposits that contain a high proportion of salt.

Left: An eroding Solonetz landscape from South Africa with salt tolerant vegetation. (EM)

Below: Solonetz from Namibia. The profile shows light coloured surface horizon (0–20 cm) overlaying a dense, strongly structured, sodium-rich subsoil horizon (20–80 cm) that exhibits a blocky or columnar top. Note the abrupt transition to the sodium-rich subsoil. (EM)

The map shows where Solonnetz are dominant. They cover around 1% of Africa.

Soil Taxonomy classifies most of these soils as Aridisols.

Umbrisols

Acidic soil with a dark surface horizon rich in organic matter (from Latin *umbra*, shade)

Umbrisols have a deep, dark-coloured surface layer that is rich in organic matter but has a low nutrient content. They are mainly associated with acid parent materials and areas with high rainfall. In Africa they mainly occur in mountains and highland regions and on sandy soils in the tropics in areas with high rainfall. Umbrisols are the counterpart of nutrient-rich soils with a dark surface horizon (i.e. Chernozems, Kastanozems and Phaeozems).

Left: Permanent grasslands in Natal, South Africa, give rise to significant organic matter levels in the topsoils of shallow Umbrisols that have developed on the weathering products of shale and siltstone. (EM)

Below: Umbrisol from central Angola in Kalahari sand; although the soil has a Podzol morphology (dark topsoil over an ash-white layer on top of a brownish subsoil), the content in organic carbon of the subsoil is far below the required amount. (JAR)

The map shows where Umbrisols are dominant. They cover less than 1% of Africa.

Soil Taxonomy classifies most of these soils as Entisols and Inceptisols.

Vertisols

Clay-rich soils that develop deep, wide cracks upon drying (from Latin *vertere*, to turn)

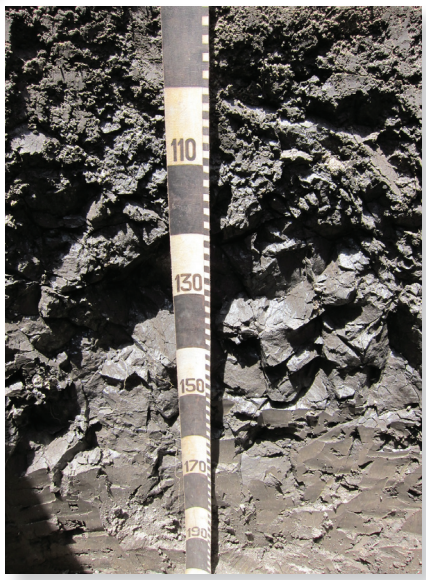
Vertisols are clayey soils that exhibit wide cracks which open and close periodically upon drying and wetting. This is caused by the presence of the clay mineral, montmorillonite, which takes up water when it becomes wet (and expands) and releases the water again upon drying out (shrinks). This process brings material from the surface into the subsoil giving rise to a 'mixed or churned' soil (see page 27). Vertisols are widespread in Africa; especially in the Maghreb, Sudan and Ethiopia.

Left: Ethiopian farmer on the way to plough his Vertisol land with the traditional Maresha plough. (JD)

Below: Black Vertisol from near Jimma in Ethiopia. The photo shows wedge-shaped structural elements (sphenoids) with smoothened surfaces formed by shear stresses on moistening (typical for Vertisols). (EVR)

The map shows where Vertisols are dominant. They cover around 3% of Africa.

Soil Taxonomy classifies most of these soils as Vertisols.



Minor soil types of Africa

While all the soil types on this spread may be important locally, their overall extents are generally limited (<0.5% of the land surface of Africa) and their distribution is too sparse to display on very small-scale maps.

Anthrosols

Soil formed or modified by agricultural activity over a long period of time (from Greek *anthropos*, man)

Anthrosols are formed through human activities such as the addition of organic material, household wastes, lime, charcoal, earth-sods or mineral matter. The added material is usually deeply tilled into the original soil. In most cases, a buried soil can still be found at some depth from the surface. Anthrosols include 'Paddy Soil' where the long-term cultivation of rice causes unique soil characteristics as a result of the repeated lack of oxygen. The morphological and chemical characteristics of these soils vary and depend on the specific human activity.

Left: Profile of an Anthrosol that has developed in a valley bottom vegetable garden in the Usambara Mountains in Tanzania through the addition of earthy manures, compost or muds over a long period of time. (JD)

Below: Due to their high organic matter content and good soil structure, Anthrosols are intensively cultivated. (SG)

On a continental scale, Anthrosols are rarely dominant but locally can be very important.

Soil Taxonomy classifies then as Anthreps.

Chernozems

Soil with a deep, dark topsoil that is rich in organic matter (from Russian *chern* black, and *zemlja*, earth).

Chernozems have a very dark-brown or blackish surface horizon with a significant accumulation of organic matter and a neutral pH. Secondary calcium carbonate deposits occur within 50 cm of the lower limit of the humus-rich horizon. They show high biological activity and are typically found in the long-grassland areas in humid-temperate climates (e.g. prairies). Chernozems are among the most productive soil types in the world.

Left: A Chernozem from the coastal plain south of Rabat, Morocco. The darker topsoil (0 – 45 cm) contains significant amounts of organic matter. The lighter material in the subsoil is calcium carbonate. Chernozems are very rare in Africa. (OS)

Below: Considered as one of the world's best soils, this Chernozem in Morocco supports the cultivation of cereal crops. Irrigation may be required in dry conditions. (EM)

Soil Taxonomy classifies these soils as Mollisols.

Cryosols

Soil of cold regions with permafrost and/or cryoturbation (from Greek *kraios*, cold or ice)

Cryosols develop in cold regions where permanently frozen subsoil (permafrost) is found. In this type of soil, water occurs primarily in the form of ice and cryogenic processes such as freeze-thawing cycles, cryoturbation (warping), frost heave, cryogenic sorting, cracking and ice segregation are the dominant soil-forming processes. Cryosols often exhibit distorted horizons and/or patterned ground.

Left: A 10 cm organic layer on the top of a highly cryoturbated (mixed) horizon (10–70 cm) with permafrost at 70 cm. The cavity at the base of the profile is caused by melting of the ice due to the excavation of the soil pit. The grey colours indicate waterlogging. Photographs from Africa are very difficult to find – this example is from Siberia! (SB)

Below: The snow-covered summit of Kilimanjaro. While their distribution is very small on a continental basis, this arctic environment also occurs on Mount Kenya and on the Ruwenzori. (PDI)

Soil Taxonomy classifies most of these soils as Gelisols.

Durisols

Soils with accumulation of silica (from Latin *durus*, meaning hard)

Durisols are associated with old surfaces in arid and semi-arid environments in western South Africa, southern Namibia and along the coast of Morocco. They display hardened (secondary) accumulations of silica (SiO_2) in the soil. Durisols develop over long periods during which the soil reaction is so alkaline (pH > 8) that silicon becomes mobile. The dissolved silicon precipitates as an amorphous opal, nodules (durinodes) and eventually, hard layers known as duripans develop (in South Africa these are known as dorbanks). Eventually, such hard pans may turn into silcrete.

Left: Durisol with hard pan and a shallow, loose topsoil in South Africa. (FE)

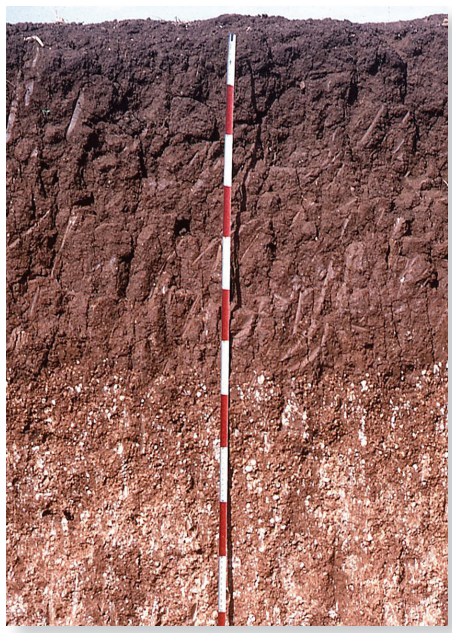
Below: Duripan capping an old land surface in South Africa. Below the soil, a deeply weathered white rock is visible. (FE)

While locally significant, on a continental scale, Durisols occupy less than 0.5% of Africa.

Soil Taxonomy classifies most of these soils as Durids.

Kastanozems

Soil with an organic-rich surface horizon and calcium carbonate or gypsum accumulation in the subsoil (from Latin *castanea*, chestnut, and Russian *zemlja*, earth)



Kastanozems have a deep, dark coloured surface layer with a significant accumulation of organic matter and high base saturation and an accumulation of (secondary) calcium carbonate in the subsoil. Kastanozems are mostly found in the Mediterranean part of Africa and as localised occurrences in southern Africa. They develop in the drier parts of the savannah regions where there is still sufficient biomass production to form the organic-rich surface layer and dry enough to facilitate the precipitation of carbonates or gypsum.

Left: Kastanozem from the Triffa Plain, Morocco, showing a dark coloured, humus-rich surface layer. Secondary calcium carbonate is visible below 70 cm. (AR)

Below: Hill slopes in the Rif Mountains, Morocco. The dark areas correspond to Kastanozems, lighter patches are Calcisols – a result of topsoil erosion. (SH)

While locally they may be significant, on a continental scale, Kastanozems occupy less than 0.5% of Africa.

Soil Taxonomy classifies most of these soils as Mollisols.

Podzols

Acid soil with a bleached horizon underlain by an accumulation of organic matter, aluminium and iron (from Russian *pod*, under, and *zola*, ash)

Podzols have a distinctive ash-grey horizon which has been bleached by the loss of organic matter and iron oxides. This sits on top of a dark accumulation horizon of redeposited humus and/or reddish iron compounds. Typically occurring in temperate zones, Podzols are not well developed in Africa; most of them barely exhibit the ash-grey layer and the amount of accumulated organic matter in the subsoil is not very high. Podzols have been recorded in the Kalahari Sands (Angola), Congo, Zambia, South Africa and Zimbabwe and some coastal sand deposits in western Africa.

Left: A classic Podzol in saprolite from southern South Africa showing a contrasting grey leached horizon overlaying a dark reddish-brown iron and humus accumulation horizon. (MP)

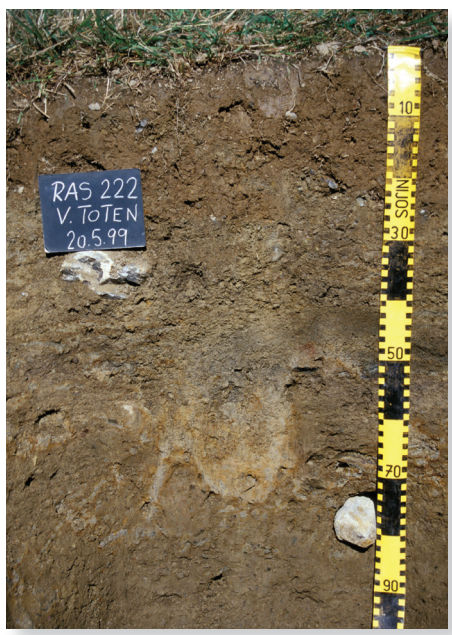
Below: Road construction in Côte d'Ivoire. The white sand is the bleached layer of the Podzol. Once left bare, vegetation will have great difficulties to re-establish itself. (AR)

Podzols are not widespread on a continental scale and occupy less than 0.5% of Africa.

Soil Taxonomy classifies most of these soils as Spodosols.

Stagnosols

Soils with periodic water stagnation (from Latin *stagnare*, to flood)



Stagnosols are soils with a perched water table, often caused by the presence of an impermeable barrier deep in the soil. Perched water tables lead to temporary water logging and the mobilisation of iron and/or manganese. This process gives rise to a characteristic colour pattern; aggregate surfaces are bleached and depleted of iron whereas the centres are enriched showing brown to orange colours. A common name in many national classification systems is pseudogley. They have been recorded in Côte d'Ivoire, Central African Republic and Chad.

Left: A vertical section in a Stagnosol shows the intricate colour patterns that exist in such soil. (RS)

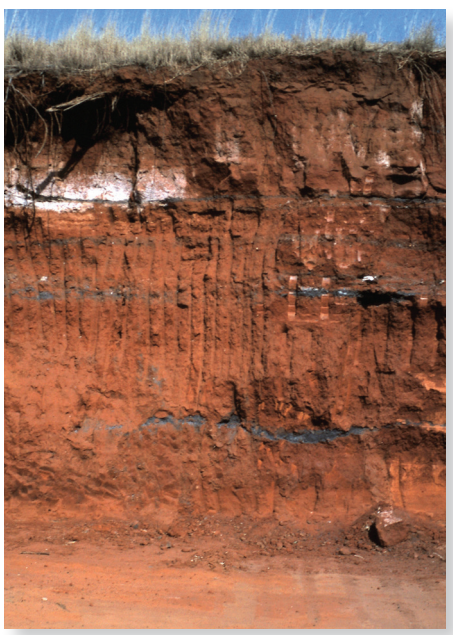
Below: Surface ponding of water and stagnant conditions after rainfall is characteristic of Stagnosols. (EM)

While locally they may be significant, on a continental scale, Chernozems occupy less than 0.5% of Africa.

Soil Taxonomy classifies most of these soils as the epiaquic members of Inceptisols.

Technosols

Soils that are sealed or contain a significant amount of artefacts (from Greek technikos, skilfully made)



Technosols contain large quantities of man-made artefacts (e.g. household garbage or industrial waste), or contain material that has been brought to the surface (e.g. mine dumps or oil spills) or are soils that have been sealed by an artificial surface (e.g. roads, hard standing areas). They often contain toxic material. Most Technosols occur in and around urban areas and mining areas.

Left: Technosol from South Africa containing layers of coal. (OS)

Below: Mine dumps and wastes are considered Technosols. The grey and white heaps in the background (left-side) of the image shows spoil and waste ground associated with an opencast copper mine north of Lubumbashi in Katanga, DR Congo. (EVR)

While locally they may be very significant, on a continental scale, Technosols occupy less than 0.5% of Africa.

While Technosols are referred to as urban or mine soil, there are no equivalents in Soil Taxonomy.

African Soils: Strengths, Weaknesses, Opportunities and Threats

This section highlights the strengths, weaknesses, opportunities and threats for each of the main soil types found in Africa.

Acrisols

Strengths: Usually under natural vegetation but can support some agriculture if managed appropriately.

Weaknesses: In climates with a pronounced dry season Acrisols may become very hard; land preparation for the next rainy season is tough, especially by hand.

Opportunities: Can be productive if fertiliser is applied. However, doses must be in small, regular quantities that are applied close to the plants as Acrisols do not have the capacity to hold large amounts of nutrients. Acid-tolerant crops such as pineapple or tea and low-demanding crops such as cassava can do well, but care is needed to protect the soil when the surface is left bare for significant periods. Frequent loosening of the topsoil, together with removal of weeds, will permit rain to infiltrate thus preventing erosion by sheetwash.

Threats: Acrisols are notorious for their susceptibility to erosion and capping once left bare. As their productivity is low, they are best left under natural vegetation.

Alisols

Strengths: Alisols are potentially fertile soils once soil acidity is reduced by liming and the soil is replenished with nutrients. After restoration of the soil's fertility, Alisols may have been transformed into Luvisols and a wide range of crops can be successfully grown. Increasingly, Alisols are planted with acid-tolerant estate crops such as tea, rubber or oil-palm.

Weaknesses: Very acid - caused by rapid weathering of minerals which release a large amount of aluminium into the soil. Often levels of aluminium are so high that they are toxic to most crops. In subsistence agriculture their productivity is low as regeneration from chemical exhaustion is slow.

Opportunities: Shallow-rooting crops can be cultivated thus avoiding the acidic subsoil.

Threats: Once left fallow, Alisols are very prone to erosion.

Andosols

Strengths: Andosols are high in nutrients and easy to cultivate.

Weaknesses: High levels of phosphate fertiliser are needed to affect yields due to fixation by iron compounds in soil. The use of heavy machinery may pose problems because of their low bearing capacity, prone to smearing and stickiness.

Opportunities: They can be planted with a wide variety of crops such as sugar cane, tobacco, sweet potato (tolerant to low phosphate levels), tea, vegetables wheat and orchard crops.

Threats: Andosols on steep slopes are best kept under forest to prevent erosion.

Anthrosols

Strengths: Favourable physical properties for cultivation (porosity, rootability and moisture availability).

Weaknesses: If not maintained, may have less satisfactory chemical characteristics (acidity, nutrient deficiencies). Sufficient manpower and supply of soil improvement media must be readily available.

Opportunities: Provide cultivation opportunities in unfavourable natural conditions – support local produce.

Threats: Land abandonment, climate change.

Arenosols

Strengths: Sandy soils are easy to work and therefore much sought after by farmers.

Weaknesses: They only hold a small amount of organic matter, nutrients and water. Crops have to be irrigated frequently to provide the necessary moisture.

Opportunities: As Arenosols occur mainly in the drier parts of the continent, land use is normally limited to extensive (nomadic) grazing.

Threats: Without good soil conservation measures, Arenosols are prone to wind erosion. Wind breaks are essential in conserving the soil, which is easily turned into shifting sands and dunes.

Calcisols

Strengths: Cultivation can often be successful with irrigation.

Weaknesses: High pH unsuitable for many crops. Fertilisation with nitrogen, phosphorus and trace elements like iron and zinc may be necessary as these are only available naturally in small amounts.

Opportunities: In the Mediterranean region, extensive areas are used for the production of irrigated winter wheat, melons and cotton.

Threats: Lack of vegetation makes them prone to wind and water erosion. Crusts can develop easily.

Cambisols

Strengths: Cambisols are among the better agricultural soils in Africa as they are less depleted of nutrients than other tropical soils and have a sufficiently high nutrient-holding capacity to retain fertilisers.

Weaknesses: Strongly weathered Cambisols contain limited amounts of nutrients.

Opportunities: Depending on their depth, their water-holding capacity can be high.

Threats: In hilly or mountainous areas, where Cambisols are most frequent, care should be taken to prevent erosion when the surface is bare. In such conditions, these soils are best be kept under forest or perennial crops such as tea.

Chernozems

Strengths: Very fertile soils.

Weaknesses: Preservation of a favourable soil structure needed through timely cultivation and careful irrigation at low watering rates. Application of P fertilisers is required for high yields.

Opportunities: High agricultural potential.

Threats: Wind erosion if allowed to dry out and water erosion on slopes following tillage.

Cryosols

Strengths: Carbon sink – permafrost and cryoturbation lock frozen organic matter in the soil.

Weaknesses: Frozen ground limits vegetation development. Collapse and subsidence due to thawing (thermokarst).

Opportunities: High ecological and environmental value.

Threats: Warming climate will lead to thawing. Already very limited extent in Africa.

Durisols

Strengths: Many Durisols in southern Africa are excellent for vine-growing.

Weaknesses: Their use is fairly restricted once a pan has developed.

Opportunities: Only after breaking up the pan, and with irrigation they can be successfully be planted with crops.

Threats: Crust development can hamper cultivation.

Ferralsols

Strengths: Sustain natural vegetation – commonly under tropical rainforest. Can sustain limited cultivation with addition of lime and fertilisers.

Weaknesses: Ferralsols require specific soil management. As both inherent nutrient levels and nutrient retention are low to very low, soil amendments have to be given in small portions. Some Ferralsols are so strongly weathered that they do not hold nutrients anymore. The strong micro-aggregation leads to loose packing of the aggregates and the dominance of large pores; consequently, most Ferralsols have a low water-retention capacity. During significant dry spells supplementary irrigation may be needed to prevent drought stress.

Opportunities: Although most Ferralsols are acidic and have a high aluminium saturation, actual amounts of exchangeable aluminium are low and can easily be corrected by liming. However, the high iron content results in the fixation phosphorus from fertilisers.

Threats: Maintaining soil fertility and prevention of surface soil erosion are important management requirements.

Fluvisols

Strengths: Fluvisols, except for the very acid ones, are fertile because of the regular supply of nutrients. Riverine Fluvisols are highly suitable for wetland rice because of the close proximity to fresh water.

Weaknesses: Flood control or drainage may be needed due to proximity of rivers. Low-lying backswamps, if not suitable for wetland rice, are best left under the natural vegetation; these areas may be used for extensive grazing when they are accessible.

Opportunities: High agricultural potential.

Threats: Flooding and waterlogging. Prone to urbanisation and sealing.

Gleysols

Strengths: Gleysols normally occur in level terrain. The proximity to groundwater makes them very suitable for growing wetland rice.

Weaknesses: Care is needed if large amounts of iron are present as this can lead to bronzing of the leaves and yield reduction. Most crops need to be drained and water levels in the soil need to be controlled.

Opportunities: Adequately drained Gleysols can be used for arable cropping, dairy farming and horticulture.

Threats: Waterlogging, lack of air for roots, compaction.

Gypsisols

Strengths: Can support limited extensive grazing. Weaknesses: Gypsisols do not hold much water. Due to the presence of gypsum the soils have a high pH, normally over 8, which creates disorder in plant-available nutrients. The sandy nature, the alkaline character and the lack of water make most Gypsisols unsuitable for cropping. Moreover, when irrigated gypsum dissolves, water will easily seep through the soil and become unavailable to plants.

Opportunities: Limited. Cultivation possible on soils with relatively low gypsum content if irrigated.

Threats: When high amounts of gypsum are present, the soil structure may collapse under irrigation.

Histosols

Strengths: Contain more than 20% organic matter and have a high water content.

Weaknesses: Their bulk density is very low, some 0.4 kg dm^{-3} or less. Bearing capacity is very low. Nutrient imbalances are rampant and macronutrients such as calcium or magnesium are often lacking or occur only in very small quantities.

Opportunities: High ecological and environmental value – important store of terrestrial carbon.

Threats: When drained, they suffer from risk of fire, irreversible shrinkage and surface subsidence.

Kastanozems

Strengths: Kastanozems are highly fertile soils and therefore much sought after by farmers.

Weaknesses: They may suffer from nutrient imbalances because of the excess of calcium in the soil system. To make them productive during the dry, hot summer season, irrigation is necessary.

Opportunities: Kastanozems in the Mediterranean region are planted mainly with winter wheat during the rainy season.

Threats: When dry and under fallow conditions, the soil is susceptible to wind erosion; when situated on slopes the soil may suffer from water erosion under high-intensity rainfall.

Leptosols

Strengths: They provide a solid foundation for construction.

Weaknesses: Leptosols are unsuitable for growing crops. They have a limited rooting depth, a low water-holding capacity and their nutrient supply is confined to what is available in the shallow top layer.

Opportunities: Farmers use Leptosol areas only for grazing of their cattle.

Threats: Erosion

Lixisols

Strengths: Lixisols can be fairly productive. The low inherent fertility and nutrient-retention capacity dictate a split-application of necessary fertilisers, preferably close to the plants. Liming is not required.

Weaknesses: Occurring mainly in the dry savannah region with low biomass production, Lixisols do not hold much organic matter. Consequently, high-intensity rainfall will destroy any soil structure present.

Opportunities: Surface mulch during fallow periods will help prevent the development of a crust. As Lixisols mainly occur in the drier parts of Africa, irrigation may be needed to grow crops during the dry season or to overcome dry spells during the rainy season. The use of water traps is recommended to store as much rainwater as possible in the soil.

Threats: Like their acid counterparts the Acrisols, Lixisols are prone to erosion. If not protected, a crust may develop which prevents rain from entering the soil. Overland flow will then erode the topsoil which is the most fertile part. Also wind erosion may take its toll; loose soil particles on the surface can easily be blown away.

Luvisols

Strengths: Luvisols are productive soils, in northern Africa they are planted with winter wheat and vegetables under irrigation during summer. They have a large mineral nutrient reserve and a good aeration. Rooting depth is normally unlimited unless they overlie continuous hard rock or a petrified layer.

Weaknesses: Due to long and continued cultivation, in northern Africa since Roman times, most Luvisols have lost their topsoil; therefore they are poor in organic matter and nitrogen-deficiency is quite common.

Opportunities: Productive soils if managed appropriately.

Threats: Prone to erosion on slopes.

Nitisols

Strengths: Nitisols are suited for a wide range of crops. In eastern Africa many Nitisol areas are used to grow coffee.

Weaknesses: In annual cropping, fertiliser application is necessary to make these soil productive. Due to the high amount of active iron, Nitisols suffer from phosphate-fixation. Retention rates of 80% or more are common.

Opportunities: Intensive liming can overcome the aluminium toxicity.

Threats: Erosion on slopes.

Phaeozems

Strengths: Phaeozems are highly productive soils, provided rooting if not inhibited by continuous hard rock.

Weaknesses: Such soils may suffer from drought because the water-holding capacity is limited to the surface layer.

Opportunities: Good agricultural potential.

Threats: Drought, wind erosion.

Planosols

Strengths: Most areas with Planosols are best kept under natural vegetation, usually grassland; some are used for wetland rice.

Weaknesses: Because these soils are subject to frequent waterlogging, their use is limited.

Opportunities: Grasslands with supplemental irrigation in the dry season are a good land use in climates with long dry periods and short infrequent wet spells. Strongly developed Planosols with a very silty or sandy surface are best left untouched.

Threats: Waterlogging, wind erosion if allowed to dry out.

Plinthosols

Strengths: When still soft, the plinthite can be cut and dried to use as building stone. When it hardens as loose concretions, it can be used for road surfacing or airstrip construction.

Weaknesses: When cultivating Plinthosols, care must be taken that water levels do not drop below the depth where the iron-rich layer occurs.

Opportunities: Limited for agriculture. Plinthosols are a source of raw material as aggregate or ore deposit.

Threats: Plinthosols may also occur on slopes where groundwater comes close to the surface; in this position they must be protected from erosion.

Podzols

Strengths: Tropical Podzols normally sustain a light forest cover that recovers very slowly after cutting or burning.

Weaknesses: The low nutrient status, low level of available moisture and low pH make Podzols unattractive soils for arable farming.

Opportunities: Limited. Mature Podzols are generally best used for extensive grazing or left idle under their natural vegetation.

Threats: Lacking nutrients. Once left bare, vegetation may have great difficulties to re-establish itself.

Regosols

Strengths: Most Regosols are well supplied with nutrients as they occur in young weathering material.

Weaknesses: Water-holding capacity is often low and water stress of crops is common.

Opportunities: Shrub and tree cultivation where climate allows. Otherwise, best left under natural vegetation.

Threats: A weakly developed soil formation makes these soils prone to erosion.

Solonchaks

Strengths: Support natural habitats. Little agricultural value apart from extensive grazing.

Weaknesses: As salts are harmful to most crops, these soils are not directly suitable as farmland. When they dry out, the soil becomes very hard making land preparation, especially with hand tools, very difficult.

Opportunities: Cultivation possible only after salts have been flushed from the soil (which then ceases to be a Solonchak). Irrigation must satisfy the needs of the crop and maintain downward water flow to flush excess salts from the root zone.

Threats: Salinisation and wind erosion.

Solonetz

Strengths: Support natural habitats. Grazing.

Weaknesses: As high pH is harmful to most crops, these soils are not directly suitable as farmland. Land preparation becomes difficult when they dry out.

Opportunities: Can be improved if pH lowered or gypsum added.

Threats: Increased alkalinity and wind erosion.

Stagnosols

Strengths: Drained Stagnosols can be fertile owing to their moderate degree of leaching.

Weaknesses: Limited because of their oxygen deficiency and saturated status.

Opportunities: Can be improved by deep ploughing.

Threats: Climate change.

Technosols

Strengths: Can buffer toxic material and provide foundations for structures.

Weaknesses: Sealed by artificial surfaces and can contain toxic material – loss of soil functions, often total.

Opportunities: Limited unless greatly restored.

Threats: Loss of most soil functions.

Umbrisols

Strengths: Occurring in humid areas, suitable for woodland.

Weaknesses: Acidity.

Opportunities: Require heavy investment to make them productive. Natural acidity must be countered with lime.

Threats: Erosion risk for cultivation on slopes.

Vertisols

Strengths: Vertisols can be productive provided the right measures are taken.

Weaknesses: As most Vertisols occur in level areas water movement in the soil is limited and during wet periods water can stagnate on the surface. Heavy to work when wet. Swelling and shrinkage may destroy the foundation of structures (e.g. roads, irrigation canals).

Opportunities: Raised beds made out of the surface layer, which is often crumbly, are good seed beds as the water drains quickly into the adjacent furrows.

Threats: Can be susceptible to droughts.

A cultivated Bathiplinthic Ferralsol from Ghana. The distinct horizon occupying the uppermost 30 cm is a plough layer where the soil has been mixed by cultivation. Termite activity has created the distinct voids that are visible in the profile. A dark red nut-like nodule horizon (plinthite) is visible below a depth of 110 cm. (EM)

Africa's missing soil!

The WRB recognises 32 Reference Soil Groups, of which 31 are identified in this atlas. The missing group is Albeluvisols - soils with a thin, dark surface horizon on a bleached subsurface horizon that tongues into a horizon which has accumulated clay. The clay-rich horizon has an irregular or broken upper boundary resulting from the tonguing of bleached soil material into the subsoil. Albeluvisols are formed mostly in unconsolidated glacial till, lacustrine or fluvial materials on flat to undulating plains under coniferous forest or mixed forest in boreal and temperate climates with cold winters and short cool summers. The tonguing has a horizontal component similar to ice wedges which makes some suggest that their formation is indicative of a very cold, periglacial environment. Such conditions have been generally absent in Africa, which lacks glacial landscapes.

An Albeluvisol from southern Germany. The profile clearly shows a bleached topsoil with tounging onto the subsoil and polygonal patterns in the horizontal cross-section of the compacted subsoil. (EM)

An aerial view of termite mounds (also known as termitaria) on the Mozambique coastal plain. In savannah regions, such mounds are typically two to three metres high. Individual termite species may be identified by the shape of their mounds. Termites are responsible for significant soil mixing as a result of their burrowing and nest development. Note the associated vegetative growth due to the soil improvement actions of the insects. Soil surveyors use such features as proxies to denote changes in soil characteristics when preparing maps. Termite mounds act as islands of biodiversity in the savannah's. Birds use them as landing places, leave seeds of trees behind in their droppings which form fertile ground for germination. In this picture old termite mounds are fully encroached by savannah bush trees and shrubs, whereas the fresh mounds are bare. (MS)

Termites are significant in soil formation in tropical Africa. A highly organised and social group of insects, termites feed mostly on dead plant material, soil or animal dung. Some species of termite cultivate a specific species of fungi which can often be found in cavities in the soil. While termites can be regarded as a pest by some farmers, termites can have pronouced impact on soil characteristics. Termite activity can improve the soil structure by sorting soil particles, increase infiltration by improving porosity or decrease infiltration by producing compact surfaces which assist runoff and erosion. Other effects involve the chemical alteration of the soil, collecting and transporting organic matter to their nest structures and by increasing soil carbon and nutrient levels, especially nitrogen, phosphorus, potassium and exchangeable magnesium and calcium. (EVR)

Soil mapping in Africa

Soil survey or soil mapping is the process of identifying and delineating areas which have similar soil characteristics.

One of the key problems with mapping soil is that it is a continuum with gradual changes in characteristics over the landscape. Sometimes these changes occur over a few metres. More often, change occurs gradually and can only be recognised over long distances. Thus, boundaries between different types of soil or soil properties are often diffuse making it difficult to show true changes on a map, where sharp lines are drawn to separate one soil type from another.

Why map soils?

Soil mapping can be carried out for a number of purposes:

- To provide information to assist land and environmental management (e.g. for farmers) by identifying the natural capacity of the soil;
- To provide strategic information on the current status of soil quality (e.g. for national policy development);
- To provide a framework for extrapolating the results of local studies and soil monitoring networks;
- To demonstrate how local and national soil variability fits into the global pattern (trans-national policy).

The type or range of information required for each of these purposes is varied, although there is often overlap between them. Because of this, the techniques used to map soil and the information gathered during the survey can be very different, depending on the purpose of the mapping. In general there are two broad categories: General Purpose and Specific Purpose soil surveys. General Purpose surveys attempt to quantify and delineate a wide range of soil properties, most often associated with soil classes, so that they can be used for many different applications. General Purpose soil mapping tends to cover large areas ranging from individual river catchments to regions, countries or even continents. Specific Purpose surveys focus on quantifying the amount and spatial variation of a specific soil property or attribute. For example, the nutrient content, water-holding capacity and texture. Most Specific Purpose soil mapping is carried out within relatively small areas such as experimental plots or areas of land where a particular activity occurs or a specific incident may have contaminated the soil.

Soil mapping – current trends and the future

Since the 1980s, soil surveying has increasingly embraced a range of highly-sophisticated computer-based tools. The use of remote sensing technology (i.e. sensors and cameras mounted on aircraft and satellites), global positioning systems (GPS) to fix the information collected during fieldwork, hand-held tablets to log field observations and soil databases to store information are all now commonly employed by soil survey organisations. By using Geographic Information Systems (see page 136), all these data can be brought together in a single computing environment to speed up the production of soil maps in an accurate and precise manner. In the future, data from higher spectral and spatial resolution sensors, coupled with novel geo-statistical software, will be increasingly used to supplement information captured by traditional field surveys.

How are soil maps made?

Soil maps are based on field observations and interpretations of how and where the observed soil characteristics and associated soil types change between observation points. Such interpretation is based on conceptual models of how the local soil-forming factors and processes determine the variation of soil characteristics across the landscape. For most of the soil maps created during the previous century, these conceptual models were never explicitly defined or quantified, they were simply based on the experience of the soil surveyors and observations of local soil variation. With the advent of the digital age and Information Technology, these conceptual models are increasingly being quantified and made more consistent [64].

Field observations are the key to making good soil maps. The location of each inspection point is chosen by the field surveyor to provide information as to how the soil characteristics being mapped vary in relation to the local geology, landscape, vegetation and climate – all factors used to develop the conceptual model of soil spatial variation. Often, inspection points are located on a straight line that crosses the landscape where the topography (how slopes vary across the landscape creating different land forms) and geology vary the most. In other cases, where the landscape has little variation, inspection points are located more randomly. In some cases, particularly for national 'inventory' purposes, observation points are located at predetermined intervals on a standard grid, for example, at 10 km x 10 km.

Collecting soil data. From left to right: Inspecting the boundary between the topsoil and subsoil in a road exposure in Tanzania (SD); the highly weathered nature of many sois in Africa require deep soil pits, as shown by this example from Ghana (EM); measuring soil pH in western Kenya (RMX). The status of regional soil survey in Africa is unsatisfactory given challenges such as food security, water scarcity, climate change and land degradation.

At each inspection point, soil characteristics are examined either by digging a small pit to reveal a profile or by using an auger (a handheld screw drill) to extract soil samples. Both techniques normally sample to a depth of up to 2 m, less if bedrock is encountered. Each sample point is geo-referenced and the characteristics of the soil are entered onto recording sheets, often in the form of symbols or 'shorthand' notes.

In modern soil mapping, the information is entered either directly as digital data, or onto standardised forms which are then digitised. The information recorded for each horizon usually varies but generally includes the thickness, colour, texture, size and shape of soil structures, presence of carbonates, stones, etc. [65]. In addition, at a limited number of inspection points, soil samples are taken for more detailed laboratory analysis.

Once a number of field observations have been made, the field surveyor begins to develop a conceptual model of the relationships between soil characteristics and local topography, climate, parent material and land use. Tentative boundaries are sketched between different soil areas and the changes in soil characteristics between these boundaries are checked by further field observation. This process usually results in amendments being made to both the conceptual model used to interpolate between points and the boundaries placed on the field map sheets. By the end of the field survey, a set of field map sheets showing the boundaries between different soil areas will have been finalised.

Soil survey in Africa

Unfortunately, many African countries have very limited detailed mapping of their soil resources. What exists is of variable age and quality and only partly correlated with other countries. Most countries have a general soil map at very small scales, usually substantially smaller than 1:250 000. For many, the only national coverage is still the Soil Map of the World at a scale of 1:5 Million produced by the FAO and UNESCO in the 1970s. Detailed soil information for regional or project planning is usually not available. For example, only 15% of the DR Congo has been mapped at scales of 1:50 000 to 1:500 000.

The adjacent table shows the national coverage of soil maps of selected African countries, from which the following general conclusions may be drawn:

- Cartographic coverage for regional master planning of scales between 1:100 000 and 1:250 000 is largely incomplete, making it difficult to identify high-potential areas or, conversely, critical problem areas and their priority for more detailed inventories;
- Soil maps appropriate for project planning at scales around 1:25 000 cover very small areas;
- Soil maps suitable for operational planning, usually at scales larger than 1:25 000, are limited to specific projects.

	Small scale 1 : 500000 - ± 100000 (%)	Medium scale 1 : 100000 - ± 50000 (%)	Large scale 1 : 25000 (%)
Algeria	-	5	5
Benin	100	10	2
Botswana	40	5	-
Burkina Faso	100	25	-
Burundi	100	-	-
Cameroon	30	5	1
DR Congo	10	5	-
Egypt	100	10	10
Gabon	30	-	-
Gambia	100	-	100
Ghana	95	-	-
Kenya	100	25	-
Mali	50	-	-
Morocco	-	40	20
Nigeria	70	35	-
Rwanda	100	100	-
South Africa	70	-	-
Swaziland	100	10	5
Tanzania	50	-	-
Togo	80	20	-
Uganda	100	-	-

National soil survey coverage in selected African countries. [60]

SOTER

The SOil and TERrain (SOTER) methodology was developed by the FAO and ISRIC to provide a rapid update of the 1:5 Million Soil Map of the World. Existing soil maps and their associated information are converted into digital data to identify areas of land with a distinctive pattern of landform, lithology, surface form, slope, parent material and soil at scales of 1:1-2 million. SOTER data exist for Kenya, Northeastern Africa, Southern Africa, Central Africa, Senegal, The Gambia and Tunisia.

http://www.fao.org/nr/land/databasesinformation-systems/soter/it/

Legends

How does a legend work?

A legend explains the cartographic symbols used to construct a map and is intended to aid the understanding of the map content. Legends consist typically of a symbol or a series of symbols with specific colours or shades that are repeated on the map sheets in a consistent manner on all maps associated with the particular legend.

Construction of the legend

The 2006 version of the World Reference Base for Soil Resources (WRB) has been used to construct the legend of the soil maps in this atlas. The WRB recommends that the Reference Soil Group with a single prefix qualifier be used for small-scale maps (i.e. smaller than 1:1 million). This recommendation has been followed in the construction of the legend for this atlas with a few exceptions where key diagnostic information was lacking.

On this page, the Reference Soil Groups are listed alphabetically. The division within an individual Reference Soil Group follows the order of prefix qualifiers in the 2006 version of WRB (the same applies for the suffix qualifiers). A simple explanation of the main soil characteristic is presented on page 66.

For this atlas, the most prevalent soil type in each polygon is represented by a colour that corresponds to a specific WRB Reference Soil Group and a four-character code indicating the dominant characteristics of that soil (see pages 51 for a detailed descriptions of the specific soil characteristics). For example, the blue box that contains the code combination GLmo represents Mollic Gleysols on the soil maps which correspond to soils with a predominantly high water table for long periods of the year and have a nutrient- and organic rich, dark-coloured topsoil.

Cartographic symbols

International boundary

Disputed boundary

National capital — ABUJA

Locality (by population)

- 5,000,000 + — LAGOS
- 1,000,000 – 5,000,000 — Abidjan
- 200,000 – 1,000,000 — Nampula
- 100,000 – 200,000 — Gweru

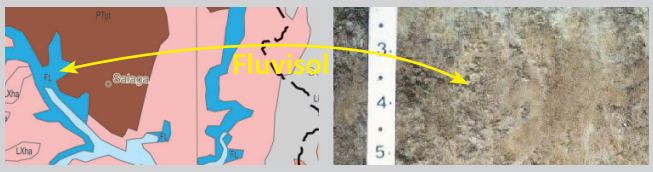
Soil Maps

The next section in the atlas contains a series of maps showing the regional distribution of WRB Reference Soil Groups across Africa.

As illustrated by the diagram below, a soil map depicts areas where soil properties, according to the classification scheme used, are similar. Hence, the light blue tones on the map correspond to the soil profile shown while the pink areas on the map correspond to a different soil type.

It is important to realise that a soil map is a two-dimensional representation of a three-dimensional object and that only the spatial or geographical change in soil properties is depicted.

Pages 64 - 66 present the legend to be used to interpret the regional maps while page 67 provides an index to the individual map sheets.



- Acrisols
- Alisols
- Andosols
- Arenosols
- Calcisols
- Cambisols
- Chernozems
- Cryosols
- Durisols
- Ferralsols
- Fluvisols
- Gleysols
- Gypsisols
- Histosols
- Kastanozems
- Leptosols
- Lixisols
- Luvisols
- Nitisols
- Phaeozems
- Planosols
- Plinthosols
- Podzols
- Regosols
- Solonchaks
- Solonetz
- Stagnosols
- Technosols
- Umbrisols
- Vertisols
- Water Body

Acrisols	
AC	Undifferentiated Acrisols
ACfr	Ferric Acrisols
ACha	Haplic Acrisols
ACpl	Plinthic Acrisols
ACum	Umbric Acrisols
Alisols	
ALgl	Gleyic Alisols
ALha	Haplic Alisols
ALpl	Plinthic Alisols
ALum	Umbric Alisols
Andosols	
ANsn	Silandic Andosols
ANvi	Vitric Andosols
ANzm	Mollic Silandic Andosols
ANzu	Umbric Silandic Andodols
Arenosols	
AR	Undifferentiated Arenosols
ARab	Albic Arenosols
ARbr	Brunic Arenosols
ARca	Calcaric Arenosols
ARfl	Ferralic Arenosols
ARha	Haplic Arenosols
ARpr	Protic Arenosols
ARwl	Hypoluvic Arenosols
Calcisols	
CLha	Haplic Calcisols
CLlv	Luvic Calcisols
CLpt	Petric Calcisols
CLzy	Haplic Calcisols (Yermic)
Cambisols	
CM	Undifferentiated Cambisols
CMca	Calcaric Cambisols
CMcr	Chromic Cambisols
CMdy	Dystric Cambisols
CMeu	Eutric Cambisols
CMfl	Ferralic Cambisols
CMgl	Gleyic Cambisols
CMvr	Vetric Cambisols
CMzt	Eutric Cambisols (Takyric)
CMzy	Eutric Cambisols (Yermic)
Chernozems	
CHcc	Calcic Chernozems
CHlv	Luvic Chernozems

Cryosols	
CR	Undifferentiated Cryosols
Durisols	
DU	Undifferentiated Durisols
Fluvisols	
FL	Undifferentiated Fluvisols
FLca	Calcaric Fluvisols
FLdy	Dystric Fluvisols
FLeu	Eutric Fluvisols
FLmo	Mollic Fluvisols
FLsz	Salic Fluvisols
FLti	Thionic Fluvisols
FLum	Umbric Fluvisols
Ferralsols	
FR	Undifferentiated Ferralsols
FRha	Haplic Ferralsols
FRpl	Plinthic Ferralsols
FRro	Rhodic Ferralsols
FRum	Umbric Ferralsols
FRxa	Xanthic Ferralsols
Gleysols	
GL	Undifferentiated Gleysols
GLcc	Calcic Gleysols
GLdy	Dystric Gleysols
GLeu	Eutric Gleysols
GLmo	Mollic Gleysols
GLum	Umbric Gleysols
GLza	Haplic Gleysols (Arenic)
Gypsisols	
GY	Undifferentiated Gypsisols
GYcc	Calcic Gypsisols
GYha	Haplic Gypsisols
GYhz	Haplic Gypsisols (Yermic)
GYpt	Petric Gypsisols
Histosols	
HSdy	Undifferentiated Histosols (Dystric)
HSeu	Undifferentiated Histosols (Eutric)
HSfi	Fibric Histosols
HSsa	Sapric Histosols
Kastanozems	
KS	Undifferentiated Kastanozems
KScc	Calcic Kastanozems
KSha	Haplic Kastanozems
KSlv	Luvic Kastanozems

Leptosols	
LP	Undifferentiated Leptosols
LPdy	Dystric Leptosols
LPeu	Eutric Leptosols
LPli	Lithic Leptosols
LPmo	Mollic Leptosols
LPrz	Rendzic Leptosols
LPum	Umbric Leptosols
Lixisols	
LX	Undifferentiated Lixisols
LXfr	Ferric Lixisols
LXgl	Gleyic Lixisols
LXha	Haplic Lixisols
LXpl	Plinthic Lixisols
Luvisols	
LV	Undifferentiated Luvisols
LVab	Albic Luvisols
LVcc	Calcic Luvisols
LVcr	Chromic Luvisols
LVfr	Ferric Luvisols
LVgl	Gleyic Luvisols
LVha	Haplic Luvisols
LVvr	Vertic Luvisols
Nitisols	
NT	Undifferentiated Nitisols
NTdy	Dystric Nitisols
NTeu	Eutric Nitisols
NTro	Rhodic Nitisols
NTum	Umbric Nitisols
Phaeozems	
PHgl	Gleyic Phaeozems
PHha	Haplic Phaeozems
PHlv	Luvic Phaeozems
Planosols	
PL	Undifferentiated Planosols
PLdy	Dystric Planosols
PLeu	Eutric Planosols
PLsc	Solodic Planosols
PLum	Umbric Planosols
Plinthosols	
PT	Undifferentiated Plinthosols
PTab	Albic Plinthosols
PTeu	Eutric Plinthosols
PTpt	Petric Plinthosols
PTpx	Pisoplinthic Plinthosols
PTum	Umbric Plinthosols

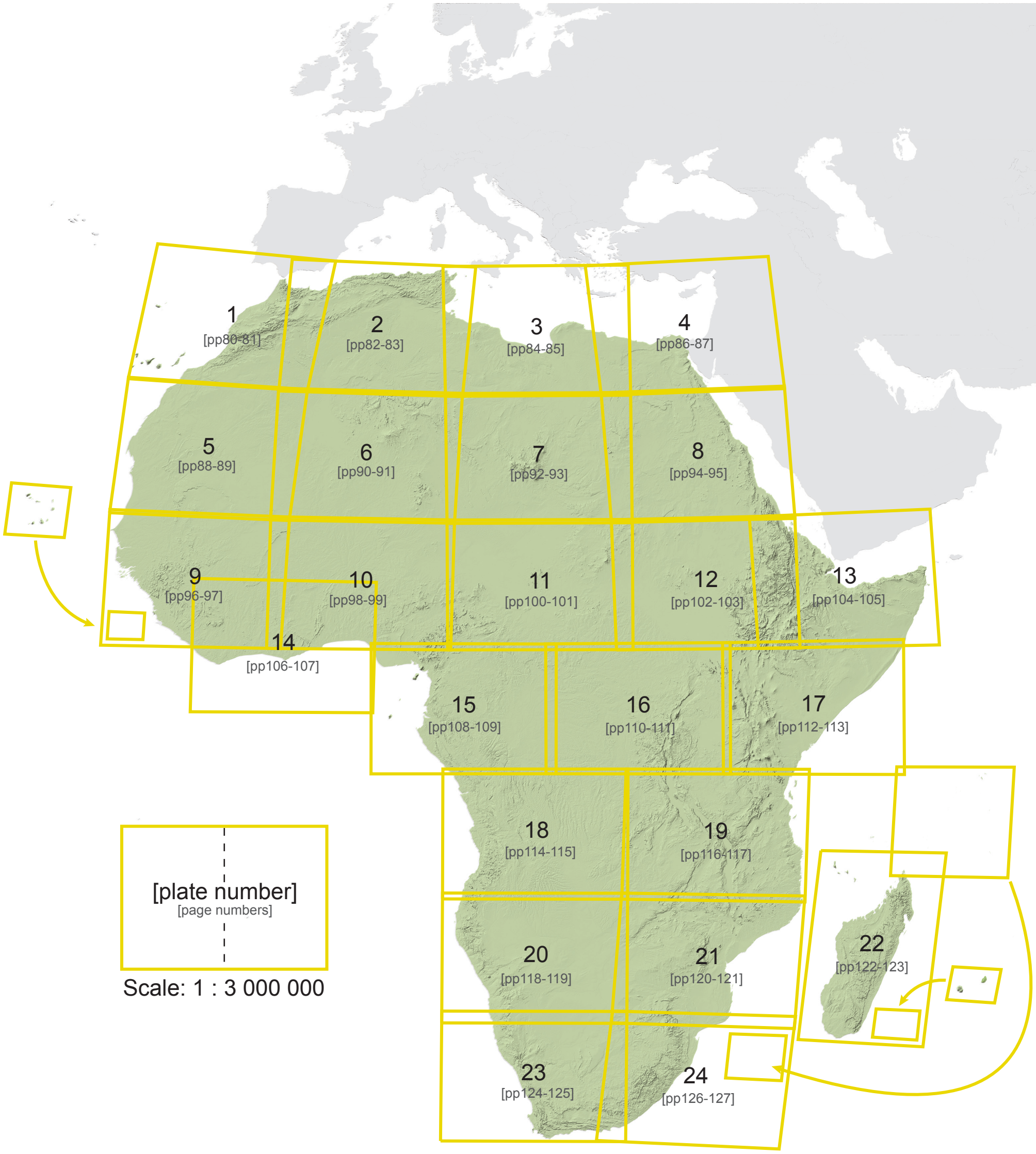
Podzols	
PZ	Undifferentiated Podzols
PZcb	Carbic Podzols
PZgl	Gleyic Podzols
PZha	Haplic Podzols
Regosols	
RG	Undifferentiated Regosols
RGca	Calcaric Regosols
RGdy	Dystric Regosols
RGeu	Eutric Regosols
Solonchaks	
SC	Undifferentiated Solonchaks
SCcc	Calcic Solonchaks
SCgl	Gleyic Solonchaks
SCha	Haplic Solonchaks
SCso	Sodic Solonchaks
SCzt	Haplic Solonchaks (Takyric)
Solonetz	
SN	Undifferentiated Solonetz
SNcc	Calcic Solonetz
SNgl	Gleyic Solonetz
SNha	Haplic Solonetz
SNmo	Mollic Solonetz
SNst	Stagnic Solonetz
Stagnosols	
STlv	Luvic Stagnosols
STlx	Lixic Stagnosols
STmo	Mollic Stagnosols
Technosols	
TC	Undifferentiated Technosols
Umbrisols	
UMcm	Cambic Umbrisols
Vertisols	
VR	Undifferentiated Vertisols
VRcc	Calcic Vertisols
VRha	Haplic Vertisols
VRpe	Pellic Vertisols
VRzz	Haplic Vertisols (Mesotrophic)

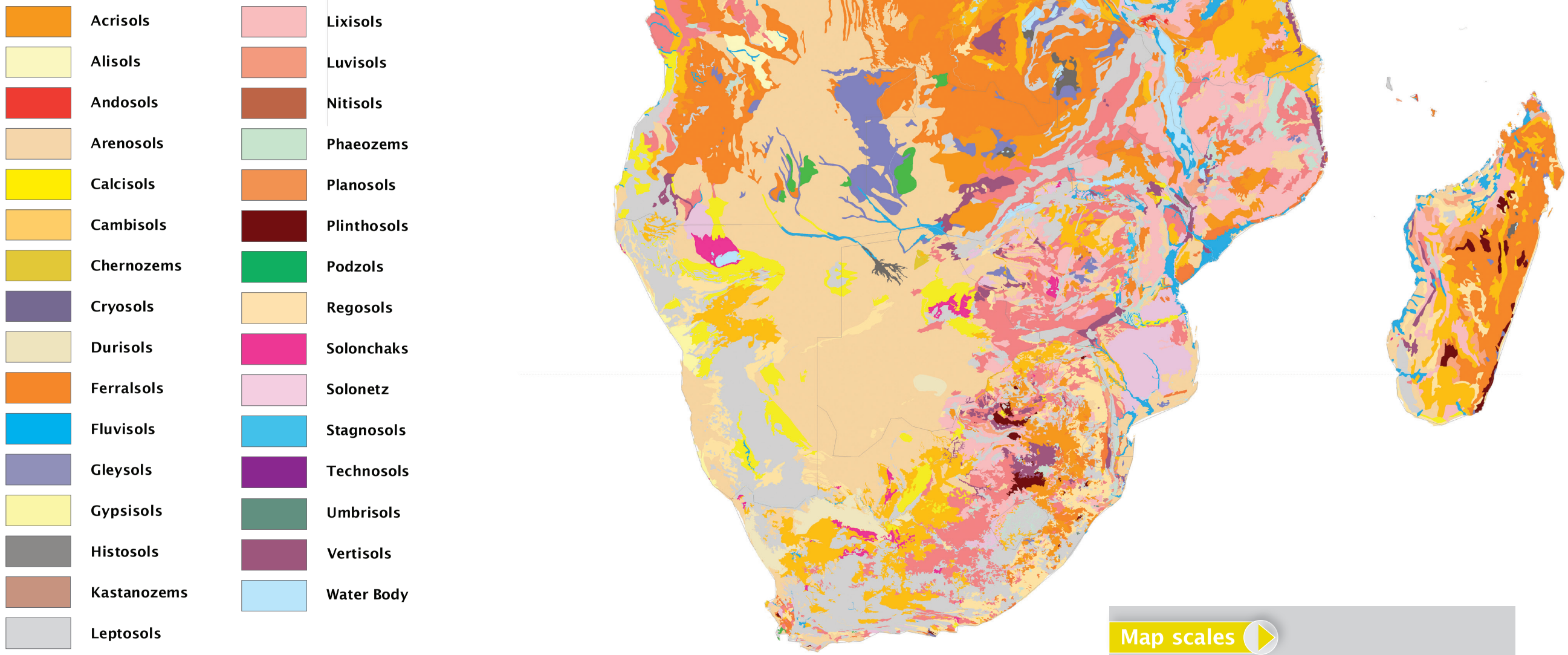
Miscellaneous Categories	
	Water body

Alphabetical listing and brief description of legend codes

AC	**Undifferentiated Acrisols** – Very acid with a clay-rich subsoil
ACfr	**Ferric Acrisols** – Very acid with a clay-rich subsoil but with distinct iron nodules
ACha	**Haplic Acrisols** – Very acid with a clay-rich subsoil showing typical characteristics
ACpl	**Plinthic Acrisols** – As AC with iron-rich, humus-poor, clay-rich horizon which hardens irreversibly
ACum	**Umbric Acrisols** – As AC with thick, dark coloured, acid surface horizon, rich in organic matter
ALgl	**Gleyic Alisols** – Very acid, clay rich subsoil and high nutrient-holding capacity, waterlogged conditions
ALha	**Haplic Alisols** – Very acid, clay rich subsoil and high nutrient-holding capacity
ALpl	**Plinthic Alisols** – As ALha with iron-rich, humus-poor, clay-rich subsurface horizon which hardens irreversibly
ALum	**Umbric Alisols** – As ALha with thick, dark coloured, acid surface horizon, rich in organic matter
ANsn	**Silandic Andosols** – Soil on volcanic material where allophane and similar minerals are predominant
ANvi	**Vitric Andosols** – Soil containing volcanic glass
ANzm	**Mollic Silandic Andosols** – As Ansn with dark coloured, acid surface horizon with moderate organic matter content
ANzu	**Umbric Silandic Andodols** – As Ansn with thick, dark coloured, acid surface horizon, rich in organic matter
AR	**Undifferentiated Arenosols** – Sandy soil
ARab	**Albic Arenosols** – Sandy soil with pale coloured topsoil
ARbr	**Brunic Arenosols** – Sandy soil with leached, redish horizon
ARca	**Calcaric Arenosols** – Sandy soil with notable levels of lime
ARfl	**Ferralic Arenosols** – Sandy soil, intensely weathered with high levels of iron
ARha	**Haplic Arenosols** – Sandy soil showing no major characteristics
ARpr	**Protic Arenosol** – Sandy soil showing no horizon development
ARwl	**Hypoluvic Arenosols** – Sandy soil with distinct clay accumulation
CHcc	**Calcic Chernozems** – Deep, dark topsoil rich in organic matter with accumulation of calcium carbonate
CHlv	**Luvic Chernozems** – Deep, dark topsoil rich in organic matter with clay-rich horizon
CLha	**Haplic Calcisols** – Soil with significant accumulation of calcium carbonates
CLlv	**Luvic Calcisols** – As CLha with clay-rich horizon
CLpt	**Petric Calcisols** – As CLha having a strongly cemented or indurated layer
CLzy	**Haplic Calcisols (Yermic)** – As CLha with rock fragments on the surface
CM	**Undifferentiated Cambisols** – Moderately developed soil
CMca	**Calcaric Cambisols** – Moderately developed soil with notable levels of lime
CMcr	**Chromic Cambisols** – Moderately developed soil with a redish hue
CMdy	**Dystric Cambisols** – Moderately developed soil which is weathered, acid
CMeu	**Eutric Cambisols** – Moderately developed soil which is not acid
CMfl	**Ferralic Cambisols** – Moderately developed soil which is intensely weathered with low nutrient retention
CMgl	**Gleyic Cambisols** – Moderately developed soil showing waterlogged conditions
CMvr	**Vetric Cambisols** – Moderately developed soil with swelling clays
CMzt	**Eutric Cambisols (Takyric)** – Moderately developed soil having a heavy textured surface horizon with surface crust
CMzy	**Eutric Cambisols (Yermic)** – Moderately developed soil with rock fragments on the surface
CR	**Undifferentiated Cryosols** – Soils affected by permanently frozen ground
DU	**Undifferentiated Durisols** – Soil with significant accumulation of silica
FL	**Undifferentiated Fluvisols** – Soil in floodplains, lakes, deltas or marine deposits
FLca	**Calcaric Fluvisols** – Soil in floodplains, lakes, deltas or marine deposits with notable levels of lime
FLdy	**Dystric Fluvisols** – Soil in floodplains, lakes, deltas or marine deposits, weathered, acid
FLeu	**Eutric Fluvisols** – Soil in floodplains, lakes, deltas or marine deposits, not acid
FLmo	**Mollic Fluvisols** – As FL with dark coloured, non-acid surface horizon with moderate to high organic matter content
FLsz	**Salic Fluvisols** – As FL with a surface horizon containing a secondary enrichment of soluble salts
FLti	**Thionic Fluvisols** – As FL with acid horizon rich in sulphur
FLum	**Umbric Fluvisols** – As FL with thick, dark coloured, acid surface horizon, rich in organic matter
FR	**Undifferentiated Ferralsols** – Strongly weathered soil with low nutrient levels
FRha	**Haplic Ferralsols** – Strongly weathered soil with low nutrient levels showing no major characteristics
FRpl	**Plinthic Ferralsols** – As FR with iron-rich, humus-poor, clay-rich horizon which hardens irreversibly
FRro	**Rhodic Ferralsols** – Strongly weathered soil with low nutrient levels, very red
FRum	**Umbric Ferralsols** – As FR with thick, dark coloured, acid surface horizon, rich in organic matter
FRxa	**Xanthic Ferralsols** – As FR with low nutrient levels, yellow in colour
GL	**Undifferentiated Gleysols** – Saturated by groundwater for long periods
GLcc	**Calcic Gleysols** – As GL with accummulation of secondary calcium carbonate
GLdy	**Dystric Gleysols** – Saturated by groundwater for long periods weathered, acid
GLeu	**Eutric Gleysols** – Saturated by groundwater for long periods not acid
GLmo	**Mollic Gleysols** – As GL with dark coloured, non-acid surface horizon with moderate to high organic matter content
GLum	**Umbric Gleysols** – As GL with thick, dark coloured, acid surface horizon, rich in organic matter
GLza	**Haplic Gleysols (Arenic)** – Saturated by groundwater for long periods having a loamy fine sand or coarser texture
GY	**Undifferentiated Gypsisols** – High levels of gypsum
GYcc	**Calcic Gypsisols** – High levels of gypsum with accummulation of secondary calcium carbonate
GYha	**Haplic Gypsisols** – High levels of gypsum showing no major characteristics
GYhz	**Haplic Gypsisols (Yermic)** – High levels of gypsum with rock fragments on the surface
GYpt	**Petric Gypsisols** – High levels of gypsum having a strongly cemented or indurated layer
HSdy	**Dystric Histosols** – Organic soil (peat), weathered, acid
HSeu	**Eutric Histosols** – Organic soil (peat), not acid
HSfi	**Fibric Histosols** – Organic soil (peat), having recognizable plant tissue
HSsa	**Sapric Histosols** – Organic soil (peat) with very decomposed plant remains
KS	**Undifferentiated Kastanozems** – Soil with an organic-rich surface horizon and calcium carbonate accumulation in the subsoil
KScc	**Calcic Kastanozems** – As KS with accummulation of secondary calcium carbonate
KSha	**Haplic Kastanozems** – As KS but showing no major characteristics
KSlv	**Luvic Kastanozems** – As KS with clay-rich horizon
LP	**Undifferentiated Leptosols** – Shallow soil over hard rock
LPdy	**Dystric Leptosols** – Shallow soil over hard rockweathered, acid
LPeu	**Eutric Leptosols** – Shallow soil over hard rock, not acid
LPli	**Lithic Leptosols** – Shallow soil over hard rock having continuous rock close to the surface
LPmo	**Mollic Leptosols** – As LP with dark coloured, non-acid surface horizon with moderate to high organic matter content
LPrz	**Rendzic Leptosols** – As LP with dark, organic-rich acid surface horizon overlies calcaric materials
LPum	**Umbric Leptosols** – As LP with thick, dark coloured, acid surface horizon, rich in organic matter
LV	**Undifferentiated Luvisols** – Soil with clay accummulation in subsoil
LVab	**Albic Luvisols** – Soil with clay accummulation in subsoil with pale top
LVcc	**Calcic Luvisols** – As LV with accummulation of secondary calcium carbonate
LVcr	**Chromic Luvisols** – As LV with a redish hue
LVfr	**Ferric Luvisols** – As LV but with distinct iron nodules
LVgl	**Gleyic Luvisols** – As LV showing waterlogged conditions
LVha	**Haplic Luvisols** – As LV showing no major characteristics
LVvr	**Vertic Luvisols** – As LV with swelling clays
LX	**Undifferentiated Lixisols** – Leached, slightly acid soil with a clay-enriched subsoil
LXfr	**Ferric Lixisols** – As LX but with distinct iron nodules
LXgl	**Gleyic Lixisols** – As LX showing waterlogged conditions
LXha	**Haplic Lixisols** – As LX showing no major characteristics
LXpl	**Plinthic Lixisols** – As LX with iron-rich, humus-poor, clay-rich horizon which hardens irreversibly on exposure
NT	**Undifferentiated Nitisols** – Deep red with a well developed, nut-shaped structure
NTdy	**Dystric Nitisols** – As NT, acid
NTeu	**Eutric Nitisols** – As NT, not acid
NTro	**Rhodic Nitisols** – As NT but very red
NTum	**Umbric Nitisols** – As NT with thick, dark coloured, acid surface horizon, rich in organic matter
PHgl	**Gleyic Phaeozems** – Slightly acid with a thick, dark-coloured surface layer showing waterlogged conditions
PHha	**Haplic Phaeozems** – Slightly acid with a thick, dark-coloured surface layer showing no major characteristics
PHlv	**Luvic Phaeozems** – Slightly acid with a thick, dark-coloured surface layer with clay-rich horizon
PL	**Undifferentiated Planosols** – Poorly structured surface layer abruptly overlying a slowly permeable layer
PLdy	**Dystric Planosols** – As PL, weathered, acid
PLeu	**Eutric Planosols** – Poorly structured surface layer abruptly overlying a slowly permeable layer, not acid
PLsc	**Solodic Planosols** – As PL having columnar or prismatic structure but lower sodium than Solonetz
PLum	**Umbric Planosols** – As PL with thick, dark coloured, acid surface horizon, rich in organic matter
PT	**Undifferentiated Plinthosols** – Soil with accumulation of iron that hardens irreversibly when exposed to air and sunlight
PTab	**Albic Plinthosols** – As PT with pale top
PTeu	**Eutric Plinthosols** – As PT, not acid
PTpt	**Petric Plinthosols** – As PT having a strongly cemented or indurated layer
PTpx	**Pisoplinthic Plinthosols** – As PT containing nodules that are strongly cemented with Fe
PTum	**Umbric Plinthosols** – As PT with thick, dark coloured, acid surface horizon, rich in organic matter
PZ	**Undifferentiated Podzols** – Acid soil with a bleached horizon underlain by an accumulation of organic matter, Al and Fe
PZcb	**Carbic Podzols** – As PZ with dark coloured horizon of redeposited clay, organic matter and aluminium
PZgl	**Gleyic Podzols** – As PZ showing waterlogged conditions
PZha	**Haplic Podzols** – As PZ showing no major characteristics
RG	**Undifferentiated Regosols** – Weakly developed soil in unconsolidated material
RGca	**Calcaric Regosols** – Weakly developed soil in unconsolidated material with notable levels of lime
RGdy	**Dystric Regosols** – Weakly developed soil in unconsolidated material weathered, acid
RGeu	**Eutric Regosols** – Weakly developed soil in unconsolidated material not acid
SC	**Undifferentiated Solonchaks** – Soil with accumulation of salt
SCcc	**Calcic Solonchaks** – As SC with accummulation of secondary calcium carbonate
SCgl	**Gleyic Solonchaks** – Soil with accumulation of salt showing waterlogged conditions
SCha	**Haplic Solonchaks** – Soil with accumulation of salt showing no major characteristics
SCso	**Sodic Solonchaks** – Soil with accumulation of salt, rich in sodium
SCzt	**Haplic Solonchaks (Takyric)** – Soil with accumulation of salt having a heavy textured surface horizon and with surface crust
SN	**Undifferentiated Solontez** – Soil with a clay accumulation horizon, rich in sodium
SNcc	**Calcic Solontez** – As SN with accummulation of secondary calcium carbonate
SNgl	**Gleyic Solontez** – As SN showing waterlogged conditions
SNha	**Haplic Solontez** – As SN showing no major characteristics
SNmo	**Mollic Solontez** – As SN with dark coloured, non-acid surface horizon with moderate to high organic matter content
SNst	**Stagnic Solontez** – As SN showing waterlogged conditions at the surface
STlv	**Luvic Stagnosols** – Soil with periodic water stagnation with clay-rich horizon
STlx	**Lixic Stagnosols** – Soil with periodic water stagnation with clay-rich horizon
STmo	**Mollic Stagnosols** – Periodic water stagnation, dark, non-acid surface horizon with moderate organic matter content
TC	**Undifferentiated Technosols** – Soil that is sealed or contains a significant amount of artifacts
UMcm	**Cambic Umbrisols** – Acid soils showing early development
VR	**Undifferentiated Vertisols** – Soil with shrinking and swelling clays
VRcc	**Calcic Vertisols** – As VR with accummulation of secondary calcium carbonate
VRha	**Haplic Vertisols** – As VR showing no major characteristics
VRpe	**Pellic Vertisols** – As VR, dark coloured
VRzz	**Haplic Vertisols (Mesotrophic)** – As VR, slightly acid

Index to map sheets





The steps involved in the production of this map are described in pages 136-137. A digital version of the maps and an illustrative wall chart on the soils of Africa can be downloaded from:

http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/index.html

Map scales

The scale of a map indicates how the size of the map relates to the size of the area on the ground. For example, one centimetre on a map with a scale of 1:100000 is equivalent to 1 kilometre on the ground.

Maps that are sufficiently detailed to show the positions of individual fields of a few hectares in size have scales from 1:5000 (1 cm : 50 m) to 1:25000 (1 cm : 250 m). Such maps are regarded as 'large scale'.

At a regional or national level, maps are more appropriate at medium scales, commonly 1:100000 (1 cm : 1 km) or 1:500000 (1 cm : 5 km).

Most of the maps shown in this atlas give a continental perspective and are based on maps compiled at scales smaller than 1:1000000 (1 cm : 10 km). Such maps are referred to as small scale.

The major soil types in Africa

The map shows the dominant WRB Reference Soil Groups for Africa. The map is a revised representation of the African part of the Digital Soil Map of the World produced by the Food and Agricultural Organization of the United Nations (FAO).

The map clearly shows the zonal arrangement of soils in Africa.

The central, wetter part is dominated by Ferralsols, depicted in brown-orange. They are associated with Acrisols (orange-brown). Towards drier parts, Lixisols start to appear (pale pink). In West Africa large areas of Plinthosols occur (dark brown), mainly as hardened surface layers or cuirasses.

The desert regions in the north and the south are dominated by Calcisols (bright yellow), Leptosols (shallow soils depicted in grey), Regosols (pale pink), Arenosols (brownish yellow) and Gypsisols (pale yellow). Very locally, especially in southern Africa, Durisols (pinkish grey) occur.

The dark purple colour on the map, mainly in Sudan and Ethiopia, indicate Vertisols whereas the bright red colours depict the dominance of Andosols, mostly associated with the African Rift valley. This is also where most of Africa's Nitisols are found (dark pink).

In the Mediterranean region pale brown and brown colours indicate areas of, respectively, Kastanozems and Phaeozems. Gleysols (dark blue) and Fluvisols (bright blue) are found throughout the map, the latter associated with Africa's river systems and deltas. Solonchaks (purple) and Solonetz (light purple) are mainly associated with coastal plains. Alisols (very pale yellow), Cambisols (orange), Histosols (dark grey), Luvisols (dark pink), Planosols (dark orange), Podzols (green) and Umbrisols (dark green) are scattered throughout the map and can be locally important.

In urbanised areas and near large mines, Technosols (highly disturbed soils) may occur. However, most of these areas will be too small to be visible at this continental scale.

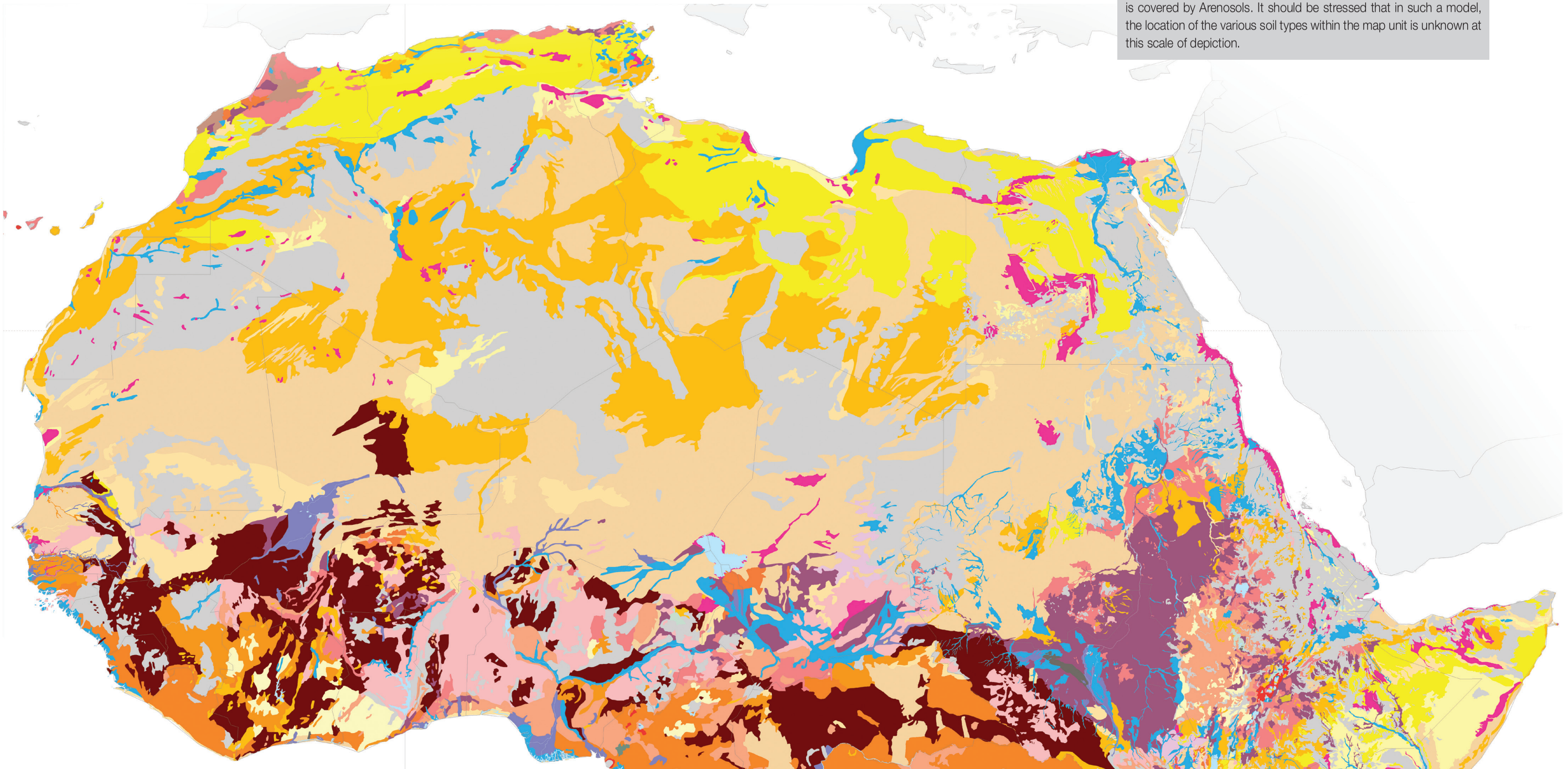
Soil mapping unit

The soil mapping unit is the basic geographic component on the soil map. A soil type is a specific soil with definable characteristics. On large scale maps, the soil mapping unit corresponds to individual soil types.

On small-scale maps, soil mapping units rarely comprise single soil types. Instead, they can consist of a combination of a dominant soil type with minor associated soils.

When the various soils of a soil mapping unit occur in a recognisable geographical pattern in defined proportions, they constitute a soil association. If such a pattern is absent, they form a soil complex. Soil associations merge into a mosaic to create a 'soilscape' or soil landscape unit.

In this context, if in the database a map unit is associated with 44% Gleyic Arenosols (sandy soils affected by shallow groundwater), 36% Lithic Leptosols (shallow stony soils) and 20% Albic Arenosols (sandy soils with a bleached topsoil), only the soil that occupies the largest areal extent is shown (i.e. the Gleyic Arenosols). If the assessment were to be based on Reference Soil Groups only, then 80% of the unit is covered by Arenosols. It should be stressed that in such a model, the location of the various soil types within the map unit is unknown at this scale of depiction.

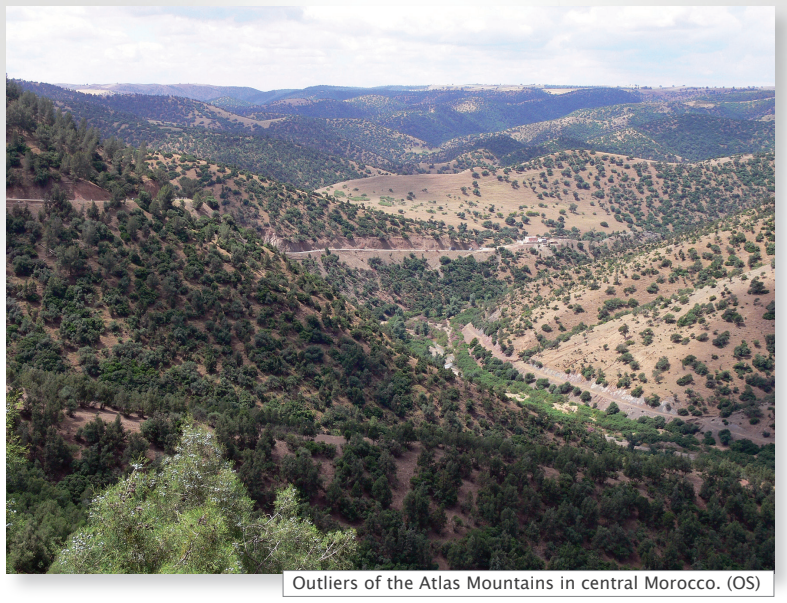


Soils of the African Economic Community

The Arab Maghreb Union (AMU)

The Arab Maghreb Union (AMU - Union du Maghreb Arabe (UMA) in French) is an economic, social and cultural agreement to increase self-sufficiency and endogenous development while creating a framework for development and mobilisation of human resources and material between Algeria, Libya, Mauritania, Morocco and Tunisia (Egypt has applied to join). The AMU covers an area of 6 041 261 km^2 (around 20% of Africa) and has an estimated population of 92 million (2010) with a density of 15 people/km^2. Per capita Gross Domestic Produce (GDP) is estimated at US$ 4 229 [66]. According to UNEP, North Africa is the most urbanised region of Africa with an average urban population of 54%. In Libya, this rises to over 80%. Agriculture employs a significant proportion of the population (over 40% in Morocco). Where rainfall is more prevalent, cereals such as barley and wheat can be grown without irrigation. Olives, citrus fruits and wine grapes are also cultivated, largely with water supplied by artesian wells. Dates are common in the southern oases. However, drought is a recurring phenomenon in the region and causes sharp annual fluctuations in crop and livestock production.

The soils of the region reflect three broad divisions. Along the Mediterranean and Atlantic coasts, the climate is characterised by hot, dry summers and mild, wet winters. Natural vegetation takes the form of oak and pine woodlands, shrubs and grasses. The dry, hot summers make much of the region prone to fires. Cooler, more humid conditions are reflected by the presence of productive Kastanozems and Luvisols.



Outliers of the Atlas Mountains in central Morocco. (OS)

Away from the coast, the Atlas Mountains extend some 2 500 km through Morocco, Algeria, and Tunisia. The highest peak is Djebel Toubkal with an elevation of 4 167 m in southwestern Morocco. The Atlas Mountains separate the Mediterranean and Atlantic coastlines from the increasing aridity and temperatures of the Sahara Desert. The extent of the Atlas Mountains is clearly visible as a broad expanse of Leptosols and Cambisols.

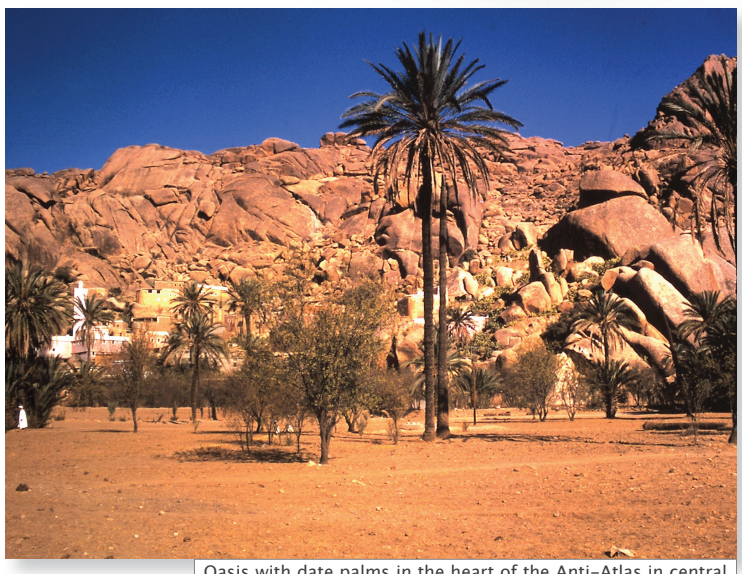
The southern part of the region is characterised by the dry, desert soils of the Sahara. Calcisols, Gypsisols, Leptosols and Cambisols abound. The large sand seas (or ergs) are denoted by the Arenosols. Organic mater levels and water retention capacity are low for these soils while very saline Solonchaks can be found in depressions or in evaporate lakes (known locally as Chotts or Sebkhas). The blue linear features are Fluvisols, denoting river systems, many of which are ephemeral in nature (i.e. dry for much of the year).

The semi-arid conditions generally lead to poorly developed soils that are vulnerable to degradation by human activities such as overgrazing and erosion, especially by flash flooding after intense rainfall. Soil organic carbon levels are generally low or very low and desertification is key concern.

Leptosol over solid sandstone in central Morocco. Roots are restricted to the thin soil layer on top of the rock. (OS)

Sand seas occupy significant parts of the Sahara. The picture shows a Protic Arenosol in a dune deposit. The cross bedding throughout the profile indicates that wind is still playing an active role. Note the presence of sparse vegetation on the surface and buried cemented layers within the dune. (ISRIC)

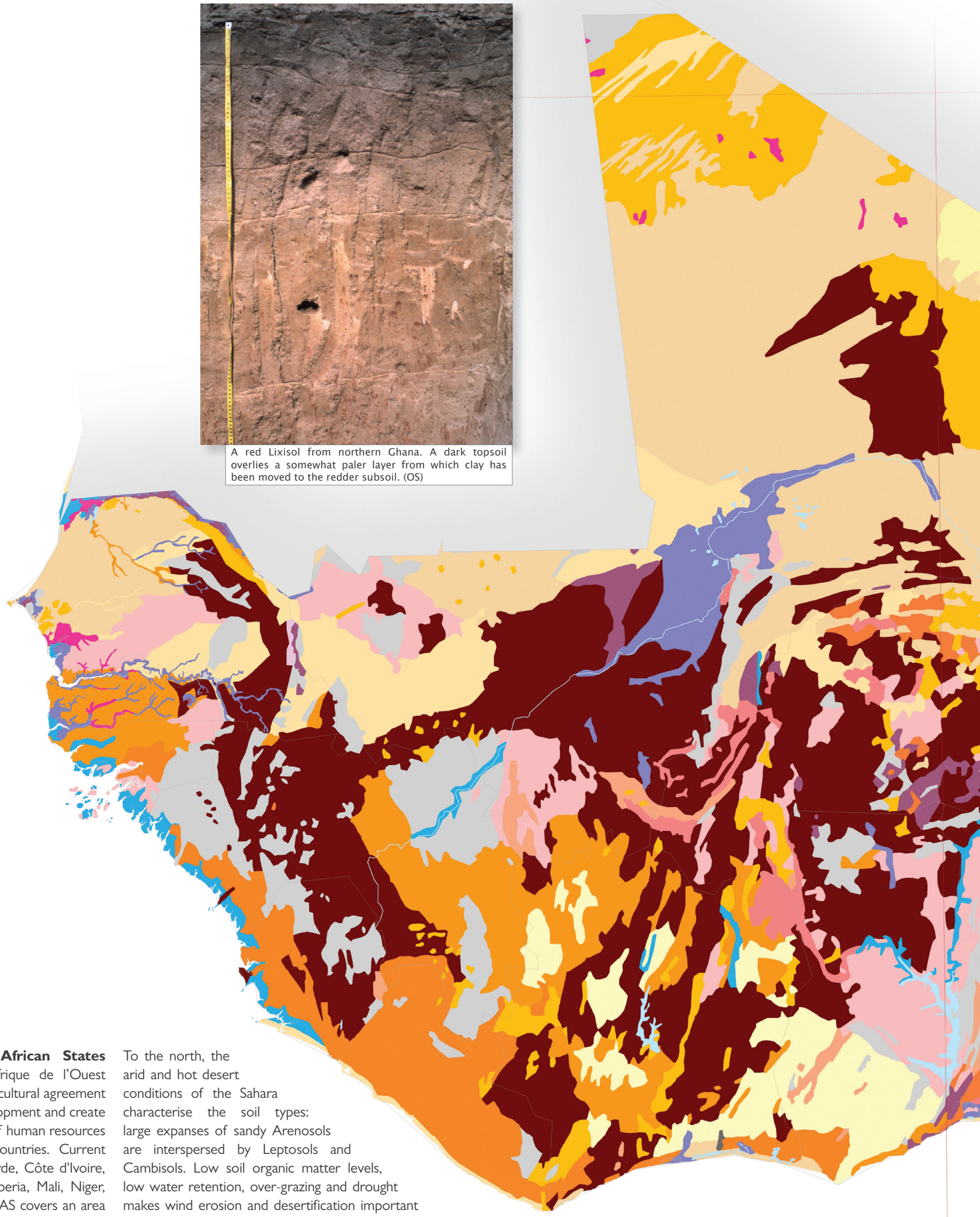
The above image shows an olive tree (*Olea europaea*) growing in a fertile, well drained soil in Morocco that develop originally under permanent grassland. Such soils, referred to as Kastanozems (from the Latin *castanea*, chestnut, and Russian *zemlja*, earth), develop organic-rich topsoils that provide essential plant nutrients while giving the soil a well defined structure and good water holding capacity. The presence of calcium carbonates makes the soil slightly alkaline. In between the olive trees, other food crops are cultivated. However, drought and maintaining soil organic matter levels are important considerations. (SH)



Oasis with date palms in the heart of the Anti-Atlas in central Morocco. The oasis is filled with material washed down from its surroundings leaving the slopes bare. (OS)

The Economic Community of West African States (ECOWAS)

A red Lixisol from northern Ghana. A dark topsoil overlies a somewhat paler layer from which clay has been moved to the redder subsoil. (OS)



The Economic Community of West African States (ECOWAS - Communauté des Etats de l'Afrique de l'Ouest (CEDEAO) in French) is an economic, social and cultural agreement to increase self-sufficiency and endogenous development and create a framework for development and mobilisation of human resources and material between fifteen West African countries. Current members include Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo. ECOWAS covers an area of 5 112 903 km^2 (around 17% of Africa) and has a population of around 300 million (2010) with a density of 49 people/km^2. Per capita GDP is estimated at US$ 2 500 [66].

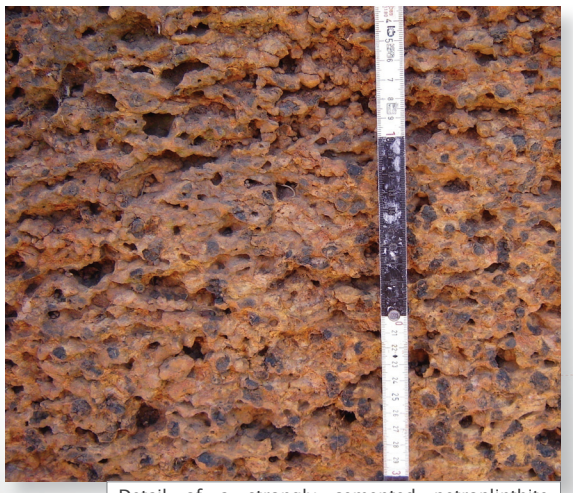
The ECOWAS area is bordered on one side by the deserts, on another side by the deciduous forest and tropical rainforest regions, and on a third side by the Atlantic Ocean. This is one of the most populated parts of Africa. Lagos in Nigeria has a population of around 8 million and is the second fastest growing city in Africa while Bamako in Mali has an annual growth rate of 4.45% and is the 6th fastest growing city in the world. A significant proportion of the population live in small villages and their main source of income is agriculture. Natural vegetation is generally open, ranging from sparse grassland to open-wooded grassland. Forests occur in more humid conditions. The climate has one or two pronounced dry seasons of several months. Rainfall varies from 300-1 000 mm per year.

To the north, the arid and hot desert conditions of the Sahara characterise the soil types: large expanses of sandy Arenosols are interspersed by Leptosols and Cambisols. Low soil organic matter levels, low water retention, over-grazing and drought makes wind erosion and desertification important considerations in these areas.

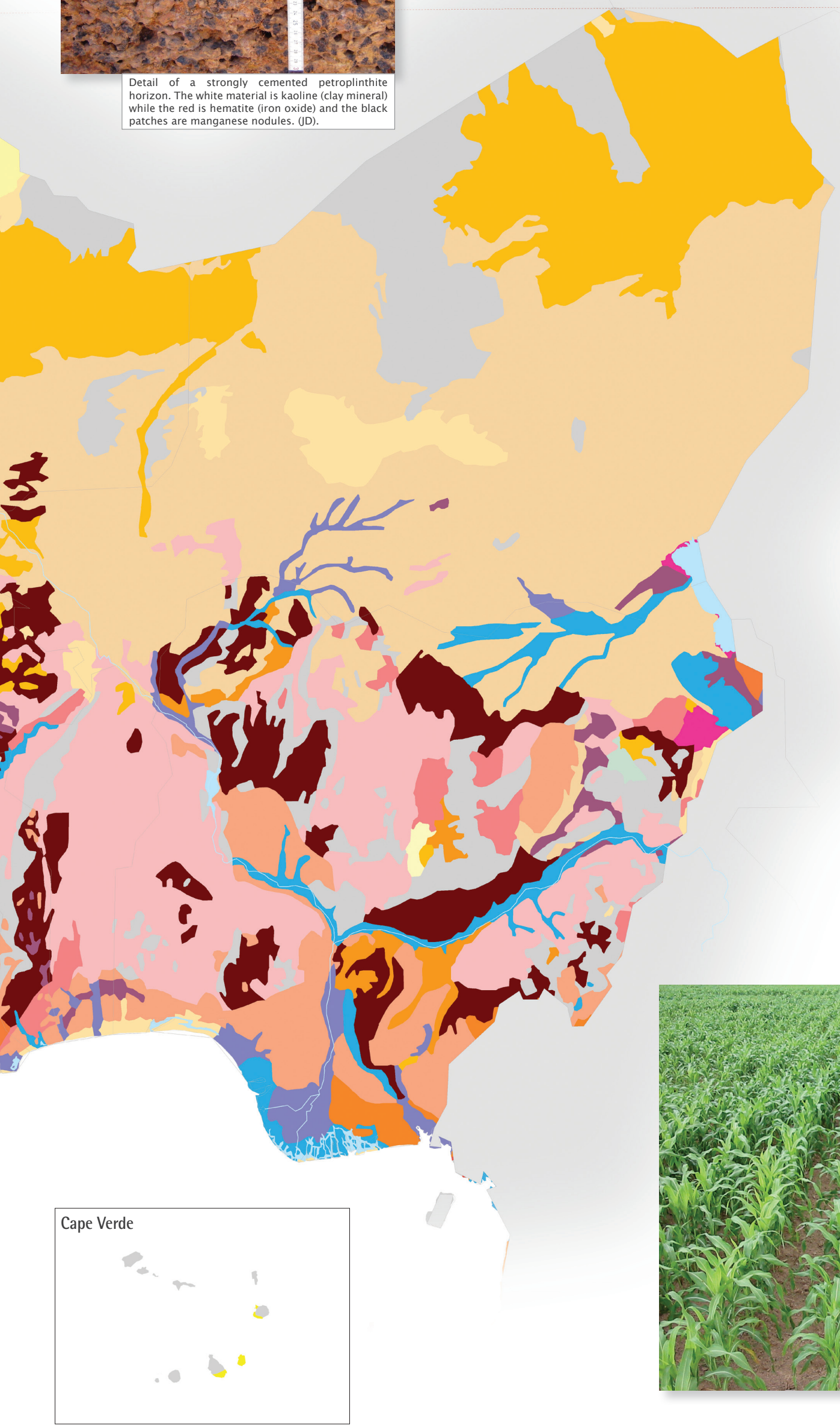
Lying between the Tropic of Capricorn and the equator, the ECOWAS region displays the full range of tropical soil development. Ferralsols and Lixisols are dominant in association with Plithosols and acid Alisols and Acrisols. Despite their deep profile, good structure and drainage, the cultivation of tropical soils is problematic. The capacity of Ferralsols, Acrisols and Alisols to supply and retain nutrients for plants is very low. Very high rates of phosphate fertilisers and lime are required for significant yields. High levels of aluminium are also toxic for many plant species. Biological activity in the soil is low. The clay-rich subsoils of Lixisols have a slightly higher fertility but become quickly depleted under agricultural use. Plinthosols have low nutrient content and can harden irreversibly on exposure to air.

Fluvisols can be found in the mangrove areas along the coast and along the principle river valleys. Very evident is the Niger River, the principal river of west Africa and the third longest river in Africa. Over 4 080 km in length from its source in the Guinea Highlands, its drainage basin covers approximately 2 120 000 km^2 (about 6% of Africa). Gleysols denote both the Inner Niger Delta in Mali (important for agriculture and fishing) and the coastal delta in Nigeria.

Soil degradation due to land use change and desertification, together with the loss of soil nutrients, are the dominant soil issues in this area.



Detail of a strongly cemented petroplinthite horizon. The white material is kaoline (clay mineral) while the red is hematite (iron oxide) and the black patches are manganese nodules. (JD).



During the past 20 thousand years soil have developed in stabilised dunes that were once active in much drier climates. The photograph above shows a Ferralic Arenosol in the north of Burkina Faso. (MB/IRD)

Storage hut in Ghana built of hardened blocks of plinthite (also known as ironstone). The porous ironstone provides good isolation against the heat from outside. (OS)

Northern regions in the ECOWAS area are prone to land degradation. This photograph from Burkina Faso shows a stone bund in a field under sorghum cultivation to break and contain the flow of water over the surface of the soil. Such practices limit erosion and conserve soils. (RZ)

Acrisols
Alisols
Andosols
Arenosols
Calcisols
Cambisols
Ferralsols
Fluvisols
Gleysols
Histosols
Leptosols
Lixisols
Luvisols
Nitisols
Phaeozems
Planosols
Plinthosols
Podzols
Regosols
Solonchaks
Solonetz
Umbrisols
Vertisols
Water Body

0 500 km

Satellite picture of Brazzaville, Kinshasa and the Malebo Pool of the Congo River. Also known as the Stanley Pool, the Malebo Pool is a lake-like widening in the lower reaches of the Congo River. About 35 km long, 23 km wide, its central part is occupied by M'Bamou or Bamu Island which has an area of 180 km^2. The pool is shallow with depths of 3 to 10 m. While water fluctuate vary by as much as 3 m, the shoreline is bounded by extensive palm and papyrus swamps while large floating mats of Eichhornia (water hyacinth) plants are prominent. (NASA)

The Economic Community of Central African States (ECCAS)

The Economic Community of Central African States (ECCAS - Communauté Économique des États de l'Afrique Centrale (CEEAC) in French) is an economic, social and cultural agreement to increase self-sufficiency and endogenous development, and create a framework for development and mobilisation of human resources and material between Angola, Burundi, DR Congo, Rwanda, São Tomé and Príncipe. Since 2003, Cameroon, Central African Republic, Chad, Equatorial Guinea, Republic of the Congo and Gabon have been associated with ECCAS through an accord with the Economic and Monetary Community of Central Africa (or CEMAC from its French name - Communauté Économique et Monétaire de l'Afrique Centrale).

ECCAS covers an area of 6 667 421 km^2 (around 22% of Africa) and has an estimated population of 152 million (2012) with a density of 71 people/km^2 – although this ranges from 5 for Gabon to nearly 300 for Rwanda. Mean per capita GDP is estimated at US$ 2 500 but this includes the three poorest economies in Africa (DR Congo US$ 348, Burundi US$ 615 and Central African Republic US$ 768) and oil-rich Equatorial Guinea which has the highest GDP in Africa (around US$ 20 000). [66].

The ECCAS area straddles the equator, almost in equal proportions. Angola and Chad are characterised by arid and semi-arid climate and soil types. Large expanses of sandy Arenosols are interspersed by Leptosols, Cambisols and Calcisols. Low soil organic matter levels, low water retention, over-grazing and drought make wind erosion and desertification important considerations in this area.

The climate is hot, humid tropical and sub-tropical. The annual temperature range is low and average temperatures are over 25°C. The Congo has the highest frequency of thunderstorms in the world and in places, annual rainfall can be more than 5 000 mm. The dominant landcover is tropical rainforest (the 2nd largest expanse in the world after the Amazon Basin). This massive expanse of lush jungle covers a vast, low-lying central basin which merges into savannahs and grasslands, then deserts to the north and south and by the Atlantic Ocean to the west. In the extreme east of DR Congo, the Ruwenzori Mountains have glaciers!

Climatic conditions, together with dense forest conditions, means that Ferralsols are the dominant soil type, often grading to Lixisols, Plinthosols, and Nitisols. Despite their deep profile, good structure and drainage, the cultivation of tropical soils is problematic. The capacity of Ferralsols to supply and retain nutrients for plants is very low. Very high rates of phosphate fertilisers and lime are required for significant yields. High levels of aluminium are also toxic for many plant species. Biological activity in the soil is low. The clay-rich subsoils of Lixisols and Nitisols give a slightly higher fertility and have reasonable water-holding capacity but become quickly depleted under agricultural use. Plinthosols have low nutrient content and can harden irreversibly on exposure to air.

Fluvisols can be found in the mangrove areas along the coast and along the principle river valleys. Very evident are Chad's major rivers - the Chari, Logone and their tributaries which flow through the southern savannahs into Lake Chad and the River Congo, the deepest river in the world with measured depths in excess of 220 m and the third largest river in the world by volume of water discharged. Over 4 700 km in length from its source in the highlands and mountains of the East African Rift, its drainage basin covers just over 4 000 000 km^2 (about 12% of Africa). Gleysols in the centre of the region denote the Tumba-Ngiri-Maindombe wetland - covering an area of 65 696 km^2 (twice the size of Belgium) and recognised by the Ramsar Convention as the largest Wetland of International Importance in the world. This vast area of forest and permanent or seasonal lakes and marshlands has great environmental and economic value.

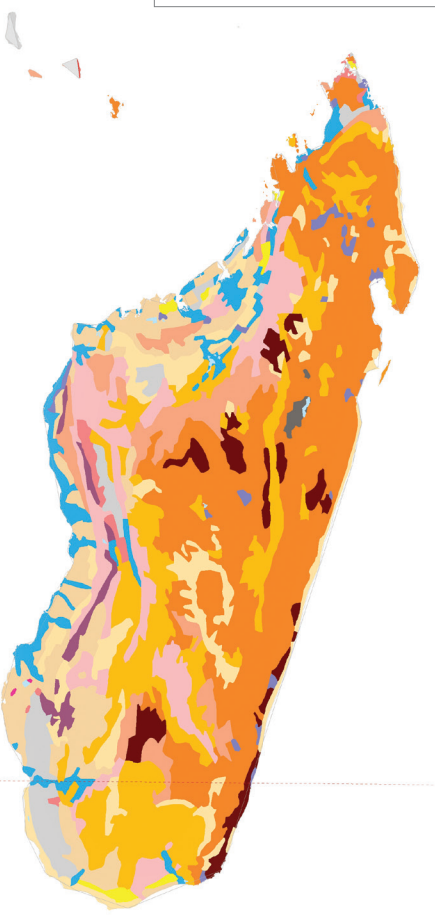
The rural population of the region is extremely poor and many suffer from endemic local conflicts as well as food insecurity. High population growth, malnutrition, poor land tenure laws and unsustainable use of firewood and charcoal contribute to forest and soil degradation through slash-and-burn cultivation. In addition, the WWF report that rainfall has declined in recent years, which could lead to further degradation.

Brick making from a clay-rich soil in Cameroon. The bricks are then stacked and dried in the sun. The red colour indicates significant levels of iron or alumuinium oxides. Note the landslide on the slope in the background. (EM)

- Acrisols
- Alisols
- Andosols
- Arenosols
- Calcisols
- Cambisols
- Chernozems
- Cryosols
- Ferralsols
- Fluvisols
- Gleysols
- Gypsisols
- Histosols
- Leptosols
- Lixisols
- Luvisols
- Nitisols
- Phaeozems
- Planosols
- Plinthosols
- Podzols
- Regosols
- Solonchaks
- Solonetz
- Stagnosols
- Umbrisols
- Vertisols
- Water Body

Clayey Gleysol on a sandy deposit in the floodplain of the Zambezi River near Mongu, western Zambia. (RH)

Nitisol landscape from southern Ethiopia. (SDD)



0 500 km

Common Market for Eastern and Southern Africa (COMESA)

The Common Market for Eastern and Southern Africa (COMESA - Marché Commun de l'Afrique Orientale et Australe in French) is an economic, social and cultural agreement to increase self-sufficiency and endogenous development, and create a framework for development and mobilisation of human resources and material. It comprises Burundi, Comoros, Democratic Republic of the Congo, Djibouti, Egypt, Eritrea, Ethiopia, Kenya, Libya, Madagascar, Malawi, Mauritius, Rwanda, Seychelles, South Sudan, Sudan, Swaziland, Uganda, Zambia and Zimbabwe. COMESA covers an area of 13 million km^2 (over 40% of Africa) with an estimated population of over 405 million (2012). Mean per capita GDP is estimated at US$ 1 900. [66]

The COMESA area is enormous: stretching from Libya to Zimbabwe, it covers almost the entire eastern half of the continent. Egypt, Eritrea, eastern Ethiopia, eastern Kenya, Libya, Sudan and much of Zambia and Zimbabwe are characterised by arid and semi-arid climate and soil types. Large expanses of thin, stony Leptosols, sandy Arenosols and lime-rich Calcisols dominate these regions. Saline Solonchaks occur in depressions or on salt-rich parent material. The main impediment to the use of these soils is excessive levels of lime and soluble salts, combined with a scarcity of water. Where water is available, clay-rich Luvisols and Phaeozems can be very productive. Low soil organic matter levels, low water retention, over-grazing, drought, wind erosion and desertification are all important considerations.

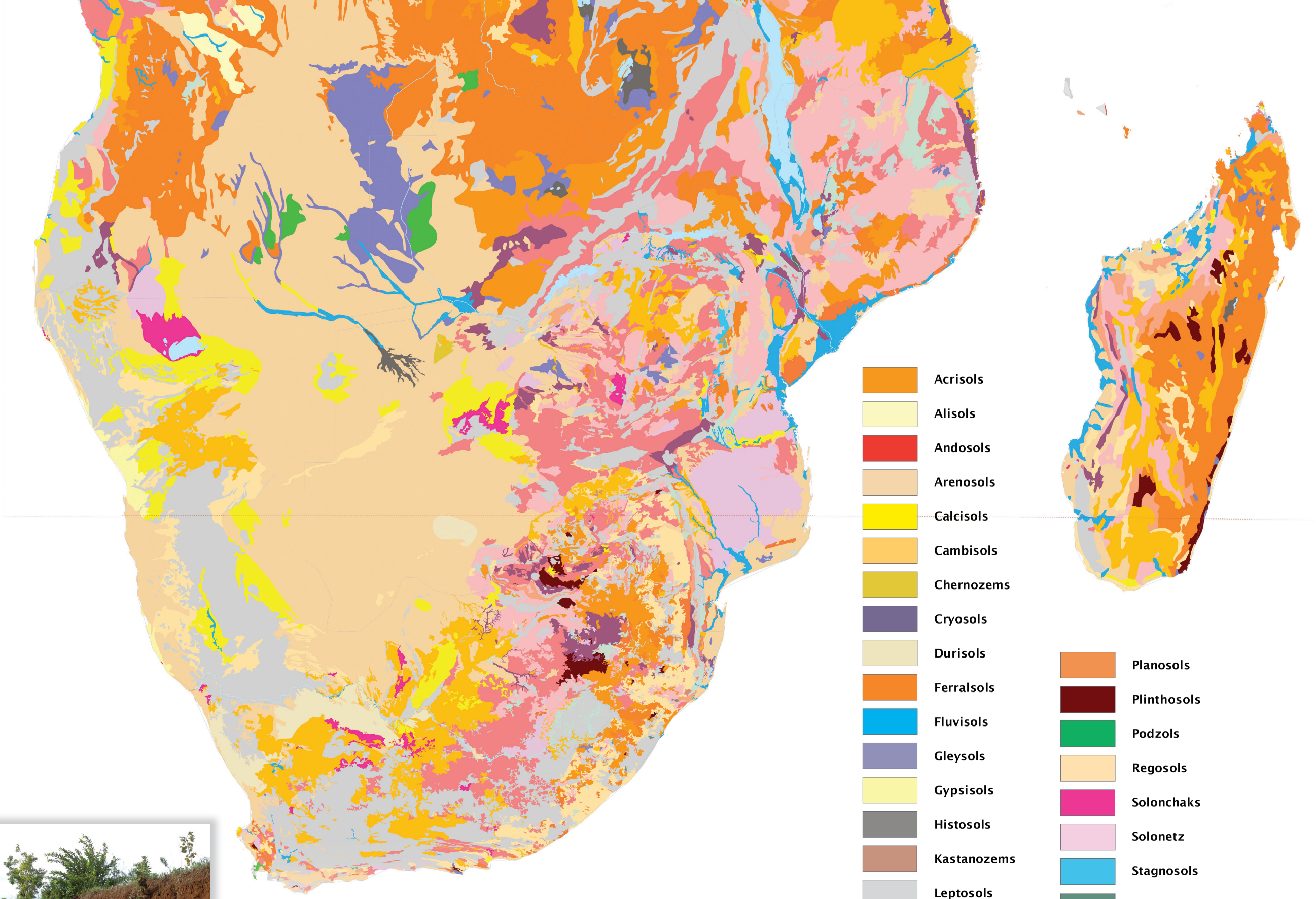
The level semi-arid and sub-humid parts of Ethiopia, Sudan, South Sudan and Uganda are characterised by significant expanses of Vertisols. In the rainy season, clay minerals in the soil expand and surface flooding becomes a problem while in the dry season, the clay shrinks and deep cracks and crusts form. While inherently fertile soils, they must be cultivated in a very narrow window. They are prone to erosion when not vegetated. Phosphorus levels are generally low.

Along the Rift Valley, the weathering of volcanic deposits have produced fertile Nitisols and Andosols that are well known for coffee and tea production. DR Congo, eastern Kenya and much of Madagascar, Uganda and Zambia are dominated by a tropical climate, rainforest and nutrient-deficient Ferralsols (see previous page). Fluvisols denote the three principle river systems in this region – the Nile, the Congo and the Zambezi and their associated marsh areas. The Nile is the world's longest river (around 6 650 km) and its drainage basin covers about 10% of Africa (3 400 000 km^2). Gleysols denote the Al-Sudd swampy lowland in Southern Sudan, the Tumba-Ngiri-Maindombe wetlands in the Congo Basin and the swampy floodplains of the Kafue and Zambezi Rivers in Zambia.

Given its vast expanse and extremes of climate and vegetation, the COMESA region displays a range of soil types and associated issues. High population growth, poor land tenure laws, nutrient depletion, desertification and soil erosion are all major concerns.

Due to space and scale restrictions, Swaziland is shown on the map spread on pages 78-79 (SADAC).

A black Vertisol – this image was taken in the dry season. Vertisols contain expansive clays known as montmorillonite that shrink and swell during dry and wet seasons. A distinctive microrelief, deep cracks when dry and a lack of distinct horizons due to the churning of soil material are key characteristics (the latter is very evident in the adjacent photograph). Vertisols typically form from the weathering of highly basic rocks, such as basalt, in climates that are seasonally humid or subject to erratic droughts and floods. In East Africa, they are known as "black cotton" soils. The natural vegetation is generally grassland or savannah – the heavy texture and unstable nature of the soil restricts the growth of trees. Sudan and South Sudan have extensive Vertisols. (EM)



Red Ferralsol exposed in a road cut in Tanzania. (EM)