STRATIGRAPHY AND PROPERTIES OF SOIL PROFILES ALONG TRANSECTS IN BURKINA FASO AND BENIN AND THEIR INFLUENCE ON PHYTODIVERSITY

Dissertation
zur Erlangung des Dorktorgrades
der Naturwisscchenschaften

vorgelegt beim Fachbereich Geowissenschaften/Geographie
der Johann Wolfgang Goethe-Universität
in Frankfurt amMain

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Frankfurt 2012

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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II. ABBREVIATIONS AND ACRONYMS

BIOTA: Biodiversity: Biodiversity Transect Monitoring Analysis

BO: Biodiversity Observatory

BIOLOG: Biodiversity and global change

CBD: Convention on Biological Diversity

BMBF: Bundesministerium für Bildung und Forschung

BF: Burkina Faso; BN: Benin

IRD: Institut de Recherche pour le Développement ex - O.R.S.T.O.M

G.E.R.D.A.T: Groupement d´Étude et de Recherche pour le Développement de l´Agronomie Tropicale

CEC: Cation Exchange Capacity

SOM: Soil Organic Matter; PSD: Particle Size Distribution

USDA: United States Department of Agriculture

UNEP: United Nations Environment Programme

ISSS: International Society of Soil Science

WRB: World Reference Base for Soil Resources

UNCCD: United Nations Convention to Combat Desertification

UNFCCC: United Nations Framework Convention on Climate Change

ACCNNR: African Convention on the Conservation of Nature and Natural Resources

CILSS: Comité Inter-état de Lutte contre la Sécheresse au Sahel

DBH: Diameter Breast Height

DCA: Detendred Correspondence Analysis; CCA: Canonical Correspondence Analysis

HZ: The Hunting Zone

PNP: Pendjari National Park

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1. THEMATIC BACKGROUND AND GOALS OF RESEARCH

1.1. The BIOTA-West Africa project

The present study is a part of the research Biodiversity Transect Monitoring Analysis (BIOTA-AFRICA). BIOTA is a research network that includes applicants of 35 research groups from different Universities in Germany and in Africa. As a part of the program BIOLOG (Biodiversity and global change) BIOTA-AFRICA is financially supported by the German ministry of education and research (BMBF*: Bundesministerium für Bildung und Forschung*). This project tries to realize the recommendations of the Convention on Biological Diversity (CBD) that were adopted in Rio de Janeiro (1992). An agreement according to international law that commends a global protection of biodiversity is covered by this convention. Ratified by 180 countries, this agreement transcends the other existing instruments about protection of species because it is not restricted to one zone and not only applied to particular species but to the biodiversity in general. Furthermore, the convention connects for the first time protection with the sustainable development and use of biodiversity (SCHNEIDER 1999).

The three important aims of the convention are:

- Conservation of biological diversity,
- Sustainable utilisation of parts of diversity,
- Fair and equilibrated distribution of benefits from the utilisation.

The main objective of the network BIOTA-AFRICA consists in the investigation and acquisition of data about the state of biodiversity in Africa that guides to a viable and sustainable management of biodiversity for the decision makers.

In the first and second phase (2001-2007) different approaches of research were scheduled:

- Analysis of spatial and temporal variability of biotic and abiotic factors, intensity and dynamic of changes in the ecosystem
- Ecological changes in the biodiversity taking into account the influence of land use etc.

The natural and socio-economic viewpoints, which are necessary for the practicability of sustainable management of biodiversity, result from these basic approaches.
In the current third phase, dynamic and predictive modelling of biodiversity is focused on, what can simplify the comparison of case scenarios and benefit the decision makers.
The BIOTA-AFRICA network is divided into three regional projects: BIOTA-South Africa (South Africa and Namibia), BIOTA-East Africa (Uganda and Kenya) and BIOTA-West Africa (BF, Benin and Côte d´Ivoire).These regional projects are connected through certain coherence in approach, structure and methodology.
As part of the BIOTA-AFRICA network, BIOTA-West Africa studies biodiversity in collaboration with scientists of the Universities in Burkina Faso (BF), Benin (BN) and Côte d´Ivoire and in conformity with the requirements of CBD. The project develops an interdisciplinary research concept that focuses on the creation of an analytical basis for a sustainable management of terrestrial biodiversity amongst others. Therefore, the studies are focused initially on naturally intact zones.

The main objective of the research is to evaluate changes in biodiversity through different land use and anthropogenic influence on the ecosystem. This can be reached with the acquired knowledge. Therefore, intact natural or less anthropogenic influenced ecosystems are compared with disturbed (land- used and degraded) ones.
Different studies aim at investigating biodiversity along a climatic gradient from tropical rain forests to arid savannas in West Africa and from dry forests via arid savannas to the Mediterranean winter rainfall region in South Africa. BIOTA-West Africa consists of 12 subprojects, aspires as emphasized in the project proposal (2003) to a scientific symbiosis and findings through multidimensional processing of different taxa and function types, an utilisation of geographic information system (GIS) within the standard areas of study (Biodiversity Observatories BO) and an exchange of data between subprojects.
The findings of biodiversity patterns and processes that control the state of biodiversity should facilitate the extrapolation to larger ecosystem regions and produce a model of evolution for predictions. Thereby, the aim is to provide instruments to the decision makers for a conscious and sustainable use of natural resources.
W11 as subproject of BIOTA-AFRICA involves different disciplines (botany, geosciences, ethno- and social science) that collaborate interdisciplinary. The major aim that consists in analysing actual and ancient changes in the phytodiversity along a climatic gradient and under different conditions makes necessary an interdisciplinary approach. The botanical research is made up of collection of new species completed by existing data from the herbarium of the University of Ouagadougou (BF) and from the Senckenberg Institute of Research in Frankfurt am Main (Germany). Remote sensing occupies an important role in the subproject for the conception of spatial and temporal vegetation pattern in different areas from collection of vegetation and soil data to their analysis.
Through ethno botanical and socio-economic research, the subproject focuses on some targets: assessment of temporal and spatial vegetation dynamics, impact of different land use in the diversity of species and impact of vegetation changes for the local population.
BIOTA-W11 is subdivided in several work packages and one of them studies the soil characteristics along transects in relation with the diversity of woody plant.

1.2. Problems and goals of research

Multidisciplinary and integrated researches are nowadays prerequisite for the achievement of widespread studies such as ecosystem and biodiversity. Referring to this, interdisciplinary approach bears a great meaning in the strategy of many projects such as BIOTA in order to counteract the description of biodiversity research as alignment of data thus avoiding deficiencies in results.
The word “Biodiversity” which is object of investigation in the BIOTA-AFRICA project was first introduced by WILSON (1988) who identified under this concept the entirety of variation of the creatures. Biodiversity or biological diversity is a dynamic that is subdivided in different sections: genetic, specific and ecological diversity.
One of the major challenges of biodiversity research consists in understanding ecosystems of a given area. Global survey of biodiversity can be conducted with difficulty but individual purposes with defined aims are more adapted for the study of some facet of biodiversity (WILSON 1988).

Climatic and ecological zones in West Africa are integrated to the Sahel and Sudan ecosystems. They represent the largest ecological unit in Africa and stand simultaneously under strong farming and degradation of soil and vegetation composition. During the last decades the population density has increased largely and at the same time natural resources are becoming scarce. This trend is aggravated to some extent through fluctuating precipitation. Furthermore, a lack of modernisation in the agriculture can be assessed generally up to now.
The consequences on population, mostly small farmers, are drastic. In fact, degradation of the ecosystem can be assessed in these areas and poverty is more and more widespread among farmers.
The strong use or misuse of resources compromises the bearing capacity of soils and their fertility. In relation to biodiversity, a change in phytodiversity is observed in cultivated areas and in woodlands. However, changes are differentially acute from the Sahel to the Sudan zone because of the climatic conditions, particularly the mean annual precipitation. The subproject which is based in Frankfurt dealt basically with the dynamic and diversity of vegetation, which represents a section of biodiversity (the specific diversity). The different studies in the whole project are oriented to zoo-ecological and botanical diversity.
However, this thesis focuses on the soil stratigraphy and properties along pedomorphological transects as well as their relation to biodiversity in South Eastern BF and Northern BN. It aims to provide findings on soil dynamics and variations in the study areas. Thereby, phytosociological relevés of the woody plants around soil profiles within the transects are surveyed with the aim of establishing the relationship between soil properties in consideration to the environmental processes and vegetation structure and composition. Nevertheless, soil data are rather deficient in the framework of the investigations within the BIOTA project. But as resource under the influence of different environmental conditions, soil occupies an important place in the whole problem of biodiversity research. Indeed, it is recognised as lying at the interface of the geosphere, hydrosphere, biosphere and atmosphere and representing the end product of a complex set of interacting processes, operating over a vast range of time scale (ELLIS et al. 1995). GRUBB (1989) assesses that soils should be the best overall reflection of ecosystem processes. It clearly emerges form these statements that soils play a significant function in ecosystem on the one hand and in biodiversity on the other hand. In fact, soils form and vary through different pedogenetic processes as weathering of bedrock, erosion processes, relief, climate, vegetation and anthropogenic influences.
One of the most important factors of soil formation and dynamic is morphogenesis. Relief influences pedogenesis in a passive way through its form or the characteristics of topography and in active way through the processes of relief formation which directly controls soil formation (MICHEL 1973). Pedogenesis and spatial distribution of soils are influenced by geomorphological evolution in the West African region but information about soil type, its distribution as well as its relation to relief are indispensable for understanding the main geomorphological features. The relation pedogenesis-morphogenesis was subject of earlier investigations in West Africa by MICHEL and TRICART (1965) who described this relation as following: “relation of pedology to geomorphology is similar to the one between geomorphology and structural geology. Geomorphological evolution provides framework to the soil formation and evolution. It is uncommon that soils form at the expense of local bedrock. Often they are developed in the superficial formations, alterites or slope deposits etc.” Because of this interaction, the different issues of this work are conducted with a pedomorphological approach.

Pedomorphogenesis in West Africa is characterized by an alternation between geomorphological stable phase of soil formation with particular massive weathering of the bedrock and an instable phase of geomorphogenetical activity (ROHDENBURG 1969, 1983). During this time, plain formation through pedimentation as well as denudation and sedimentation took place (BRÜCKNER 1955, FÖLSTER 1964). Plain formation and loss of material mainly along small slopes are summarised under the term denudation (THOMAS 1994). The latter is described as synthesis of different models and concepts that explain landscape and soil evolution, therein act biomechanical, geomorphological as well as pedological processes (JOHNSON 1993).
In consideration of this pedomorphogenetical evolution, geomorphologists as FÖLSTER (1969, 1983) and soil scientists as LEVÊQUE (1979) have assessed that soils in the study areas are normally multilayered with the bedrock, in the region mostly migmatite-granite, and its weathered product: saprolite as well as one or many layers of sediments. In fact, alternating phases in the West African pedogenesis can be followed in a soil profile through vertical succession of different layers in the undisturbed landscape, while the stratification in the degraded areas is substituted by overlapping lateral succession (FÖLSTER 1969). This succession can only be observed within a whole catena.
Another particularity of soils in West Africa is the presence of discontinuity in the profile that indicates interruption in the soil formation through sedimentation and/ or erosion processes.
The accumulation of resistant and coarse material in the form of a stone-line or *nappe de gravats* (LEVÊQUE 1969) attests to the presence of discontinuity. Stone-lines, whose thickness and continuity vary, separate weathered products of local bedrock from one or many fine grained layers (photo 1). This fine material, whose provenance and properties are not clearly identified, is designated in the French literature as *recouvrement sablo-argileuse,* and in the English literature as hill-wash. These layers (stone-line and hill-wash), resulting from the deposition surface or pediment, are defined and studied under the term pedisediments (RUHE, 1959, SEGALEN 1967). The layers showing heterogeneous composition of the material condition strongly for example hydrological and physical properties of soils and influence thereby vegetation units as well as phytodiversity.
However, this pedomorphogenetical approach based on the identification of hill-wash and stone-line layers as mentioned above is not appropriate in this thesis because of the ubiquitous absence of the stone-line layer in the surveyed soil profiles of the study areas in South East BF and North West BN. Nevertheless, the study of soil profiles is approached in consideration to the dynamic of erosion processes and lateral and vertical transport of material. Furthermore the concept soil horizon as identified and defined in a classical soil science study is replaced by soil layer on the because taking into consideration the autochthonous and/or allochthonous origin of the different layers in the soil profiles

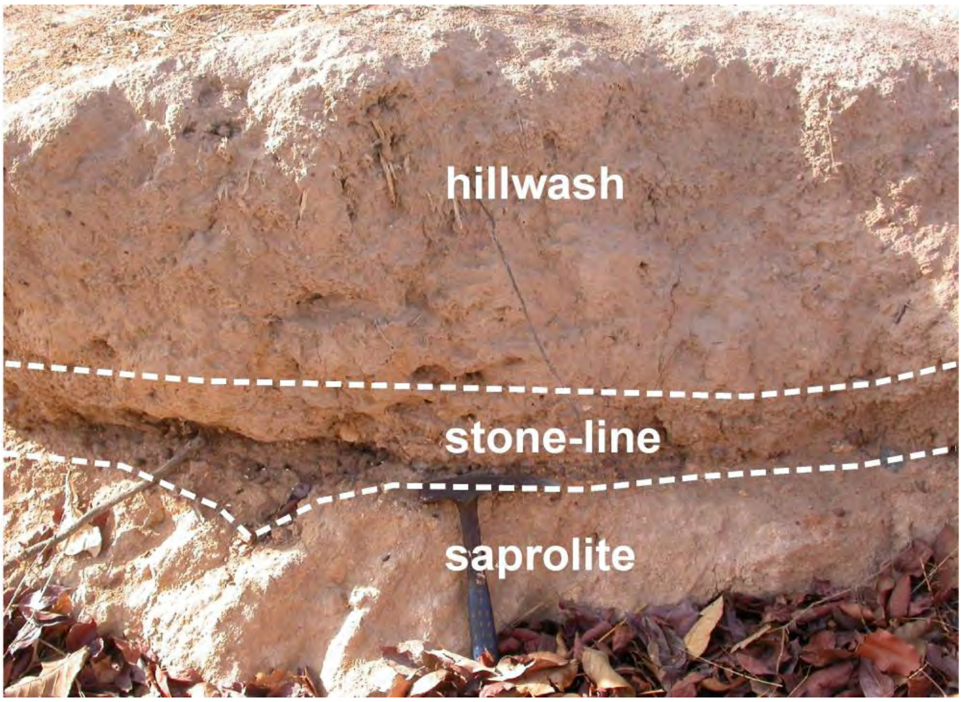

Photo 1: Fine material deposit within degraded zone of South East BF. The underlying layer is characterised by the presence of coarse gravels which might be stone-line (Anne, C. A. T. 04.2005)

The thesis analyses the physical and chemical characteristics of soil layers along transects within areas of different ecological status (protected and unprotected areas). Thereby, environmental and superficial processes leading to loss of soil particles and nutrients are pointed out. The gained information about soil properties which occur in consideration of the dynamic in pedomorphogenesis is correlated to the diversity of woody plants (phytodiversity). Vegetation is one of the important parameters in pedogenesis besides bedrock and climate. For this reason vegetation structure and composition around the different soil profiles are surveyed through phytosociological relevés.

A review of basic concepts of soil and vegetation development indicates that vegetation and soils are mutually associated with each other, both are results of the same environmental variables. Soil body is associated with specific climax vegetation. This assertion is supported by MAJOR´s deduction (1951) claiming that the same environmental factors responsible for soil formation are also responsible for the vegetation that is produced. On that score the same independent variable is involved in the following equation for soil formation of JENNY (1961):

- **Soil=f (climate, parent material, relief, organisms, time)** and
- **Vegetation=f (climate, parent material, relief, organisms, time)**, equation of plant community of MAJOR (1951).

The relationship between soil and vegetation is not easy to study because of the difficulties to choose the parameters which have to be included in the analysis and the scale of analysis. Therefore the relationship is studied here inside of pedomorphological transects (*toposéquences*), which take into account different relief units and the lateral transport and deposition of soil materials. Another difficulty of this kind of analysis is due to the lack of intact vegetation community. In this research it is aimed to study the diversity of woody plants in relation to soil parameters along transects in different relief units. Thereby, external factors like human exploitation and internal factors like characteristics of individual species and soil parameters are taken into account.

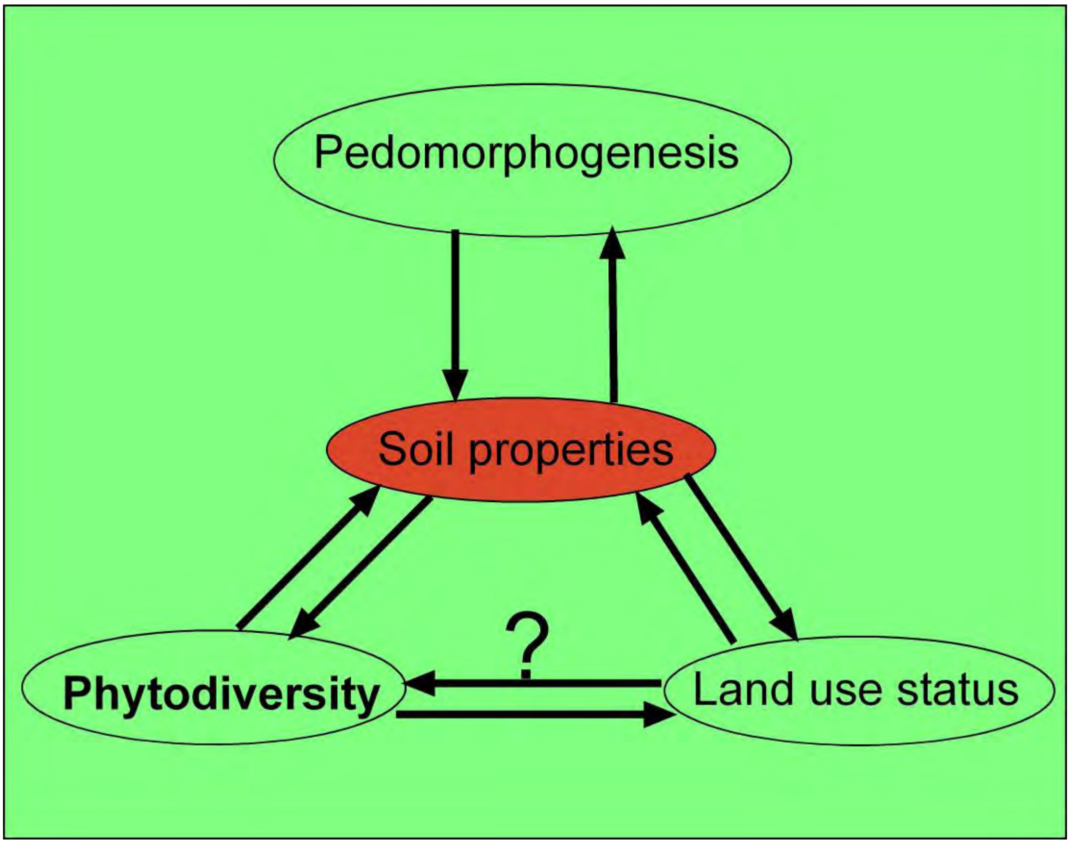

Figure 1: Interlinkage of the analysis levels of the goal researches.

Based on the above illustrated analysis levels and their interlinkage, it is aimed in this thesis to corroborate that pedomorphogenesis are determinant for the properties and types of soil within small scale of soil surveying in West Africa. Furthermore, how closed is the relationship between the diversity of woody plant and soil properties as well as land used status on the one hand and the other hand how important is the status of studied areas in the soil parameters and dynamic.

This work is subdivided into six main topics. In the current chapter, the goals of research are pointed out. In chapter 2, a review of the studies about soil formation and dynamic with a focus on prevailing pedogenesis processes is summarised. Thereby, the development of planation surfaces and their influence on the differentiation of soil units as well as distinctive processes like weathering types and duricrust formations are described and applied to the study areas. In addition, the erosion processes in the savanna landscapes and within pedomorphological transects are outlined as well as the state of biodiversity in West Africa and particularly in BF and BN. In chapter 3 the main geographical features in the study areas and in chapter 4 the methodology used to achieve the goals of research are presented. The geographical features facilitate the better understanding of general physical characteristics within the standardised study plots and in the chosen pedomorphological transects.

In Chapter 5, the results of properties, variations of soil profiles as well as vegetation dynamics in consideration to the protected and land use status of the transects are analysed and discussed. Thereby, soil layers are summarised and subdivided in topsoil and subsoil. The physical and chemical parameters in the profiles of the surveyed transects are analysed (5.1-5-2) as well as phytosociological *relevés* (5.4). In the last topic (Chapter 6), statements about the relationship of soil characteristics and vegetation structure and composition are issued and the role of geological and geomorphological features in the differentiation of soil properties and dynamics identified.

2. STATE OF THE ART

2.1. Review of pedological and geomorphological studies in West Africa

For PULLAN (1970) soil may be studied in many ways and for many different purposes. Soil science research was recognised in the 1960s and 1970s as an integrative approach in studies because of the fact that many soil processes are also geomorphological processes and the distinction between geomorphology and pedology was no more actual (GERRARD 1992) Actual researches are increasingly demonstrating the close dependence of soil and geomorphology (BIRKELAND 1999, EPPES 2002, SCHAETZL et al. 2005 etc.) which is established as new discipline soil geomorphology or pedogeomorphology as proposed earlier by CONACHER et al. (1977).

Soil science researches in West Africa which are at the beginning closely associated with the French *Office de la Recherche Scientifique des Territoires d'Outre-Mer* (ORSTOM) nowadays IRD (*Institut de Recherche pour le Développement*). ORSTOM and G.E.R.D.A.T (*Groupement d´Étude et de Recherche pour le Développement de l´Agronomie Tropicale*), tackled the issues of the evolution of tropical soils in three different ways:

- Agropedological investigations were carried out by AUBERT (1962) who is precursor of studies on soil dynamics with the aim of adapting techniques of land use to climatic conditions,

- Study of matter balance (hydric and geochemical balance at the watershed for example in ROOSE 1973, 1980, 1990),

- Advanced experiments on defined processes in soil as impoverishment in fine particle of the upper horizon in Ivory Coast and influence of runoff in soil structures (ROOSE 1973), iron pan cycle (KALOGA 1976).

Important domains of research in West Africa are studies about morphogenesis and planation surfaces that directly determine soil evolution and properties. Many authors identified in the landscape development of West Africa the presence of tertiary and quaternary erosion surfaces that are recognised in the French literature as “glacis”. MICHEL and BOULET (1978) described these surfaces and articulated them chronologically from the high, middle and low glacis. Moreover, the dynamic and mechanism on these surfaces are meaningful for this study and represent the major issues particularly in the Anglo-Saxon literature. Thereby, KING (1951) who introduced the pedimentation concept in the African savanna landscape is one of the powerful advocates for an alternative form of the erosion cycle. The pedimentation process, which received its impulse through incision of the fluvial system as well as a change or fluctuation of climate (MICHEL 1967, FÖLSTER 1971), is polycyclic and each cycle is affecting a lowering of the pediment surface by scarp retreat. With the pedimentation process, the West African landscapes have been repeatedly lowered by a degradation process identified as *surface d´aplanissement* (TRICART 1965). The pediment grew at the expense of older erosion surfaces which are also the pediplains whose remnants can be found on almost every interfluve top (FÖLSTER 1971). Pediplains are designated in the German literature as *Rumpffläche* which are the product of a long geological time span continual ablation by comparative minor tectonic activity (BÜDEL 1981). The dynamic on the erosion surfaces is mostly, nowadays, studied along the slopes. The assumption that particular slope forms are associated with particular erosion sequences led to the formulation of the catena concept from MILNE (1935) who was one of the first to consider processes of erosion as major factors leading to the differentiation, under constant climatic conditions, of several but related soils usually from a common original material. In West Africa BOCQUIER (1973) studied in Chad the soil sequences in relation to the topographic slope, which are called *toposéquences* in the French literature. Contrary to MILNE, BOCQUIER analysed two *toposéquences* from different locations and different parent material whilst BOULET (1978) analysed stability and instability of *toposéquences* from one parent material and the formation and transport of clay within them in BF. BOCQUIER (1973) set a high value on the lateral variation between profiles as well as on the vertical variation in the profile.

The catenary differentiation pattern of GERRARD (1992) assesses that differences between the soils of a catena are generally related to differences in their position and drainage characteristics so that emphasis is placed on the difference between freely drained upper parts of slopes associated to the less developed fluvisols and the imperfectly to poor drained units (fig. 2) in the valleys associated for example to the gleysols (FAO 2006) as well as to the presence and types of outcrops (fig. 3). The catena's with rock outcrop as well as those with hard laterite crust are the most common one in the savanna landscapes. Similarly studies one *toposéquences* were undertaken in BF by KALOGA (1965, 1970) in the drainage basin of the rivers and in Togo by LEVÊQUE (1979). Nevertheless, the majority of soil researches in the past years in West Africa are referred to some general consideration on the typology and the ability of soils for agriculture. However, studies, which establish relation between soil parameters, relief features and phytodiversity, are less widespread in the region.

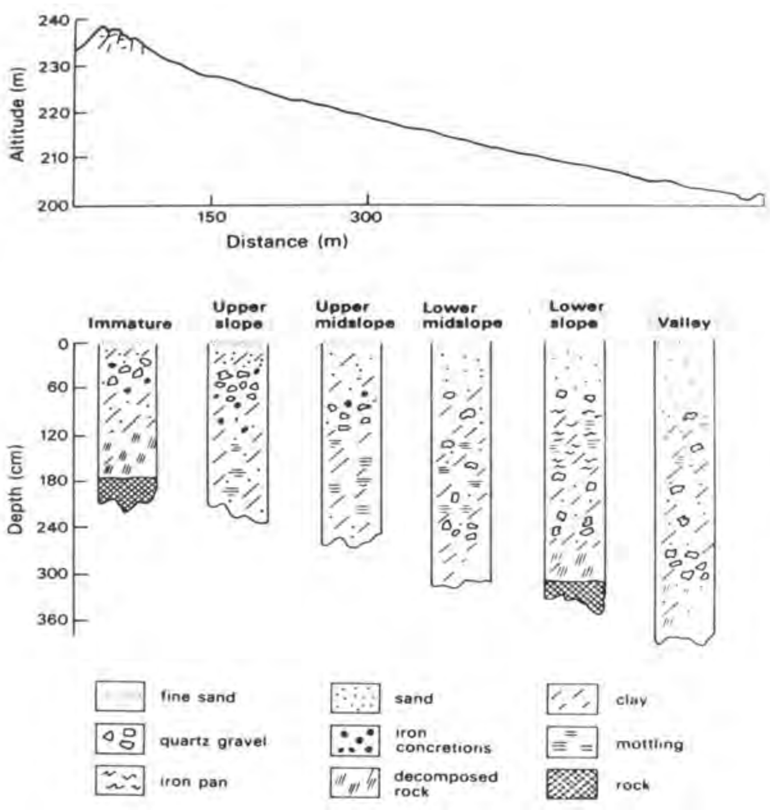

Figure 2: Changes in the profile layers along a West African catena (adapted after NYE, 1954).

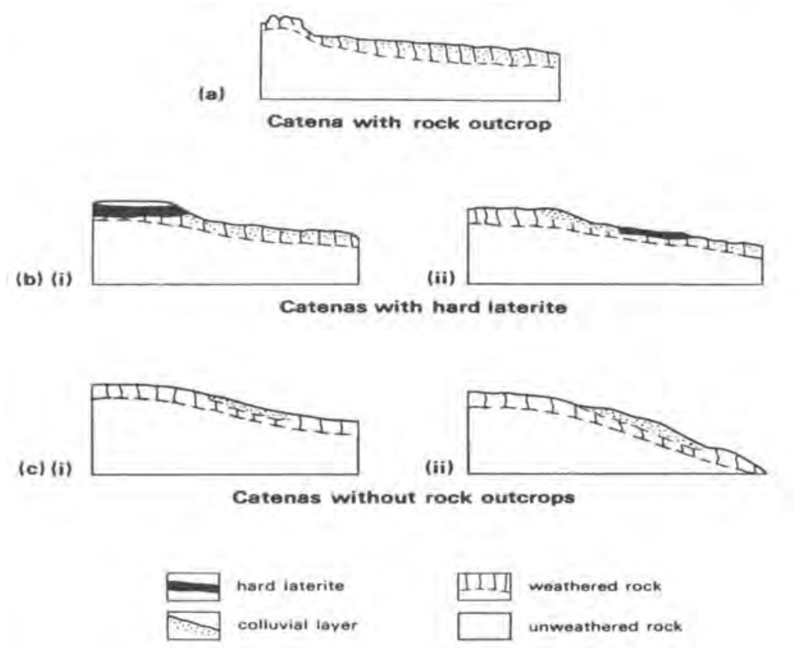

Figure 3: Basic features of tropical savanna catenas. (b) and (c) occur frequently in the study areas (adapted after GERRARD 1992).

2.2. Dynamics and properties of soils and pedisediments

2.2.1. Pedogenesis processes in South East BF and North West BN

Soil dynamics and types are closely controlled and related to the parent materials, relief and climate as described by JENNY (1961). Consequently, major soil units in the study areas reflect the climatic conditions of the north and south Sudan zone, the distribution of geomorphologic and geologic formations and at a local scale the topographic conditions. The basement in the study areas is composed predominantly of granite-migmatite formations from the Precambrian with different facies (see chapter 3).
Geomorphic processes, as formation and evolution of erosion surfaces, are analysed in this chapter with the aim of emphasising the dynamic and characteristics of soil profiles and thus soil layers within the different catenas in Kikideni, Natiabouani and in the Pendjari National Park. Soil formation occurs and develops under alternating climatic phases as well as weathering of the in-situ bedrock and denudation processes which condition and determine soil profiles and lead to their classification.

2.2.1.1. Planation surfaces and pedogenesis

In the last decades geomorphological studies have promoted interest in issues concerning planation surfaces (*surfaces d´aplanissement* or *pénéplaine* in the French school) and their relation to the evolution and characteristics of soils in West Africa. Thereby, their

identification, age, formative processes and the geodynamic and paleoclimatic conditions play an important role.
The fact that the planation surfaces can be produced by a variety of geomorphological processes (GERRARD 1992) leads to different explanatory models about origin and evolution of erosion surfaces. Nevertheless, there is a relative consensus among the scientists about the omnipresent role of climate period in the elaboration and evolution of planation surfaces.
The evolution of climate in West Africa is characterised by fluctuations of humid and arid phases. The indicators of climatic fluctuation were demonstrated in different studies in particular those related to geomorphological and pedological processes. MICHEL (1973), studying the geomorphological units of the Gambia and Senegal Rivers, recognised the role of climatic phases in the formation of the *surfaces d´aplanissement* as well as BOULET (1978) who studied different *toposéquences* in the Sahel and Sudan zone in BF. Chronological studies about the age of the different humid and arid phases was undertaken by ROGNON (1976) with an interpretation of the climatic variation in the Sahara during the last 40,000 years, while SERVANT (1974) analysed the climatic fluctuation using the relation precipitation-evaporation to assess the aridity or humidity index.
The role of climatic variation in the formation of planation surfaces in South East and North Nigeria was also focussed by ROHDENBURG (1969) and FÖLSTER (1983) with a morphodynamic approach. Thereby, the meaning of the climatic fluctuation on pedo- and morphogenesis is pointed out. They identify alternation between stable phases of soil development and morphodynamic active phases coinciding with arid phases. During the active and instable arid phase vegetation covers were less dense and supported thus the stripping of alterites and the lowering (etchplanation or *aplanissement)* by erosion while deep weathering took place during the humid and warm phases (BÜDEL 1981, MILLOT 1980, or THOMAS 1989a, b).
The identification and origin of erosion surfaces is subject of different theses. KING (1962) relates the formation of planation surfaces and landscape evolution to the pedimentation or pediplanation (scarp retreat) process which consists in tectonic activity followed by phases of incisions and lowering or downwasting (*aplanissement*) , as also stated by ROHDENBURG (1969) and FÖLSTER (1983) among other geomorphologists. The planation surfaces are identified under the term *surface d´aplanissement* by MICHEL (1973), who considers this term more neutral than pediplane (KING 1962) or peneplanation (DAVIS 1899) another denomination of planation surfaces. The peneplanation units which are identified in the German literature as *Rumpffläche* (BÜDEL 1957) are recognised geomorphological relict form (ROHDENBURG 1969) characterised by the flatness of the slope where intensive denudation processes occur. Nevertheless, MICHEL (1973) recognised the existence of different *glacis* (*haut, moyen et bas glacis,* high, middle and low glacis) in relation to the presence of duricrusts (see also chapter 2).
In the study area in South East BF geomorphological units which are characterised by wide peneplains (*Rumpffläche*) with gently slopes and small interfluves can be identified as part of Michel's *bas glacis* (1973).
Only some remnants of old erosion surfaces as the Pama Inselbergs and Mesas in the North of the East Province perturb the flatness of the region. The successive identification of glacis developed by MICHEL (1973) could not be clearly identified within the small-scale study (transects around BO). Moreover, the geological units in the study areas seem to be relict of surfaces with an important lateral transport of fine material and weathering of the bedrocks as well as the iron duricrusts. The dynamic on these surfaces characterised by an annually humid and dry season with rill and gully erosion, denudation leading to the formation of new relief units with fine and coarse material deposits (photo 2) that give the undulated physiognomy of the landscape. These dynamic can be compared in a transferable form to a "pediment

formation" or beginning of "pediment formation" through erosion according to the processes taking place in the pedimentation concept of KING (1951).

Photo 2: Sheet erosion in Natiabouani. The fine material is transported and deposed downwards in a new small lateritic scarp in the foreground which can be compared as "small erosion surface" (Anne, C. A. T. 11. 05. 2005).

While the planation surfaces in BF are less affected by tectonic activities, the Pan-African orogeny (650 ± 100 Ma) changes evidently the morphology of the landscapes in the North West region of BN with the folded, tectonised and thrusted Atakora series on the Buem unit, the Buem quartzites (*zone des collines*, hill zone), planed off and thrusted on the Volta basin sediments and the formations of the Volta basin, feebly or non-metamorphosed and discordant on the Birimian base (AFFATON 1973, 1990). The geomorphological units as identified and schematised in this zone with alternation of hill, units, pediments or peneplains (fig. 20) can allow considering that these formations were subject of pediplanation processes, which consist in the idea of an evolution punctuated by tectonic activity followed by phases of incision and lowering (*aplanissemen*t). This model of surface formation developed by KING (1951), RUHE (1959) and later ROHDENBURG (1983) involves scarp retreat. Thereby, geomorphological and pedological processes are focussed on and take place within the slopes or pediments and involve successive lowering of variable intensity.

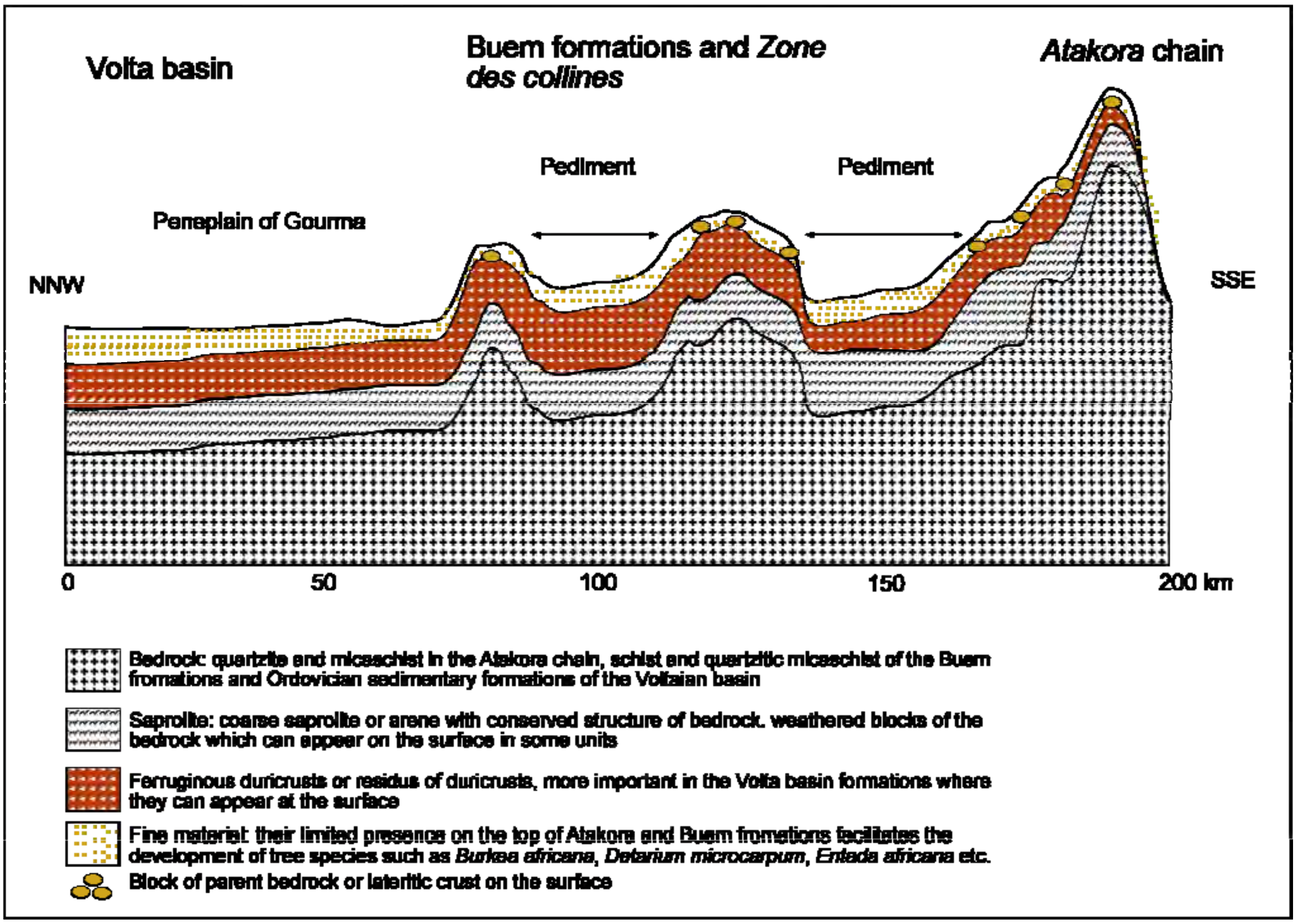

Fig. 4: Simplified representation of section geomorphological units from the Atakora chain to the Volta basin. The sections between the principal units might be identified as pediments following the hypothesis of pedimentation concept (Anne, C. A. T.).

2.2.1.2. Weathering processes and soil profiles

The weathering of the metamorphic and sedimentary local bedrock (granite and leptynic migmatite in South East BF, quartzites, schistes and micaschistes of the North West BN) is one of the important processes of pedogenesis in the north and south Sudan zone. It is a necessary condition and the first step for a number of other geomorphic and pedological processes. The weathering processes in savanna landscapes are object of a great number of works (THOMAS 1974, 1994 on the tropical geomorphology; MABBUTT (1961) who introduced the “weathering front” concept; MILLOT (1983) studying the kaolinite mantle and the topsoil etc.). It consists of breaking, decomposition and alteration of rocks and minerals at the earth’s surface. The weathered material contributes to the formation of soils by providing mineral particles like sand, clay and silt. The elements and compounds extracted from the rocks and mineral by weathering processes supply nutrients plant uptake. Consequently, the weathering processes influence different ecosystem elements (plants, soils etc.).

The climate evolution in the semi-arid regions, characterised by arid and humid alternating phases (see 3.3) played and continues to play a crucial role in the weathering processes. Indeed, weathering is driven by climate and completely dependent on the water cycle as shown by TARDY (1986).

Weathering involves chemical, physical and biological processes. The products or results of the weathering of the bedrock like saprolite and duricrusts are important elements for the analysis and characterization of soil profiles and characteristics in the savanna landscapes.

Weathering types

The material of bedrocks and all materials on or near the surface will alter over time by physical, chemical and/or biological processes. In reality, chemical and physical weathering are mostly joined, usually complementary and occur together particularly in the savanna ecosystems with alternating wet and dry climate.
Physical weathering with mechanical degradation of rocks in place, or dynamic disintegration of particles during erosion and transport, plays the important role of exposing fresh surfaces for chemical attack (MARTINI et al. 1992). It is necessary to mention that physical weathering involves temperature changes which lead to the fracturing of the rock. The mineral composition of local bedrock such as granite, leptynite migmatite, micaschistes and quartzite rocks are variable, therefore the character and rates of weathering vary.
Metamorphic rocks are more susceptible to chemical weathering because of the fact that they are formed under temperature and massive pressure conditions very different from those operating at the earth surface. They are therefore not chemically stable at the surface.
The chemical weathering involves various chemical reactions that take place between the rock minerals, water and certain atmospheric gases, such as oxygen and carbon dioxide. Rocks are penetrated by water, charged with different gases, dissolving and taking away certain minerals in solution. The chemical nature of the rock is thereby changed by transforming the original mineral compounds into new secondary compounds (Price et al. 2003). The main chemical reactions, which are determinant in the study areas, are hydrolysis and oxidation.
Hydrolysis is the reaction between the hydrogen ions of water and the ions of the minerals. As one of the major components of granite, feldspars and particularly K-feldspar (potassium feldspar $KAlSi_3O_2$) for example are broken down by hydrolysis and produce potassium hydroxide (KOH) and aluminosilicic acid containing sodium, aluminium, silicon and oxygen as described by DURGIN (1977). Aluminosilicic acid is then decomposed into clay minerals and silicic acid (H_4SiO_4), while the potassium hydroxide reacts with carbon dioxide, present in water to produce potassium carbonate (K_2CO_3). K_2CO_3 is removed in solution and silica (SiO_2) and residual clay minerals as secondary minerals are remaining (BUCKLE 1987). The reaction process can be resumed as followed:

$2KAlSi_3O_8$ +	$2H_2O + CO_2 \rightarrow$	$Al_2SiO_5(OH)_4$ +	K_2CO_3 +	$4SiO_2$
Felspar	Water Carbon minerals	**Clay minerals**	Potassium carbonate	**Silica**

Clay minerals are identified following THOMAS (1994) as “phyllosilicates or layer of silicates in which hydrated silicates, principally of aluminium and iron in the study areas, form layered structures of silicate tetrahedra or octohedra centred on the aluminium ions Al^{3+}, iron ions Fe^{3+} or magnesium ions Mg^{2+}”. Clay minerals are shared out in the savanna landscapes in two main groups: the 1:1 clay minerals and the 2:1 clay minerals
1:1 layer clay is a tetrahedral sheet linked to one side to an octohedral sheet, and the 2:1 clays have a symmetrical arrangement of two tetrahedral sheets linked to a central octohedral sheet.
Further factors are based on the isomorphous substitution that is the replacement of one ion for another of similar size within the crystalline structure of the clays, the type of bonding, the shrink-swell properties of the clays as well as the amount of Cation Exchange Capacity (CEC). Theses factors influence and determine clay types as showed in the following table.

CLAY	CEC	BOND	SUBSTITUTION	SHRINK-SWELL
Vermiculite	150	Mg	Octahedral & Neut. Tetrahedral	Partially expanded
Montmorillonit	80	Mg	Tetrahedral & Octahedral	High Amount
Illite	30	K	Tetrahedral	None to Little
Kaolinite $Al_2Si_2O_5(OH)_4$	8	H	None	None

Table 1: Factors for distinguishing clay silicates (Sulzman 2005)

Kaolinite does not experience isomorphous substitution and is also bonded by hydrogen while smectites (montmorillonite) experience different isomorphous substitutions in the octohedral layer and thus have a range of chemical compositions
(THOMAS 1994). The resulting negative charge by smectites leads to adequate conditions for exchange cations and water layers as well as good capacity to swell and shrink in relation to the amount of water presence.
The weathering pattern of clay minerals which determine partly the soil profiles and types in the hot wet climate in BF and BN are linked with the drainage conditions and the intensity of hydrolysis reaction. For example, under acid conditions with sufficient water and free drainage, kaolinite is formed and more silica can be removed. In this case, gibbsite ($AlOH_3$) which is considered as the end point of hydrolysis (THOMAS 1994) is formed. But the weathering is not necessarily complete. In zones where water is scarce, the hydrolysis reaction may be prolonged leading to the formation of intermediate clay products (illite, chlorite etc). These weathering products are related to different soil types as shown in the following illustration.

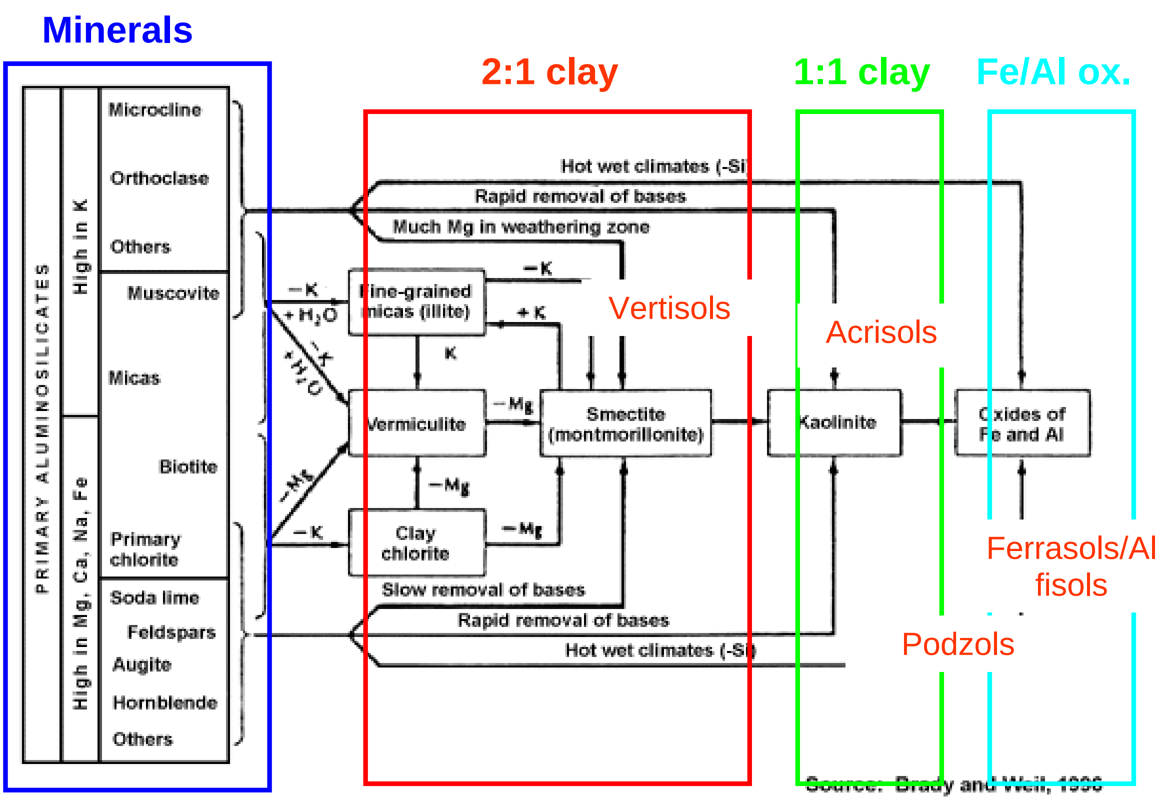

Figure 5: Weathering pattern of clay formation and associated soil types (modified from Brady and Weil, 1996).

Saprolitisation

Saprolite can be described as the weathering product formed during the intensive chemical weathering under warm and humid climatic conditions (SCHOLTEN et al., 1997). Saprolitisation process can be considered thereby as polygenetic, subdividing the saprolite into the near surface oxidation zone, a layer identified by TARDY et al. (1973) as fine saprolite or lithomarge and above the coarse saprolite. The weathering product in the coarse saprolite may be either a single mineral phase such as vermiculite, smectite, kaolinite, gibbsite or assemblages such as vermiculite-kaolinite, smectite-kaolinite, or kaolinite-gibbsite (NOVIKOFF 1974). Nevertheless, saprolite properties are related to other environmental factors. For example, in open systems like savanna landscapes kaolinite and gibbsite are good indicators of the drainage conditions. Saprolite contains often at the basis near the parent rock more unweathered material while highly weathered material is obviously present near the surface under the lateritic layer. This weathered material found in a degraded zone along the transect Kikideni conserves the particle size composition of the original bedrock granite in that case (photo 3) but original structure of the rock may be lost, mostly due to bioturbation with the action of termites and ants, wetting and drying, creep and other near-surface processes.

Photo 3: Saprolite sample collected on a degraded zone in the land-used site of Kikideni, the granular structure of granite parent material is still recognisable (Anne, C. A. T. 29.04.2005).

The thickness of saprolite is relative reduced in the study areas compared to those of the equatorial zones were higher and more intensive weathering processes occur. Saprolite is difficult to observe because it lies under the iron rich and cemented structure identified and called duricrusts and/ or laterite crust. However, the transition from saprolite to lateritic layer which is called “lower solum” can be abrupt or gradual and is controlled by the following processes (SCHAETZL et al. 2005):

- Mixing and formation of structure by fauna and plant roots
- Accumulation of organic matter
- Thickness of the duricrust

Saprolite or weathered mantle provides through its conditions of formation and properties the main characteristics of the upper layered soil (hill-wash) and is often considered in the classification and typology of soils in the savanna landscapes. Moreover the pedogenetic profiles of these landscapes are marked by the presence of duricrust formation as empirically observed.

Iron duricrusts and soil profiles

Iron duricrusts play an important role in the characterisation and identification of soil units in the tropical landscapes. Iron duricrusts, called “cuirasse” or “cuirasses ferrugineuses” in the French literature (MAIGNIEN 1958, TARDY et al. 1988) are laterites or lateritic formations, which includes in addition aluminium duricrusts (bauxite), pisolites, clay mottled horizons, plinthite etc. (TARDY et al. 1992).
Laterite, lateritisation processes and weathering have been object of many studies since the early twentieth century (DE CHÈTELAT 1938).

Some factors affect and influence the lateritisation and duricrust formation, as those intervening in the weathering and pedogenesis (THOMAS 1994):

- Geological factors with the nature and properties of the existing bedrock
- Climatic factors, with alternating wet and arid phases, which are particularly favourable to the formation of laterite,
- Biotic factors, vegetation and biological activity of termites for example,
- Hydrologic factors including the groundwater regime, geomorphic and tectonic history as planation surfaces etc.

A relative consensus can be assessed about the definition of laterite. Indeed, KELLOG (1949) in NAHON (1976) described laterite as the weathering product formed under tropical conditions, rich in iron and aluminium, and either hard or subject to hardening upon exposure to alternate wetting and drying climatic conditions. From this definition two different processes, namely iron and aluminium enrichment and hardening or induration which are widespread pedogenetic processes in the savanna ecosystems may be highlighted. By other studies (MAIGNIEN 1964, MILLOT 1964) laterite is considered as a whole product, not restricted to indurated materials, including all kinds of tropical weathering, whose Fe and Al content is higher and Si content lower than in the kaolinised parent bedrock (SCHELLMANN 1981).

The weathering product consists thereby of goethite, hematite and aluminium hydroxide etc. Under changing and fluctuating tropical climate the weathered material is characterised by the formation of silica and clay minerals, mainly kaolinite (see above) which may be leached during the lateritisation, leaving among others the stable iron oxides. The lateritisation as process, described by FAURE (1977a, b) under “ferruginisation” individualises the sesquioxydes followed by an accumulation and induration in the upper layer of the laterite. These dynamics and redistribution of elements in the laterite lead to the identification of different zones in the lateritic profiles.

A typical lateritic profile is characterised by the succession of three domains (BOCQUIER et al. 1984, OUANGRAWA et al. 2001):

- An alteration zone at the basis of the profile which is the saprolite (coarse saprolite, fine saprolite and lithomarge), which is characterised by the incongruent dissolution. In this zone, most of the soluble materials are leached

- The least mobile elements (Al, Fe) are reorganised in situ with little or no transport

- A middle nodular or glaebular zone (MARTINI et al. 1992) with the presence of indurated accumulation of iron or aluminium either continuous (ferricretes or bauxites) or discontinuous (nodules or pisolites),

- The upper zone is considered as non-indurated with a sandy clayey texture but characterised by a relative accumulation of primary minerals such as quartz.

The layer in which accumulation and induration occurs, is identified as duricrusts. Duricrusts are characterised following the chemical constituents who determine the durricrust type (bauxite, silcrete, calcrete etc.). However, the different layers of the lateritic profiles as schematised in figure 6 are not always present in the soil profiles because of the dynamism of erosion processes and unfavourable conditions in the lateritisation processes.

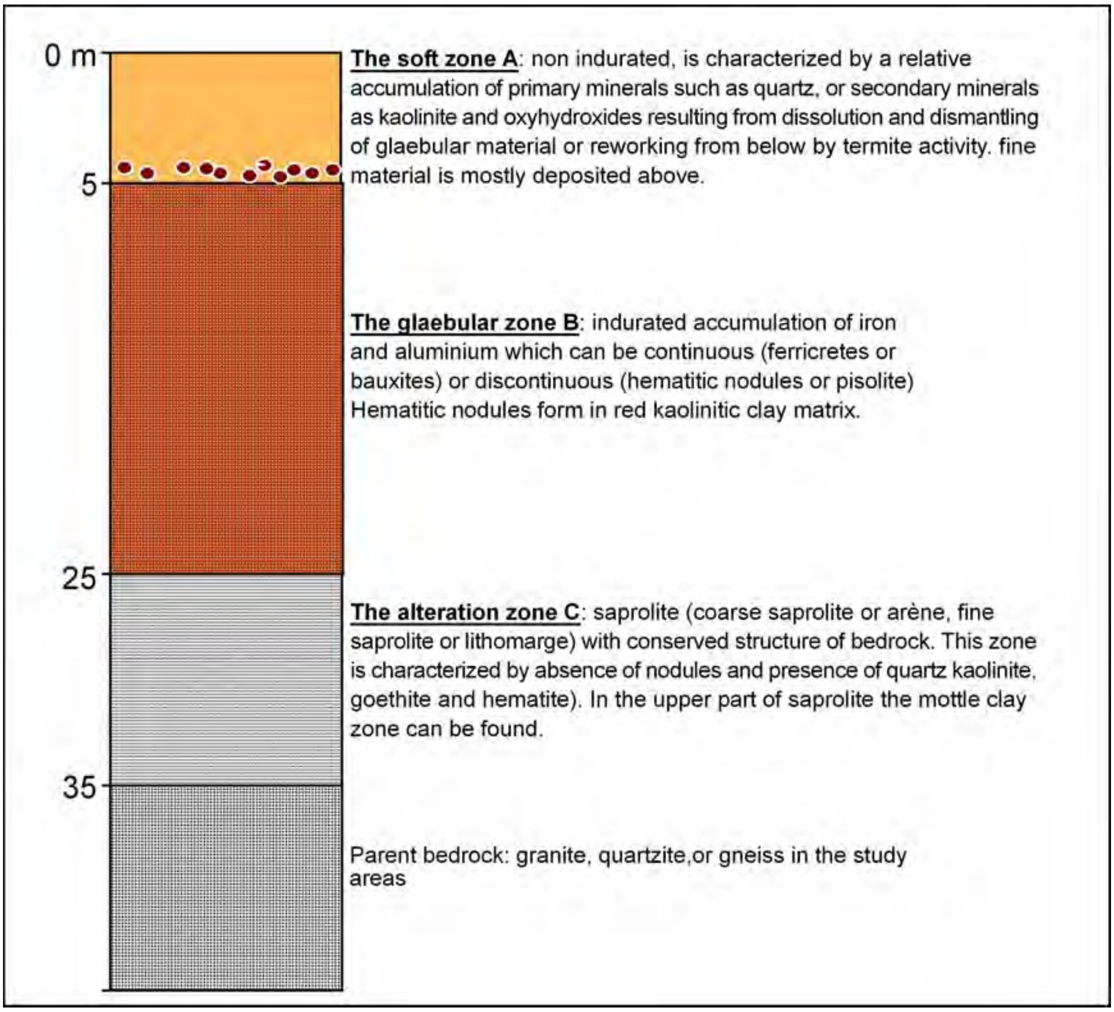

Figure 6: Schematic representation of a lateritic profile adapted to the lateritic soils of West Africa based on an illustration of MARTINI et al. (1992).

In the study area (South East BF) ferricretes appear mostly as relict features of old erosion surfaces and pedogenesis processes. Indeed, MICHEL (1973) recognised lateritic cover on the *haut glacis* and the "moyen-glacis" contrary to the *bas-glacis*. Under the fine material (hill-wash) deposited in the low erosion surfaces (*bas-glacis*) in South East BF, appears duricrust formations in various depths according to the topographic position of the profile.
Different facies can be found in ferricretes following the induration, concretion, accumulation and intensity of iron and aluminium oxides. NAHON et al. (1986) and TARDY in MARTINI (1992) identified different facies. At the base of profiles a thick gray-purple kaolinitic horizon occurs with frequent macroscopic preservation of original pre-existing structures. In such a horizon chemical balances clearly show that part of kaolinite crystals could be explained by an absolute accumulation of circulating solutions. Higher up in the profiles, Fe accumulation leads to two main facies: purple red haematitic spots and nodules and yellow kaolinitic and goethitic spots (mottled clay horizon). Theses about the allochthonous or autochthonous origin of ferricretes have been debated. Ferricretes were considered by many scientists as allochthonous occurrence because results of lateral transportation of iron in solution precipitating from a dependent saprolite following the lithology (MAIGNIEN 1958, MICHEL 1973, MCFARLANE 1976) or formed from a long distance mechanically transported material without any relationships with the in situ bedrocks (LAMOTTE et al. 1962, SERET 1978). However, the evidence of autochthonous development has become more and more established with BOULET (1978), PION (1979) and SCHELLMAN (1986) who assessed that the presence of quartz, iron and some elements reflecting the composition of the underlying bedrocks shows the litho-dependence of the ferricretes. Ferricretes which are covered by sandy and sandy silty hill-wash material originating from bioturbation through termites and lateral transport of sediments along the slopes, contain pisolites which are non-indurated and closely packed round pellets of iron or aluminium particularly in the soil surfaces of degraded zones (photo 4). The pisolites may have an allochthonous or an autochthonous origin according to the scale of investigation. However, the lateritic profiles and the fine material on the surface are very instable in the savanna landscapes because being affected by erosion processes which may modify their structure and composition.

Photo 4: Massive pisolite presence upon a duricrust on a bare surface in Kikideni in South East BF: fine material is almost eroded (Anne, C. A. T. 08.06.2007).

2.2.1.3. Denudation processes

Denudation processes refer to all the weathering and erosional processes that contribute to the lowering of the land surface, potentially to the production of a peneplain as the product of a long period of erosion (CAINE 2004). Denudation is considered as one of the important factors in the formation and evolution of the landscapes. Indeed, it divides the land into drainage basins, sculptures the mountains and valleys and forms the hill slopes.
In the previous chapter, different facies of weathering in the study areas are focused while in the following paragraphs erosion processes in West Africa in general and in the study areas in particular are examined.

Related to different factors, erosion is growing to a very serious environmental and economic problem affecting soil fertility and loss of arable surfaces. It includes the processes of detachment of soil particles from the soil mass and the subsequent transport and deposition of those sediment particles. Due to its temporal and spatial occurrence, as well as its numerous consequences on landscapes and on agricultural activities that farmers are facing since a few decades, erosion is an essential research topic to appreciate the relationship of soil properties to vegetation communities and their dynamics. For the understanding of the processes involved in the dynamics of erosion, studies may be placed in the context of environmental systems operating in the local scale: for example within transects including different relief units in the study areas of BF and BN.

Factors of soil erosion

Erosion processes are operating continually since the early geological times particularly during the instable phases of geomorphogenetical activity in the study areas and influence the dynamic and characteristics of soil formation. Erosion involves different factors that are often combined: climate, soil physics, vegetation cover and land use and overgrazing by livestock (TARDY 1990, CHAMPION 1993, TERRENCE et al. 2002).

- Rainfall is one of the determining agents of climate as factor in soil erosion but its intensity more than its quantity brings about the accelerated erosion. Rainfall may infiltrate soil surface and be stored in the root zone, pass downwards to the groundwater or be stored in surface depressions to either infiltrate, evaporate or runoff over the surfaces. The different forms of erosion result from the dynamic and use of rainfall amount on and in the soil. The savanna ecosystems are characterised by a wet and dry season with a long dry period. The long droughts result in a wilting of the vegetation cover, a drying and crumbling of the surface of the soil, so that precipitation which is characterised by its high intensity in a very short time (around 60 mm /hour for example at Ibadan in Nigeria; LAL 1985), washes away the soil particles during the first rains. Surface runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil to absorb and transmit rainwater. The intensity and rates of runoff influences particularly the identified forms of erosion in the study areas (see below).

  Extreme temperatures may play a role in soil erosion. Indeed, it is established that the strong solar radiation during all the year in West Africa often completely dries up the vegetation cover. The consequent heating of the soil surface causes a loss of nitrogen as well exposure to rainfall and wind (CHAMPION 1993).

- Soil physic is determinant for the evaluation of soil erodibility. Soils in West Africa are derived from the underlying bedrock, obviously granite and quartzite in the study areas which may be eroded easier than other bedrocks. The experimental studies (ROOSE 1977-1991, LAL 1985) show that ferruginous soils, characterised by their low organic matter, cation exchangeable capacity and clay content are less resistant to erosion particularly after two or three years of cultivation while ferralitic soils are more resistant to erosion. The high erodibility of ferruginous soils is due to their high content of silt and fine sand (ROOSE 1989).

However, soil structure and properties are strong related to the vegetation cover and the land use practices.

- Vegetation cover and land use are by far one of the most important factors affecting, conditioning or accelerating soil erosion. If vegetation cover is uninterrupted, whether it is in the forest ecosystems, savanna or pastureland, erosion and runoff rates may be small (tab. 2a, b).

Stations	Period of observations	Rainfall	Soils types	Vegetation
Adiopodoumé (Côt d´Ivoire)	1955-75	2100 mm	Impoverished ferralitic	Secondary evergreen forest
Bouaké (Côte d´Ivoire)	1960-75	1200 mm	Eroded ferralitic on granite	Dense shrub savannah
Korhogo (Côte d´Ivoire)	1967-75	1400 mm	Reworked ferralitic on grani	Clear shrub savannah
Allokoto (Niger)	1966-71	500 mm	Vertisol/calcareous	Shrub savannah
Ouagadougou (BF)	196 7-73	850 mm	Leached ferruginous on gran	Sparse tree savannah
Sefa (Sénégal)	1954-68	1300 mm	Leached ferruginous	Woodland
Cotonou (BN)	1964-68	1300 mm	Impoverished ferralitic on tertiary, argillic - sandy material	Woodland
Boukombe (BN)	1960-61	1100mm	Leached gravel-filled ferruginous on schist	Park savanna

Table 2a: Precipitation, soil characteristics and vegetation cover in some experimental sites in West Africa (adapted after ROOSE 1978).

		EROSION			RUNOFF		
Stations	Slope	Natural environment	Bare soil	Cropped so	Natural environment	Bare soi	Cropped so
Adiopodoumé (Côte d´Ivoire)	4.5%	0.03	138	0.1 to 90	0.14	33 [95]	0.5 to 30 [8
Bouaké (Côte d´Ivoire)	4%	0.20(burned surface b.s.)	18 to 30	0.1 to 26	0.3 (b.s.)[16]	15 to 3	0.1 to 26
Korhogo (Côte d´Ivoire)	4%	0.15 (b.s)	10 to 20	0.6 to 8	10 (b.s.) [50]	40 to 60[70]	2 to 32 [60]
Allokoto (Niger)	3.0	-	-	0.10 to 18.	-	-	1 to 20

Ouagadougou (B	0.5%	0.15 (b.s.)	10 to 20	0.6 to 8	10 [50]	40 to 60[70]	2 to 32 [60
Sefa (Senegal)	1 to 2	0.02 to 0.50 (b.s.)	30 to 55	2. to 20	0.3 to 1.5	25 to 5	8 to 40
Cotonou (BN)	4%	0.3 to 1.2	17 to 27.5after land clearing	10 to 85	0.1 to 0.9	17	20 to 35
Boukombe (BN	3.7	-	-	0.2 to 1.6	-	-	1 to 12

Table 2b: Erosion (t/ha/year) and runoff (% of annual precipitation) of different soil surfaces and slope percentages (adapted after ROOSE 1978).*[ ] represent the maximum coefficients of flow during a unit rainfall of 10-years frequency.

The monitoring of these different sites in West Africa shows that the intensity of erosion and runoff processes are strongly correlated to the conditions and environmental properties of the soil surfaces. Indeed, in Adiopoumé (near Abidjan) for example with a rainfall average of more than 2000 mm the material eroded in a natural soil environment is evaluated at 0.03 tonnes while on bare soils erosion reaches an average of 138 tons and 0.1 to 90 tons/hectare/year on agricultural sites. Consequently, this trend is confirmed by the runoff amounts with 33 tons on bare soil surfaces and 0.14 under natural environmental soil conditions. The high erosion on bare soils in Adiopoumé may be related also, to the slope (4.5 % up to 20 % in some positions with erosion amount reaching 570 tons/hectare/year).

Erosion types in the study areas

Soil erosion, recognised as the major cause of land degradation worldwide, occurs in the agro-ecological Sudanian zone (north and south Sudan zone) in the South East BF and North West BN because of the intensity and temporal distribution of rainfall (between 900 to 1100 mm/year) as described above and with the crop production system of the local population. The erosive action of rainfall on the soil surface results from the impact of raindrops (splash) which can break down soil aggregates and disperse them, according to their intensity and to the ratio infiltration-runoff. Runoff occurs when rainfall intensity exceeds the infiltration capacity of the soils. The rate and amount of runoff is influenced by some climatic conditions as intensity, duration, distribution and amount of rainfall, factors affecting the evapotranspiration as temperature, season and wind as well as physical properties of the soil units and the soil environment characterised by land use system, vegetation cover, soil types and slope. Following the intensity and rate of runoff, different erosion types (sheet, rill and gully erosion) are identified in the study areas:

Sheet erosion which occurs mostly with rill erosion is one the most effective forms of erosion processes within the study areas. As a dynamic process by which transportation of soil particles begins, sheet erosion is caused by the unconfined flow of water running across the soil surface. In this process, uniform soil layers are removed by raindrop impact and transported. Thereby, the loss of fine soil materials that contain most of the available nutrients for plants and organic matter can be assessed (TERRENCE et al. 2002) as well as reduction of the soil profiles. The gradual process of sheet erosion is dependent on soil type, velocity and quantity of runoff as well as on the length and steepness of slopes. Indeed, long and steep slopes are favourable to more sheet erosion because they carry more volumes of runoff (GERRARD 1992). The vegetation cover plays an important role in the sheet erosion processes. Surfaces that are most vulnerable to sheet erosion are the overgrazed and cultivated ones (example of the BO of Kikideni), because there is little vegetation to protect and hold the soil surface. Early signs of sheet erosion, which are difficult to recognise or to observe, are the visible grass roots, exposed tree roots and exposed subsoil or stony soils. All these signs of sheet erosion could be assessed in the study areas particularly in Natiabouani (partly protected area).

Rill erosion is a great threat in the West African Sahel and Sudanian zones and occurs when runoff begins to form small concentrated channels. As a dynamic process, rill erosion consists of the detachment and transport of soil materials by concentrated flow. This concentrated flow leads to formation of shallow drainage lines or channel flow (CAREY et al. 2006) which is less than 30 cm deep. Sheet erosion, slope properties and vegetation cover determine the intensity and severity of rill erosion. Rill erosion is common to the bare surfaces where vegetation is scarce due to the shifting cultivation, fire etc. Within the study areas, rill erosion is particularly visible in the land use site of Kikideni and lead to important loss of fine soil material and outcrop of bare ferruginous crusts (photo 5). Rill erosion is often described as the intermediate stage between sheet erosion and gully erosion.

Photo 5: Rill erosion within gentle slope in the land use site of Kikideni (South East BF). The soil surface is characterised by the presence of lateritic crust (partly pisolites) and by scarce vegetation cover (Anne, C. A. T. 11.05.2007).

Gully erosion forms attract more attention in the international scientific community because of their spectacular character and are subject of recent international conferences in Leuven/Belgium (POESEN et al. 2003) and in Chengdu/China (LI et al. 2004). This growing interest is due to the highly visible appearance of this erosion form on the landscapes. Gully erosion is defined as the erosion process whereby runoff water accumulates in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths (SOIL SCIENCE SOCIETY OF AMERICA 2001). Moreover, this process involves the concentration of water moving in rills which form larger channels. There is no consensus about the minimum width and depth required for the identification of gully system. Nevertheless, a minimum depth of 0.5 m has been established to differentiate gullies from rills, both resulting from the concentrated and partly intensified runoff (BOCCO 1991). Gullies involve deep transformation on the soil surface and lead to the loss of soils as resources for crop production.
Gully processes are triggered mostly by anthropogenic factors as inappropriate farming and irrigation systems, overgrazing, road building and urbanization and by intensive rainfall as

well as by landscape instability (VALENTIN et al. 2004). The exposure of soil ferruginous crust or soil crusts due to the hardening of soil surface in relation with the vegetation clearance may play an important role in the formation and development of gully erosion in the study areas as shown by other studies in arid and semi-arid landscapes in South Africa (KAKEMBO et al. 2002) and Spain (MARTINEZ-CASASNOVAS et al. 2002). Furthermore, the parent material and the pedogenenesis conditions in BF and BN characterised by deep weathering material (presence of saprolite in the subsoil) may be an important factor for the occurrence of gully erosion.

The fact that gully erosion could be assessed in land use and open systems within the site of Kikideni as well as within the protected areas of Natiabouani and Pendjari Park (photo 6) indicates that the land use factor is less important for the occurrence of such erosion type. It is important to mention that spectacular gully erosion occur principally in the Sahel zone of BF and are developed on easily eroded sandy soils with omnipresence of soil crusts. The slope steepness may play a marginal role in the development and proliferation of gullies. Indeed, studies in a Sahelian zone of Senegal show that despite very low slope gradients (i.e. <0.05 $m\ m^{-1}$) and the presence of sandy soils (sand content >80 %), gullies tend to develop rapidly (POESEN et al. 2003). While sheet and rill erosion can disappear temporarily with cultivation or with local technical tools (*cordons pierreux* etc.), soil affected by gully erosion are difficult to recover. All of these erosion processes have drastic impact on land crop availability and production.

Gully erosion in the Biodiversity Observatory of Kikideni (south east BF). In foreground, soil fine material deposits, vegetation clearance in the gully and outcrop of residus of the lateritic crust.

Gully erosion in the partly protected zone of Natiabouani (SE of BF). It might be related to the importance of rill erosion, which is accelerated by the management techniques (fire) and clearance of vegetation.

Photo 6: Gully developed in different sites and different land use conditions: protected and unprotected areas (Anne, C. A. T. 20.04.2005).

Consequences of erosion

Different elements of soil properties are affected by soil erosion as fertility, organic matter content in the topsoil, rooting depth, available water holding capacity, and soil texture. Erosion involves the degradation of soil structure and nutrient content. The topsoil which is eroded and transported during the erosion processes is enriched with organic matter. The soil organic matter (SOM) affects both the chemical and physical properties of the soil (FAO 2005). Thereby, SOM provides soils with large pores and ameliorates de facto the soil structure, thus reducing soil density and enhancing water infiltration. The nutrients availability for plants (Nitrogen, Phosphorous, Sulfur, Magnesium etc.) are released by SOM which is with the clay content one of the major source of cation exchangeable capacity of soils.

The loss or lowering of SOM influences the density of vegetation cover and consequently vegetation diversity. Reduction of soil depth impedes the growth of some trees. But erosion processes are accelerated with changing in vegetation cover through farming systems in land use areas and through fire in protected areas. The following table shows the amounts of lost nutrients in the soils through erosion according to the vegetation cover (tab. 3).

	TOTAL EROSION (kg/ha/yr			SELECTIVITY OF SOIL LOSS AS FUNCTION OF SOIL IN PLACE (10 cm)		
	Forest	Crop	Bare soil	Forest	Crop	Bare soil
Total Carbon	26.4	855.6	2725	12.8	2.1	1.5
Total Nitrogen	3.5	98.3	259	22.5	3.1	1.9
Total phosphoru	0.5	28.5	111	6.6	1.4	1.3
Exchangeable CaO	3.0	49.29	113	492	18.5	9.7
Exchangeable MgO	2.2	29.0	45	327	14.1	5.1
Total CaO	3.7	57.1	139	216	8.8	5.0
Total MgO	2.3	39.0	78	60	5.8	2.7
Clay 0-2 micron	64.5	5142	18275	5.9	1.2	1.1
Loam 2-5 micro	33.8	2179	7115	7.7	2.5	1.9
Fine sand 50-20 microns	1.7	5174	23135	0.1	0.6	0.6
Coarse sand 200 2000	0	19305	89375	0	0.9	0.9
			138			
Total erosion	0.11	32				
Runoff m3/ha	210	5250	6300			

Table 3: Measurements of the selective losses of nutrients from sheet erosion on a 7 % slope in south west Côte d´Ivoire (Adiopoumé) as a function of vegetation cover (adapted from ROOSE 1973).

This table emphasizes influence of vegetation cover in the processes of erosion and washing of nutrients which are required for plant and crop development. For example the amount of total carbon and nitrogen losses increase radically from the forest cover to a bare soil. The particle size with fine sand and coarse sand follows the same variation. Even though sheet, rill and gully erosion processes are closely related to the vegetation cover, the dynamics and evolution of vegetation cover are dependant to the soil properties as well as to the human activities. Soil erosion involves apart form the climate different processes as vegetation dynamics and human activities which can interact one belonging to the other and conduct to the loss of biodiversity as resumed in the following diagram.

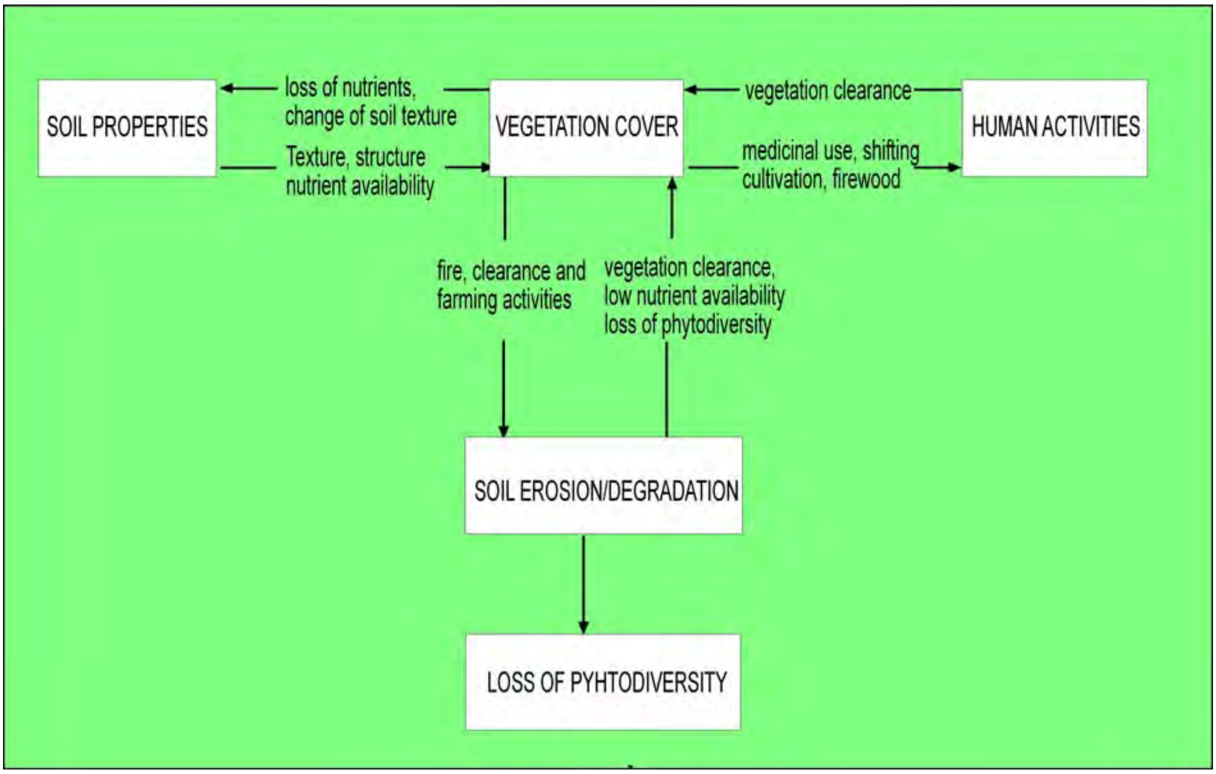

Figure 7: Interaction of soil erosion with environment conditions and its influence on phytodiversity (Anne, C. A. T.).

2.2.2. Soil Classification

In West Africa soils as vital resource for the rural economy were for decade object of precise and methodological observations and classification attempts. Indeed, the first attempts of soil classification go back to the local farmers. For example in Senegal the "*Woloff*" (dominant ethnic group) farmers used to categorise soils principally in consideration of fertility conditions, agricultural productivity and easiness to be cultivated. Two main groups were identified: the sandy soil "*Dior*" corresponding to the luvisols (*Sols ferrugineux lessivés*) and the soil "*Deck*" developed in temporary inundated sites corresponding approximately to the gleysols or *Sols hydromorphes bruns* (ANNE 2001).

The purpose of any soil classification is to organise knowledge about soil properties and their relationship to environmental conditions with the aim of simplifying the identification of a soil unit. The classification of soils in West Africa was impressed by the French soil scientists because of the colonial Francophone history. Soil science was characterised by the multitude of classification models and schools (United States Department of Agriculture USDA, FAO-UNESCO soil maps, etc) and suffered from a lack of harmonisation between the different systems. The World Reference Base for Soil Resources (WRB) that was originally an initiative of FAO and UNESCO and supported by the United Nations Environment Programme (UNEP) and the International Society of Soil Science (ISSS), established a framework through which ongoing soil classification could be harmonised and standardised (FAO 2006). With the final objective which consists in reaching an international agreement concerning the identification and recognition of pedological structures, soil groups and their significance, a facilitation of the exchange of information and experience between scientists (geologists, botanists, agronomists, hydrologists, ecologists, farmers, foresters, civil engineers and architects etc.) can be assessed. Otherwise, the WRB provides a useful and simplified groundwork for the decision makers worldwide and is actually mostly used by the West African researchers.

2.2.2.1. Principles and rules of soil classification

Soil units in West Africa are identified and classified following a certain number of general principles according to the FAO soil guideline based on the WRB (FAO 2006):

- Soil properties which are based on the soil classification and defined in terms of diagnostic horizons and characteristics should be measurable and observable in the field;

- Selection of diagnostic horizons and characteristics occurs in consideration of their relationship to soil forming processes which are important to a better characterisation of soils but can not be applied as a differentiating criteria;

- For a high level of generalisation of soil groups it is attempted to select diagnostic features which are of significance for management purposes;

- Climatic parameters and conditions should not be applied in the classification of soils in spite of the fact that climatic features are determinant for the interpretation of soil units in relation with the physical and chemical properties;

Soils condition by relief	Soils condition by pare material	Soils (semi-) ar regions	Soils of the step regions	Soils of the tropic regions
FLUVISOLS	ARENOSOLS	CALCISOLS	KASTANOZEMS	LIXISOLS
GLEYSOLS	ANDOSOLS	DURISOLS	CHERNOZEMS	ACRISOLS
REGOSOLS	VERTISOLS	GYPSISOLS	PHAEOZEMS	ALISOLS
LEPTOSOLS		SOLONETZ		NITISOLS
			SOLONCHAKS	FERRALSOLS
				PLINTHOSOLS
Organic soils	Soils of limit age		Soils of the arct regions	
HISTOSOLS	CAMBISOLS		CRYOSOLS	
	UMBRISOLS			
Human-made soil				
ANTHROSOLS				

Table 4: Overview of the WRB reference soil groups following the environmental conditions responsible for soil factors and properties. Reference soil groups are defined by a vertical combination of horizons within a defined depth, and by the lateral organisation of these horizons (NACHTERGAELE et al. 2000).

The WRB classification system consisting of combination and association of a prefix set as unique qualifiers added to the reference groups (NACHTERGAELE 2000) allows precise and informative characterisation and classification of individual soil profiles in consideration to different parameters as rooting depth, acidity, pH values, organic matter etc. A total of 121 qualifiers are distinguished in WRB. For each Reference Soil group a list of applicable qualifiers has been established in a priority sequence. The modifiers can be used to identify specific soil problems as presented in the following illustration (tab. 5). Both the number of qualifiers and the sequences may be subject to change in the future (NACHTERGAELE et al. 2000). In the savanna landscapes of West Africa different soil groups are represented following the FAO-UNESCO classification and their properties are strongly related to relief, human activities as well as lateral and vertical variations in the sensitive ecosystems.

Abruptic Planic	Stagnant water, rooting depth obstacle, increased erosion risk on sloping land.
Aceric	Cat clay; turns extremely acid when drained.
Acric	Acid, presence of low activity clays, clay increase with depth.
Acroxic	Extremely poor nutrient retention.
Albic	Presence of a sandy poor layer at shallow depth.
Alcalic	Alkaline (pH> 8,5)
Alic	High (> 50 %) Al- saturation
Alumic Andic	High Phosphorus fixation
Arenic	Sandy upper horizons often low inherent fertility and poor moisture holding capacity (dries out quickly)
Arzic	Presence of gypsum and a high water table
Calcaric Calcic	Presence of calcium carbonate. Fe deficiency possible.
Dystric	Acid.
Ferralic	Presence of low activity clays. Low inherent fertility.
Geric	Poor nutrient retention. Low inherent fertility.
Gibbsic	Al- toxic, low inherent fertility.
Gleyic	High groundwater table.
Grumic	Vertisols with a self mulching layer.
Gypsic Gypsiric	High gypsum content. Structure may collapse when wet or irrigated.
Histic	Peat soils. Do not drain.
Leptic	(Very) Shallow rooting depth available.
Mazic	Vertisols with hard surface horizon.
Natric Sodic	High sodium saturation. Na-toxic, bad soil structure.
Ochric	Generally poor in organic matter.
Petric	Strongly cemented, impermeable, stagnant water, limited rooting depth
Skeletic	High gravel content, good aeration but low moisture holding capacity.
Thionic	Presence of sulfidic materials (mangrove).
Toxic	Presence of toxic elements for plant growth.
Vertic	Deep cracks and very hard when dry, very sticky when wet.
Vitric	Volcanic soils, high phosphorus fixation.

Table 5: World Reference Base modifiers and related soil management problems (adapted to West Africa, FAO 2006).

2.2.2.2. Soil groups in West Africa

Eight reference soil groups can be found in West Africa: Acrisols and lixisols or luvisols, alisols, ferralsols, gleysols, planosols, and nitisols. Apart from alisols, all theses other groups are well represented and occur in defined environmental conditions as described below.

Acrisols and Lixisols or *sols ferrugineux tropicaux lessivés ou ferralitiques fortement dessaturés* according to the old French classification system are quite similar and characterise strongly weathered, illuvial and acid soils with low base saturation, a subsurface of clay accumulation or iron sesquioxides and organic matter . A higher clay content in the subsoil compared to the topsoil due to the pedogenetic processes (particularly clay migration) can be assessed and lead to an argic subsoil horizon. They are adequate for cropping systems but with additive fertilisation necessary for sedentary farming, agro-forestry recommended for soil protection. Acrisols occur predominantly in the sub-humid zone of West Africa (Côte d´Ivoire, Guinea, Liberia, Sierra Leone, etc.).

Ferralsols (*Sols ferraltiques*) are soils which have ferralic and nitic horizon (clay rich subsurface horizon) within 100 cm from the surface. In many sites, the top of the ferralic horizon is marked by a clay increase sufficient to fulfil the requirements for the argic horizon. Ferralsols are characterised by deep weathering and dominance of kaolinitic clay minerals but low clay activity, accumulation of iron, high content of sesquioxides; great soil depth, good permeability and stable microstructure, less susceptible to erosion. The fertility of these soil may be maintained by manuring, mulching.

Gleysols (*Sols hydromorphes à gley ou à accumulation de fer en carapace ou cuirasse*) describe soils with permanent or temporary wetness near the surface; suitable for arable cropping, dairy farming and horticulture if drained appropriately.
The main change in the gleysols compared to the 1988 Revised FAO Legend is the more restrictive conditions in the diagnostic criteria for “gleyic properties” with respect to the percentage of the soil mass affected by oximorphic and/or reductomorphic properties. WRB requires gleysols to have these properties in either more than 50 percent of the soil mass, or in 100 percent of the soil mass below any surface horizon. Oximorphic properties reflect alternating reducing and oxidizing conditions, whereas reductomorphic properties reflect permanently wet conditions (NACHTERGAELE et al. 2000). The result of this change may be that soils, presently classified as Gleysols in the Revised Legend, may become a gleyic subdivision of one of the other Reference Soil Groups in WRB.

Planosols (*Sols ferrugineux tropicaux lessivés pro parte*) characterise soils with a bleached, temporarily water-saturated topsoil on a slowly permeable subsoil; low clay content in the topsoil, more clay in the sub horizon, low fertility level and consequently land use of low intensity. They are present mostly in flat to gently undulating terrain with natural sparse grass vegetation, scattered with shrubs or trees climax vegetation of grasses or open forest, mostly used for extensive grazing.

Nitisols (*sols Fersialitiques, Ferrisols*) are deep soils, well drained, and with accumulation of clay dark red, brown or yellow clayey soils having a pronounced shiny, nut-shaped structure;

very productive soil of the humid tropics, less strongly weathered than ferralsols, resistant to erosion; used for plantation crops and food crops alike.

Regosols (*Sols minéraux bruts et sols peu évolués d´apport éolien*): are soils with very limited soil development, unconsolidated windblown materials; low moisture holding capacity, often used for extensive grazing.

2.3 Biodiversity in West Africa

The African continent is well endowed with both variety and abundance of living organisms, referred to as biological diversity, or biodiversity. Biodiversity can be considered at three major levels (SCHOLES et al. 2005):

- Genetic variation within populations,
- The number, relative abundance and uniqueness of species,
- The variety, extent and condition of ecosystems.

The ecosystems are broadly arranged in a latitudinal pattern (WHITE 1983) with increasing species richness towards the equator (MUTKE et al. 2005).
In comparison with most parts of the world, such as Western Europe, North America and South East Asia, Africa’s biodiversity is still in stable condition (HOEKSTRA et al. 2005, SCHOLLS et al. 2005). Indeed, the African landscape is characterised by important resources, which includes forests and woodlands, arable land, mountains, deserts, coastal lands and freshwater systems that provide opportunities and improve human well-being. In West Africa, a wide range of ecosystems - forests, savannas, deserts, rivers, mangroves and seas - provides to the sub-region its richness in biodiversity. The Sahel zone has several wetlands, including the Niger and Senegal rivers, Lake Chad and flood lands in Senegal and Niger which are very important for migratory birds. Other important sub-regional biodiversity values include the Guinea forest which contains half the mammal species on the African continent, including the rare *pygmy hippopotamus*, the *zebra duiker* etc. (UNEP and NESDA 2004). The following table (tab. 6) shows the biodiversity features in West Africa and figure 8 represents general distribution of ecosystem units and plant species richness in Africa.

Biodiversity opportunity								Threat	Response
		Mammals		Birds		Plants		% of land	% of land
Country	Area km²	Endemic	Total	Endemic	Total	Endemic	Total	transformed	protected
Benin	11 2620	0	188	0	307	0	2500	9	6
Burkina Faso	274 000	0	147	0	335	-	1100	48	12
Cape Verde	4 030	0	5	4	38	86	774	-	-
Gambia	11 300	0	117	0	280	not known	974	42	0
Ghana	238 540	1	222	0	529	43	3725	17	5
Guinea	245 860	1	190	0	409	88	3000	14	0
Guinea-Bissau	36 120	0	108	0	234	12	1000	7	-
Côte d´Ivoire	322 460	0	230	2	535	62	3660	25	6

Liberia	111 370	0	193	1	372	103	2200	30	1
Mali	1 240 19(	0	137	0	397	11	1741	15	4
Mauritania	1 025 52(	1	61	0	273	not know	1100	3	0
Niger	1 267 00(	0	131	0	299	not know	1460	2	8
Nigeria	923 770	4	274	2	681	205	4715	34	4
Senegal	196 720	0	192	0	384	26	2086	47	11
Sierra Leone	71 740	0	147	1	466	74	2090	38	2
Togo	56 790	0	196	0	391	not know	3085	7	8
All countries	**6 138 03(**	**7**		**10**		**710**		**16**	**4**

Table 6: Biodiversity opportunities in West Africa, Nigeria, Ghana and Côte d´Ivoire have the greatest number of mammals, birds and plant biodiversity opportunity (source: Biodiversity information taken from Groombridge and Jenkins (2002). Calculation of the proportion of transformed land was based on the reclassification by Hoekstra and others (2005) of the GLC3 Global Land cover Classification (Mayaux et al. 2004)).

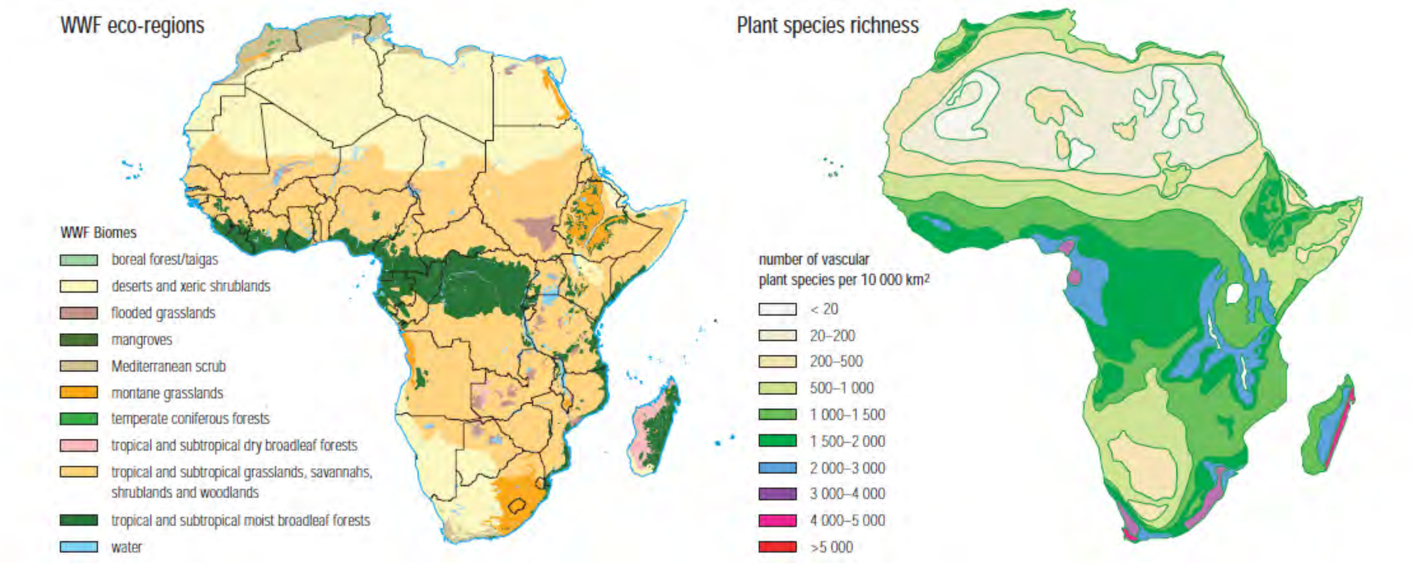

Figure 8: The distribution of biodiversity following the eco-regions, which are large units of land or water that contain a distinct assemblage of species, habitats and processes. The plant species richness are determined per 10 000 km^2 (UNEP/DEWA/GRID 2006).

The total forest cover in West Africa is about 115 Million ha, representing 12 per cent of the total land area (FAO 2005). It varies considerably from country to country as shown in figure 9. The forest cover surface decreased from 1990 to 2005 almost in all countries except in Côte d´Ivoire. The country with more forest cover is Guinea-Bissau with 73 per cent forest cover (fig. 10). This country is a part of the Guinea forest of Western Africa which extends from the coastline of Guinea to the boarders of Cameroon and considered as a biodiversity hotspot (NORMAN et al. 2000) because of its importance from a biodiversity perspective.

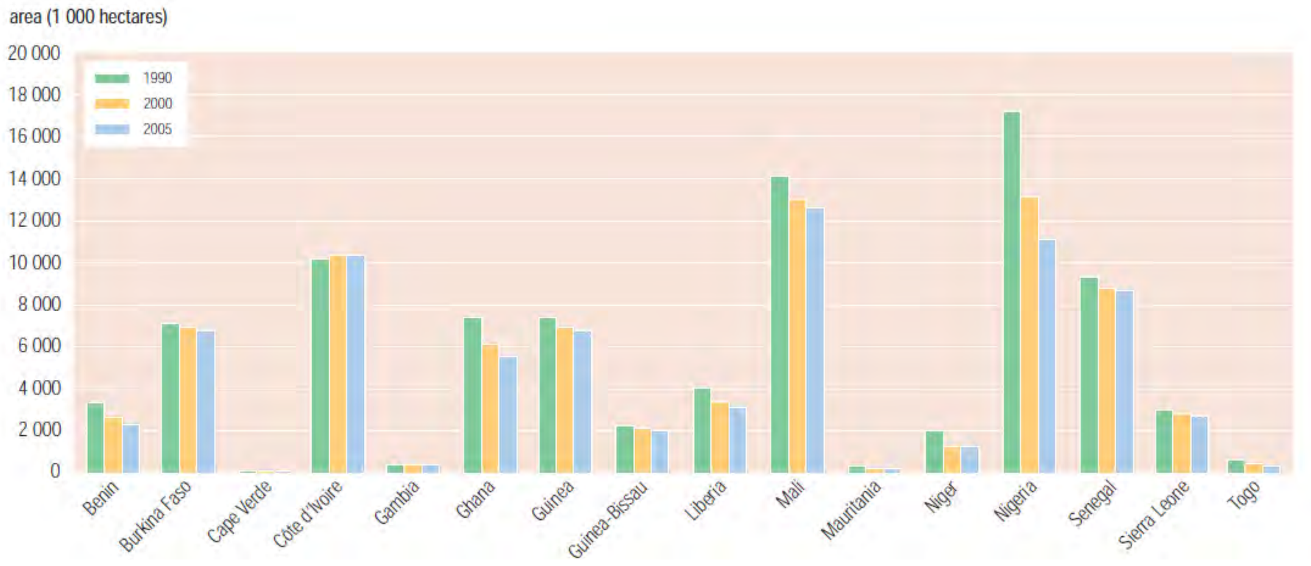

Figure 9: Variation of forest covers in West Africa from 1990 to 2005 (source: UNEP 2006, data FAO 2005).

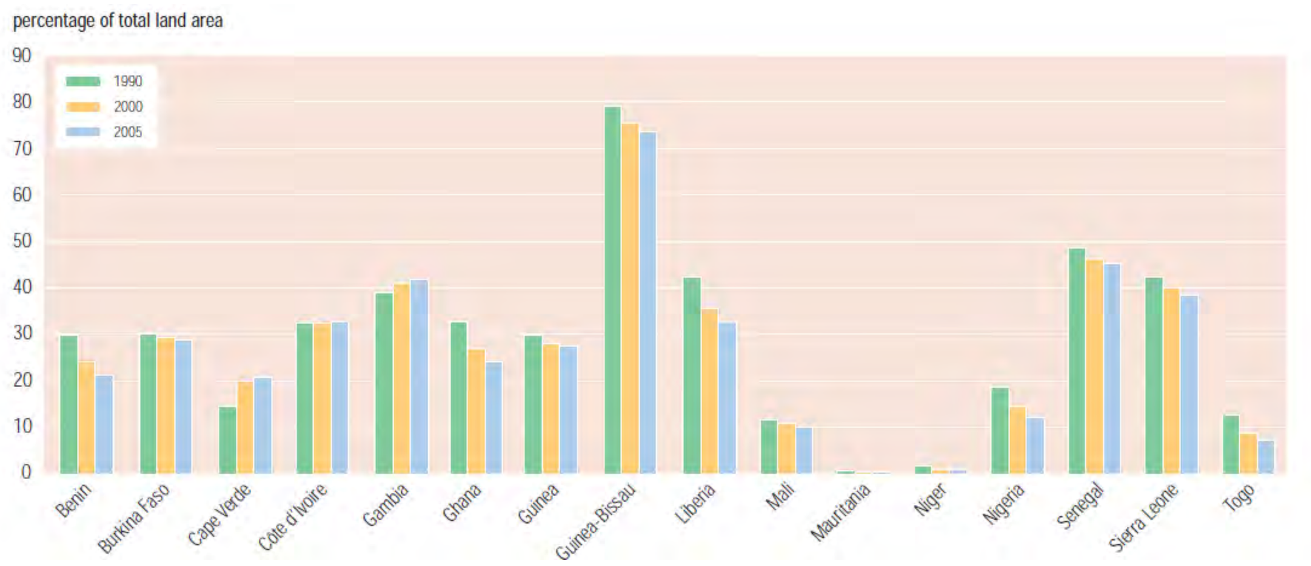

Figure 10: Forest areas in West African countries (UNEP 2006, data source FAO 2005).

Researches on biodiversity are applied over large geographical extents but in a given ecological region one or two issues may be important. Ecological diversity involves different parameters: climate, soil and its properties, as well as human beings who are jointly responsible for many changes in ecosystem. The environmental influences are observed in soil material on the slopes and valleys under the influence of erosion or denudation, in transport of soil material as well as in land use and in the bioturbation processes through termites that modify biomantle characteristics. The properties of soil and to an extent bioturbation influence the vegetation pattern and the distribution of several plant species (DOHERTY et al. 2000).

In West Africa land degradation and desertification are the major phenomena which involve loss of biodiversity. These phenomena are caused by a combination of indirect factors such as population growth and density with a strong dependence on natural resources, socio-economics and policy factors as well as direct factors such as land use patterns and practices (deforestation, overgrazing) and climate change related processes (recurrent droughts). The processes of land degradation and desertification affect grasslands, steppes, savannas and woodlands by fragmenting forests and altering their structure and composition, especially when they are followed by recurrent forest and bush fires. Fragmentation of forests and fire reduce surface water potentiality and their associated plants and strongly deplete animal populations. Forest degradation involves soil erosion and loss of fertility and notably reduces the number of endemic and vulnerable species through habitat degradation. The following graphic (fig. 11) shows the linkages and feedback loops among desertification, global change and biodiversity loss.

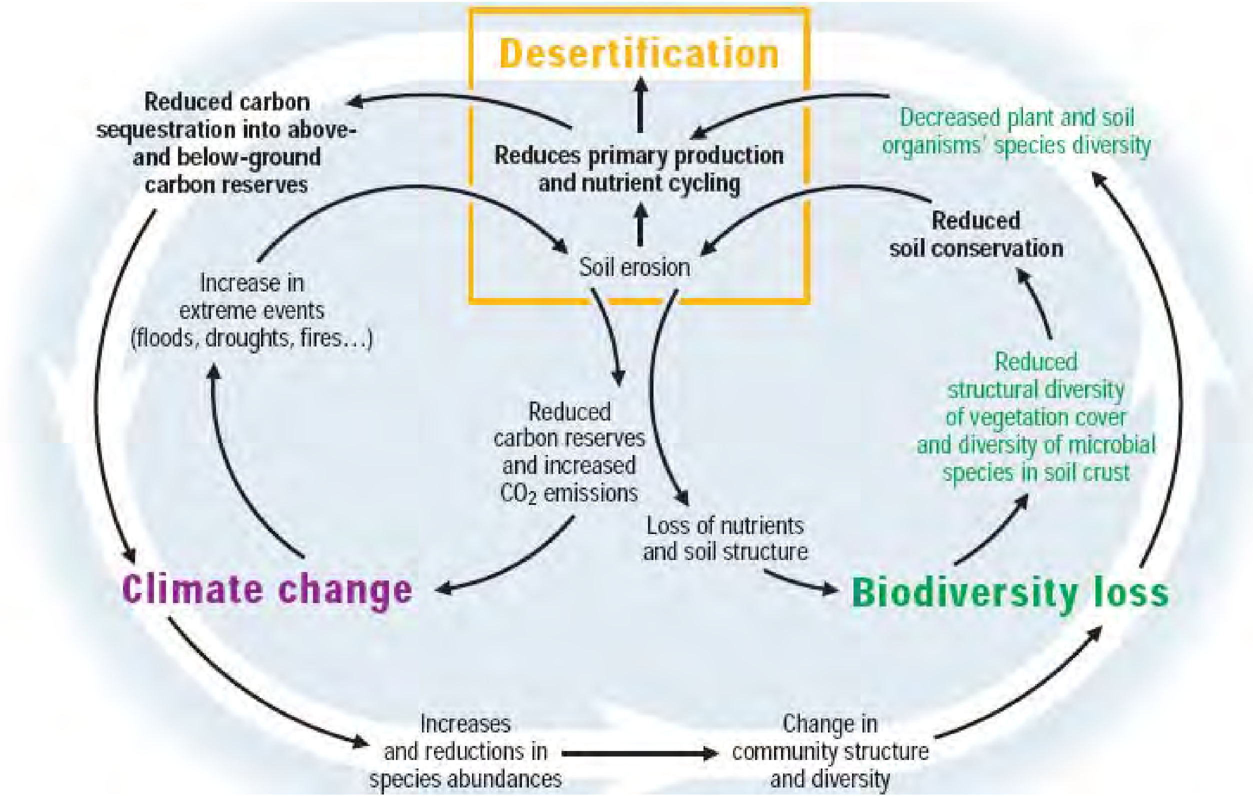

Figure 11: Relations desertification-climate change-biodiversity; green text represents major components of biodiversity involved in the linkages and bold text major services impacted by biodiversity losses (source Millenium Ecosystem Assessment 2006).

Land degradation is the main threat to the opportunities and challenges associated with biodiversity. Conscious of the fact that biodiversity is still the most important resource endowed sustaining both national economies and communities livelihoods, West African governments developed strategies, actions, plans and programmes destined to rehabilitate a socio-economic and ecological balance susceptible of contributing to food self-sufficiency and of permitting the start of a sustainable development process. These are materialised through the ratification in these countries of biodiversity related Multilateral Environmental Agreements (MEAs) to promote biodiversity protection such as the United Nations Convention on Biological Diversity (CBD 1992), the Ramsar Convention (in Iran, 1971) for the wetlands protection of international

importance, the United Nations Convention to Combat Desertification (UNCCD 1994) and the United Nations Framework Convention on Climate Change (UNFCCC 1994). These global MEAs are completed by sub-regional and regional agreements such as the African Convention on the Conservation of Nature and Natural Resources (ACCNNR 2003) and through organisms like the *Comité Inter-état de Lutte contre la Sécheresse au Sahel* (CILSS).
However, biological diversity and its challenges have had high priority in BN and BF particularly since the big droughts of the 1970´s. In both countries, as well as in other West African countries, national monographs on biodiversity have been elaborated. They are the foundation for the development of national strategies and action plans concerning the conservation of biodiversity, the sustainable use of its constituent components and the promotion on fair and equitable sharing of benefits arising from the utilisation of genetic resources. The monographs aim at collecting and analysing ecological, biological, economic and social data which enables the elaboration of the framework for the development of national strategies and plan of actions concerning biological diversity (UNEP 1993). They were edited in February 1999 in BF and in November 2001 in BN through the project of national strategies and action plans for the conservation of biological diversity (Project BEN/97/G3). In addition, it must be mentioned that biodiversity researches have been taken into account in both countries earlier in multiple frameworks and disciplines through scientists and national organisms.

In BF, general studies on ecosystems have been conducted. Investigations about vegetation cover and distribution have been undertaken (GUINKO 1984) completed by research on plant formations according to phytogeographical zones (OUADBA 2003), biological diversity of woody plants (DIALLO et al. 1995), and agriculture and biological diversity (BALMA et al. 2003). Specific studies on dynamic and regeneration of woody plants such as *Combretaceae* (THIOMBIANO 1996, 2005; OUEDRAOGO 2006) have been done. Other studies on the biological reproduction of certain species such as *Anogeissus leiocarpus* (KAMBOU 1997) or *Detarium microcarpum* (BATIONO 2002) and on genetic diversity, reproduction of *Parkia biglobosa* (SINA 2006) have been surveyed. In the framework of biological diversity in BF the terrestrial and aquatic fauna have been studied particularly the diversity of wild fauna, mammals, birds and reptilians (OUEDRAOGO 1995) while TRAORE (1994) dealt with the aquatic fauna.
General studies into biodiversity and ecosystems in BN are less widespread except some phyto-geographical studies (ADJANOHOUN et al., 1989; WEZEL et al. 2000 and FAO/PNUD 1980). Indeed, the greatest number of publications about vegetation and biodiversity tools is concentred on the local level or on some specific themes of biodiversity.
While some authors are interested in the biological diversity and conservation of medicinal plants (ADJAKIDJE, 2000) or protected areas (AGBO 1994; OTCHOU 2000), others focus their research on ecological units and their evolution and strategies of management in defined zones (SOKPON 2002, SINSIN 1993, TENTE 2002). Investigations on terrestrial and aquatic fauna in BN are well developed (KASSA 2002, SINSIN 1999-2001, LALEYE 2000 and D´ALMEIDA 2000).Biodiversity research is plentiful and diversified but less integrated. For this reason this study integrates different patterns of the ecological biodiversity (soils characteristics and phyto-geography).In spite of many studies in the different biodiversity levels and patterns in West Africa, biodiversity research is still an important challenge for decision makers, scientist and particularly for the local population whose survival depends unavoidably on preservation of biodiversity services.

3. PHYSICO-GEOGRAPHICAL FEATURES OF THE STUDY AREAS

The study areas extend over two West African countries: Burkina Faso (BF) and Benin (BN). The first study area lies in the South East region of BF (*Région de l´Est*) southern of the city Fada Ngourma while the second is situated in North West BN, in the Pendjari Biosphere Reserve and its surrounding hunting zone (*zone cynergétique* fig. 12). The Biodiversities observatories (BO) of Natiabouani, one of the two study sites in South East BF, is a protected area at the borders of *forêt classée et réserve partielle de faune de Pama* (partial reserve of Pama) while the BO of Kikideni is an agricultural and pastoral land used site. In northern BN, study sites are chosen in the park as well as in the hunting zone. Both sites are entirely protected areas.
These study areas are nearly in the same geo ecological unit and share to some extent common geographical features.

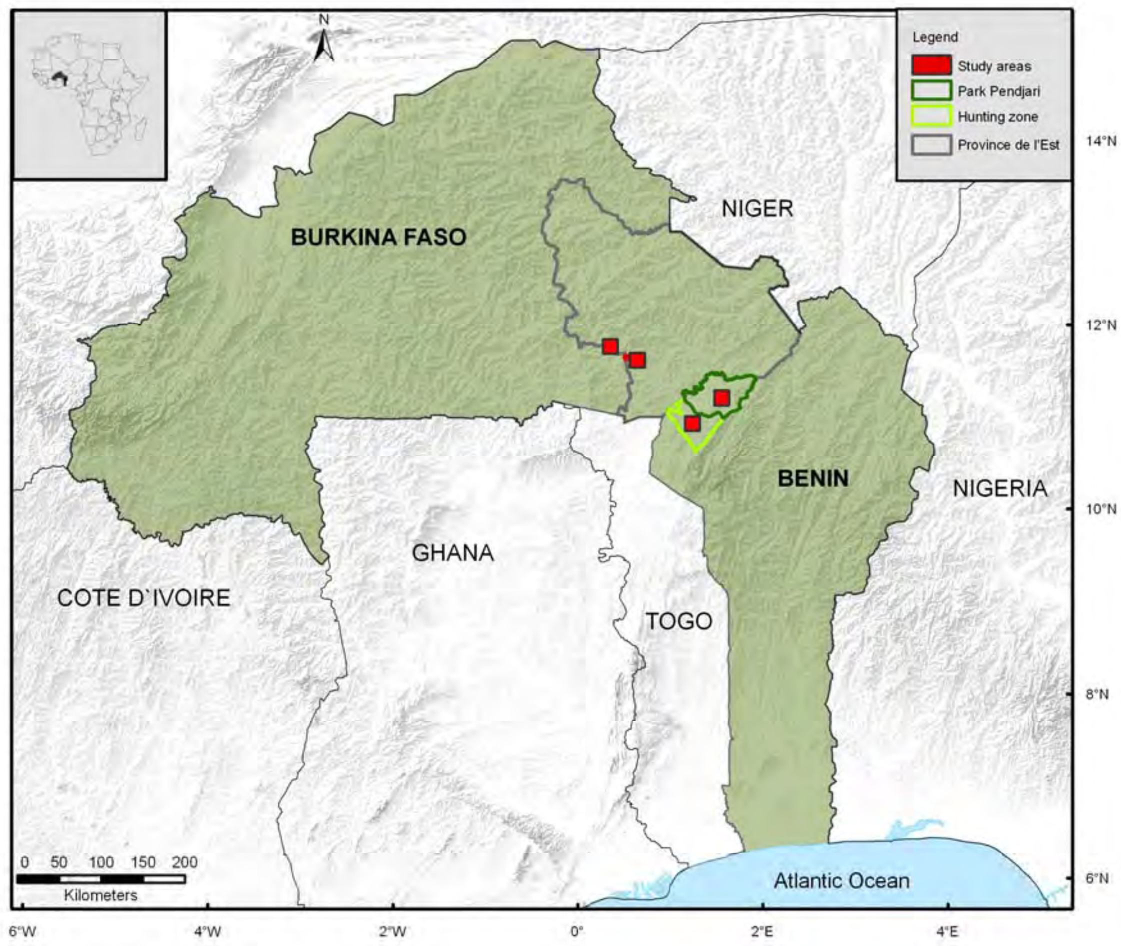

Figure 12: Study areas in the East province of Burkina Faso and in the PNP in North West Benin (map background: Shuttle Radar Topography Mission ((SRTM 2000) and Digital Chart of the World (DCW 2003)).

3.1. Transects in the Biodiversity Observatories (BO)

The BO represents a central study plot within the framework of BIOTA investigations. Indeed, data of different studies are collected at this scale (zoological, socio-economic and biophysical data). Measurements and analyses conducted in these plots facilitate certainly the gathering of data about the state of biodiversity and the interdisciplinary processing but the choice of the location of BO doesn’t necessarily take into account the given factors of geological and geomorphological conditions and processes which determine largely the ecological properties of the chosen plots. Therefore, climatic conditions and human activities in and around the plots have been considered in the choice of hectare plots.

BO in South East BF

The BO of Natiabouani and Kikideni in the South East BF are situated in the climatic north Sudan zone of West Africa characterised by annual rainfall between 600 and 1000 mm. The South East of BF is characterised by the presence of many total or partial protected areas as well as national parks such as *le Parc national du W* extending through the areas of BN, Niger and BF with 235000 ha, *la réserve totale de Faune d´Arly* (76000 ha), *la réserve total de Madjoari* (17000 ha) located in the Tapoa province, *la réserve totale de Singou* (192600 ha) and *la réserve partielle de Faune d´Arly* (90000 ha) in the Gourma province and *la réserve partielle de faune de Pama* (223700 ha) in the Kompienga province (*Ministére de l´environnement et du cadre de vie BF* 2006). The region has an important agricultural potential however limited by the numerous protected zones.
The BO of Kikideni in the near of the village Kikideni is situated within a landscape characterised by farming activities as well as pastureland. The farmers come principally from the surroundings villages. Small Fulbe villages can be found in the zone. Fulbe is an ethnic group which is devoted principally to cattle rearing. Situated around 30 km away from the BO of Kikideni, The BO of Natiabouani which has derived his name from the village Natiabouani is part of the *réserve partielle de faune de Pama* and is totally protected (fig.13). Wildlife presence particularly elephants could be observed through the uprooted of trees or through the superficial structure of soils characterised by traces of elephant pads.

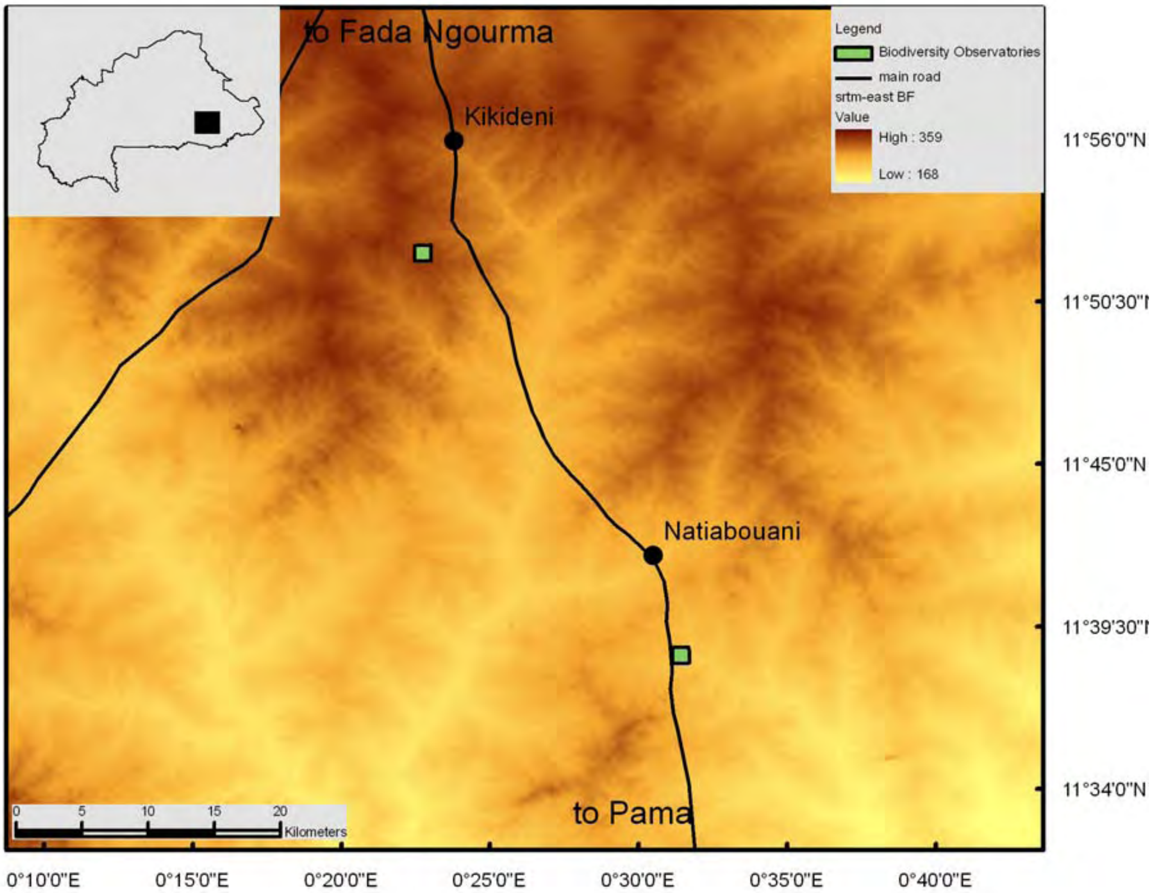

Figure: 13: Biodiversity Observatories Kikideni and Natiabouani in South East Burkina Faso (source: SRTM 2000 and DCW 2003).

BO in northern BN

The study plots in northern BN are located in the Pendjari Park and its surrounding hunting zone (*zone cynergétique*) and are under the influence of the south Sudan climatic zone characterised by an annual rainfall amount over 1000 mm (see 3.3). The Pendjari National Park (PNP) is one of the biggest parks in West Africa (275000 ha) and is famous for its wildlife including elephants, monkeys, lions, antelopes, birds etc. It is contiguous to a vast protected areas unit (Arly, park W and Singou) in BN, BF and Niger (fig. 14).

Two observatories (C2 and C3) are chosen and surveyed in the hunting zone which is a protected area except a small cultivated surfaces at the near of the village Batia. Thus C1 is not retained because of the fact that it has similarities with C3. In the Park 4 observatories (P1 to P4) are first identified during the second phase of BIOTA (2004-2007) and completed by other sites serving mainly botanical issues. In this study 5 observatories including a common plot studies have been chosen.

The BO in the park and those of the hunting zone provide ideal conditions for the study of soil properties and vegetation units/dynamic in a protected area as well as their comparison with a land use observatory. In addition, the BO in northern BN are characterised by geological and geomorphological processes (see 3.2) which are different of those prevailing in the BO of BF.

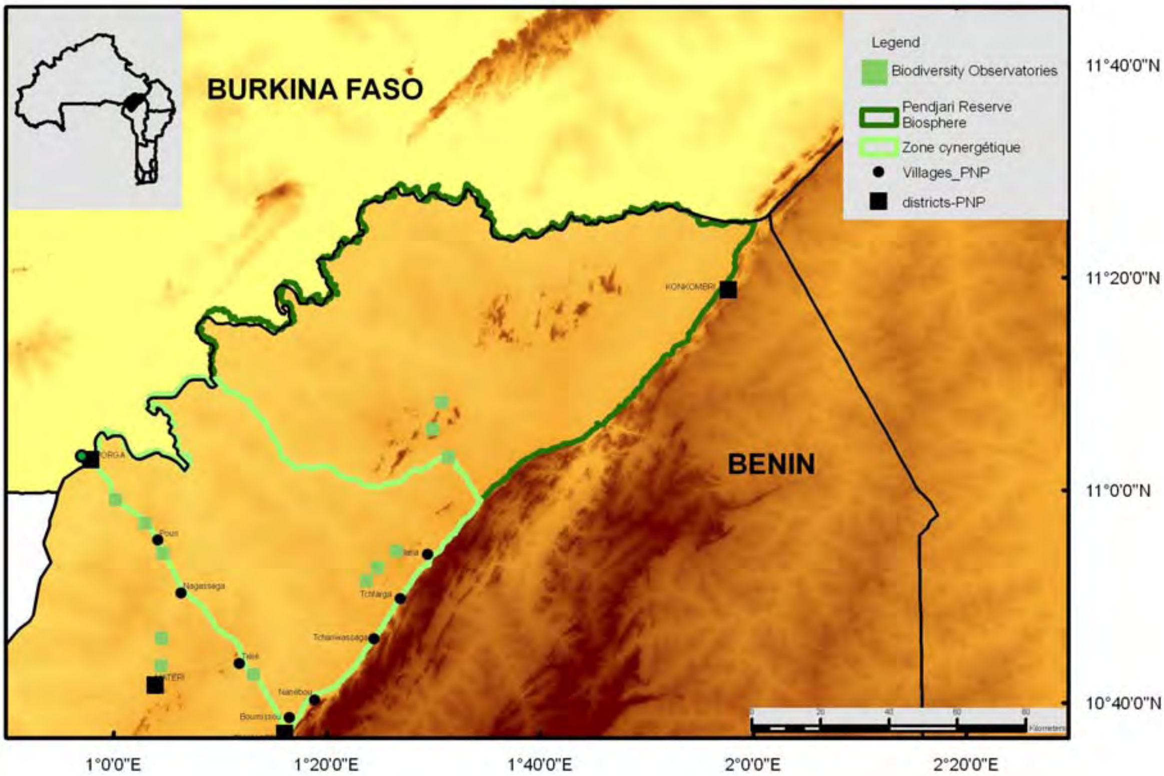

Figure 14: Biodiversity Observatories in the hunting zone and in the central part of The Pendjari National Park (source: SRTM 2000).

Pedomorphological transects in the BO

Transects represent a key function in the promotion of interdisciplinary researches through sharing of sites and resources. They are organized in study areas along a well-defined gradient including different soil and relief units as well as environment factors (human activities, fauna, vegetation cover) and thereby allow analysing how the latter factors influence soil characteristics and state of biodiversity in general and phytodiversity particularly.
The Kikideni and Natiabouani transects which are located generally in a gently inclined relief (<1 %) are characterised by small undulated interfluves, take into account the different units of the landscapes as valleys, plateaux and permanent or temporary rivers through identification of profiles in these different units. This approach allows us to follow lateral dynamic process in the soil layers according to the variation of environmental features. The identified transects in BF can adequately directly be compared for the analysis of soil characteristics and

phytodiversity in protected and unprotected areas because being located in the same agro-ecological zone and being subject to similar pedological processes.
In the PBR Transects are influenced by the more accentuated relief units with slopes (which can reach around 20 % or more) within the relief units of *zone des collines*. The relief is here characterised and influenced by the Pan African orogenesis (fig. 15). Nevertheless, the similar approach as in the BO in South East BF is adopted. All transects take into account the lateral transport of fine materials from the surroundings mounts through the study plots to the valleys or depressions if they exist. The profiles of these transects permit to assess the dynamic of erosion processes as well as the characteristics of soils and phytodiversity in South Sudan agro-ecological and moreover in protected sites against human activities.

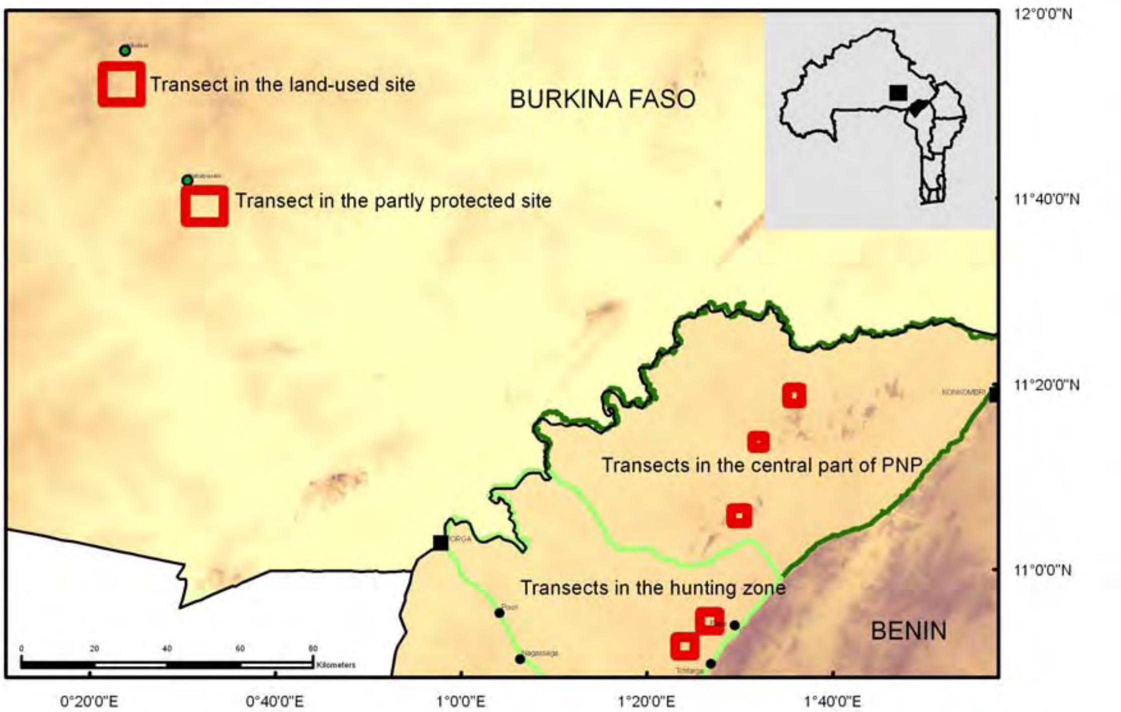

Figure 15: Surveyed transect in South East Burkina Faso, in the hunting zone and central part of the PNP in North West Benin (source: SRTM 2000 and DCW 2003).

3.2. Geological and geomorphological features

The geological framework in BF and BN is part of the West African craton which is bounded, according to WRIGHT (1985) by the Guinea Rise to the West, by Infracambrian to lower Palaeozoic sediments of the great Taoudeni Basin, obscured in the East by continental Tertiary to Quaternary deposits. The Eastern part of the craton is overlain by Infracambrian to lower Palaeozoic sediments of the Volta Basin, separated by rocks of Togo Belt from the mainly Pan African rocks of Togo-Benin-Nigeria swell, which are known as Benin-Nigeria shield (fig. 16).

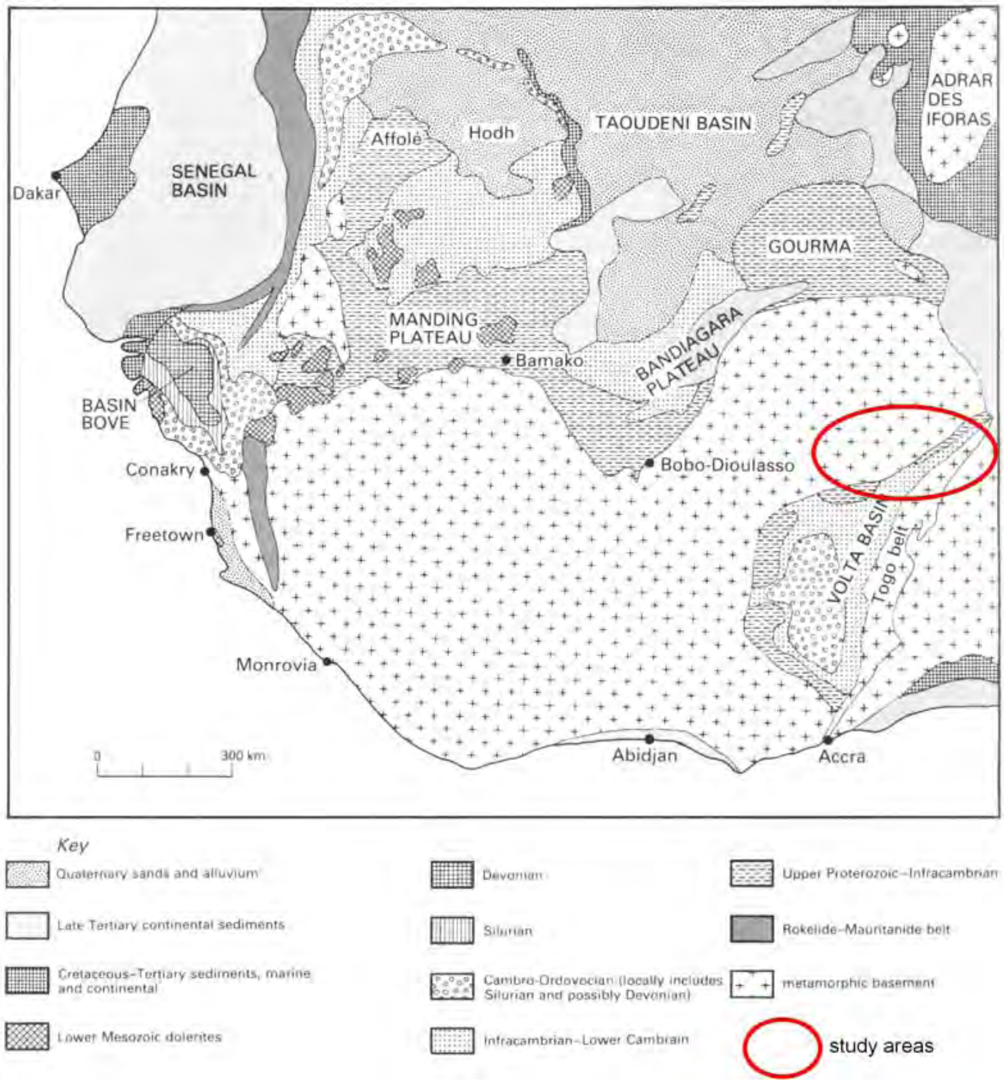

Figure 16: Generalised geological map in West Africa with the main geological units and periods (WRIGHT 1985).

The basement of BF is essentially formed by crystalline Precambrian formations (more than 80 %) of West-African craton dating from approximately 2600 Ma to 1600 Ma. These formations are covered in discordance by Precambrian A at the north and North West borders of the Taoudeni Basin and by the northern limit of Volta Basin (bassin voltaien see below) at the South East border. From the Early Proterozoic, these old formations identified as Precambrian D and C in BF is metamorphosed crystalline rocks belonging to the pre-Birimian and Birimian groups (HOTTIN et al. 1975). Birimian groups are considered as a super group which comprises groups of the lower and upper Birimian and Tarkwaian in a time period from 2300(±50) Ma to approximately 2100(±50) Ma.

The Eastern region of BF, from the Oudalan to the border South East (BF-BN) is formed by the Precambrian D formations (pre-Birimian) basically composed of immense cores with predominance of granite-migmatite formations

Within the study area (Fada Ngourma and its surroundings), different migmatite facies are present and shared in some units.

- Leptynites and leptynic migmatites outcrops are developed in Fada Ngourma, Diapaga and Tenkodogo. The predominant type correspond to the light coloured, massive, fine grained, lightly planar rocks, practically without biotite but often with many scattered grains of magnetite (iron oxide which common chemical name is ferrous-ferric oxide $FeO.Fe_2O_3$) and hornblende amphibole (iron dark coloured rocks). Quartz is abundant in these rocks (30 to 45 %). The migmatite associated facies are sodic alkaline *granitoides massifs*.

- Biotite migmatite and amphibole migmatite units whose distribution in the study area is comparable to the leptynites and leptynic migmatite. The general composition is granodioritic to monzonitic with an important proportion of potassium feldspar (up to 20 %) associated to quartz and oligoclase (40 %).

- *Migmatites et gnanites indifférenciés* are well represented formations in the pre-Birimian which correspond in the study area to sandy soils peneplain with outcropped heterogeneous migmatite (BOS. P. 1967). Because of this heterogeneity and interference of the different facies, only punctual observations on outcrop are possible. Nevertheless, a regional delimitation of amphibole migmatite facies in the East part of BF opposed to leucocratic and homogeneous facies in the western part of the country could be done (fig. 17).

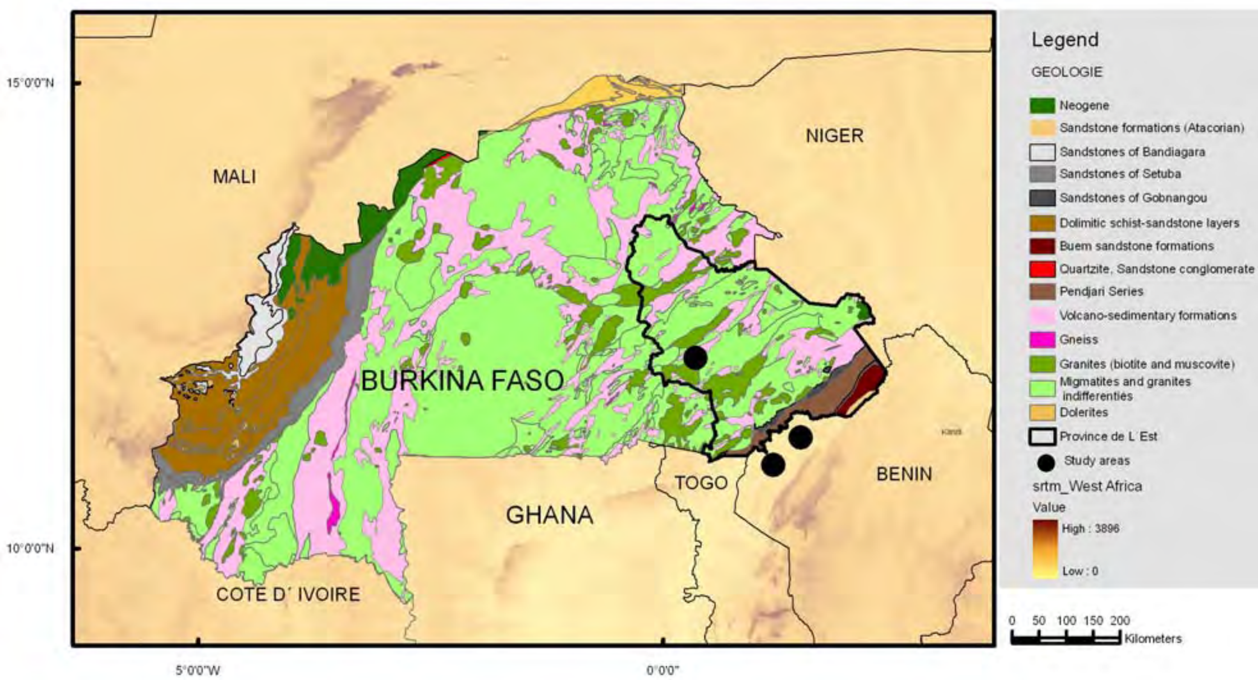

Figure 17: Geological units of BF and of the east Province (source: U. S. Geological Survey 2002, adapted to Burkina Faso, Anne, C. A. T.).

These formations were developed during the *Orogenèse Liberienne* (2700±100 WENMENGA, 2002) but often Birimian formations of greenstone belts (*sillons birimiennes* BOS, 1967) are noticed and individualized through fragmentation of the pre-Birimian basement and belong to the *Orogenèse Eburneenne* (2100±100).

Belts that can be found throughout the Eastern region for example the Fada Ngourma belt and the Birimian segments of the Tiébélé region are part of the pre-Cambrian C formations (WENMENGA et al. 2002). Birimian formations of pre-Cambrian C represent uneroded parts of the intracratonic belts sedimentary or volcanic deposits.
The Birimian formations are marked through important phases of syn-and tarditechtonic granitization. Biotite migmatite with muscovite is one of the important facie in the study area. A certain synchronism between the Eburnean granites emplaced in the belts and the granites from the pre-Birimian as mentioned above is observed (WENMENGA et al. 2002). Along the belts in the Fada Ngourma region, some detritic groups (*groupe sédimentaire terminal*) with coarse greywacke of conglomerate sandstone appear.

The pre-Cambrian A formations (1050±100) appear only in the northern, North West and eastern part of BF. In the Eastern region (Fada Ngourma-Diapaga-Pama), the dominant facies are represented by the fine grained quartzitic tabular sandstone of Gobnangou (*grés de Gobnangou*). In the South East border, sedimentary formations (*formation cambro-ordoviciennes*) which are emphasized through gullying discordance cover sandstones of the pre-Cambrian A with basal tillite layers. Cambro-ordovician sedimentary covers are located in the northern border of the Volta basin. The Volta Basin covers a total surface of around 145.700 km^2 and is extended to five countries (BN, BF, Ghana, Niger and Togo).

AFFATON (1987) identified 3 groups along the Basin: the Dapango Bombouaka Lower Voltain group in fundamental discordance on the eburnean substratum and correlated to the Cambro-ordovician formations, the middle group of Pendjari (*Groupe de l´Oti*) on the Bombouaka and eburnean basement and the upper group of Tamale (Ghana).From the end of the eburnean cycle (around 1700 Ma) BF is affected essentially by the phenomena of the Pan-African orogenesis (550±100 Ma), accompanied by metamorphism, mega-shearing and thrusting at the border regions of the south-East in the rim of the Volta Basin and the less affected folded zone in the North of Oudalan belonging to the aulacogen sedimentary cover of Gourma (HOTTIN et al. 1975). The Pan-African orogenesis affects the Late Proterozoic sandstone in the South East with presence of different facies: folded and metamorphic units of the Atakora and folded Units of the Buem. These units represent the major geological features in the study areas in the National Park Pendjari North West BN among others (fig. 18).

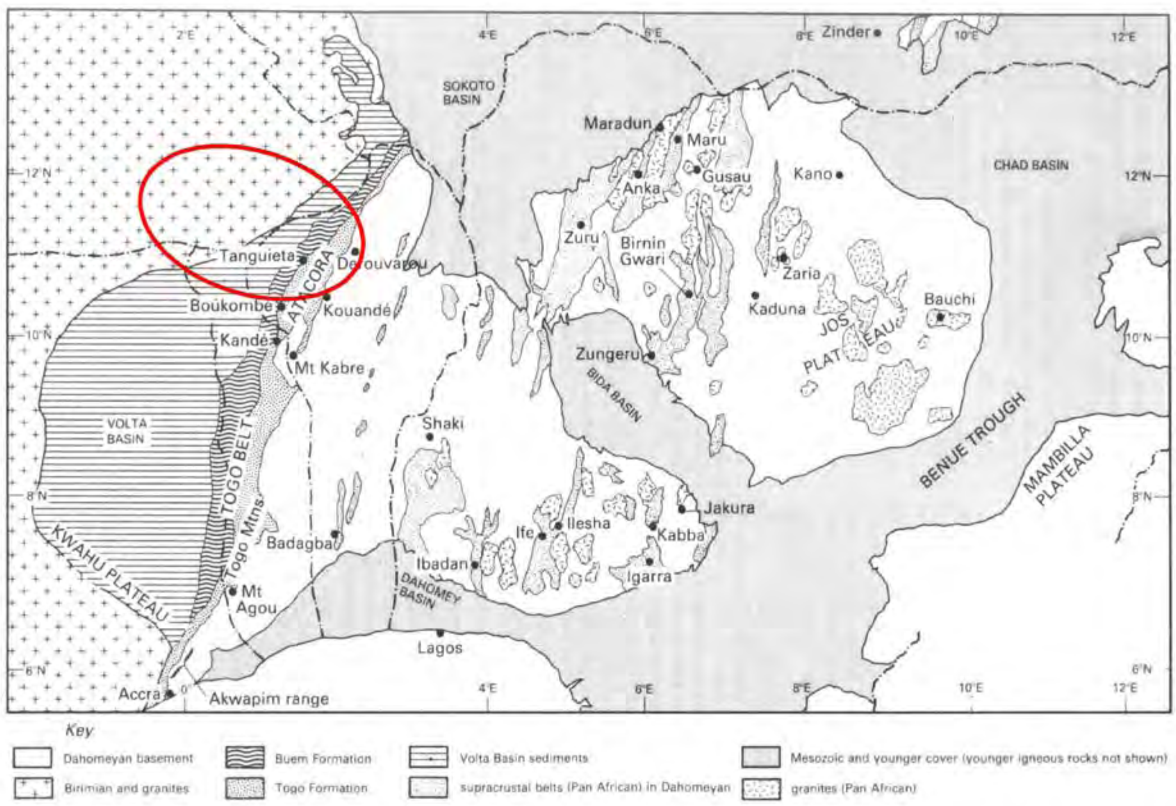

Figure 18: Generalised and simplified map of the Eastern domain of Pan African: deformed and metamorphosed units (red study areas), adapted from WHRIGHT 1985.

Because of the spatial cover of geological evolution in West Africa many studies in the north BN and its surroundings (north Togo AICARD 1959, Togo, Benin AFFATON 1987, 1990, South East BF, BOS 1967) have been undertaken.
According to FAURE (1977a), the North West region of BN can be divided in two principal geological and structural units:

- *Les formations sédimentaires de l´Ordovicien* (Ordovician sedimentary formations) which are represented by facies of argillaceous schist with sub-horizontal slopes. These units are peneplains from the Voltain basin and are situated in the North West and western part of the study area in BN.

- *Les formations métamorphiques du Précambrien* (pre-Cambrian metamorphic formations) which are divided into three levels according to AICARD et al. (1952).

    - *Les formations du Buem* extend along a long panel oriented SW-NE and cover South East of BF, and the North West of BN particularly around the district of Batia within the hunting zone of Pendjari. These formations identified by AFFATON as *l´unité de la zone des collines*, present two different facies.

Mica schist and quartz schist with folded rocks and a visible schistosity. These facies are slightly metamorphosed and incorporate an argillaceous substratum. The contact to the Atacora chain is brutal underlined through a cleft.
The second facies is represented by the visible quartz sandstones (grained quartz jointed by silicon dioxide) and jaspers formations which are composed by an alignment of outcrops under the form of hills. These hills are parallel to the Atacora formations and little metamorphosed (FAURE 1977b). The quartz sandstones are brown coloured, compact and little metamorphosed rocks. AFFATON (1980) described in detail the Buem formations in the district of Batia (fig. 19), last village adjoining the Pendjari Park. They are composed of two sub parallel bands of small hills from quartz sandstones and silexites separated by a depression where outcrop of shales and siltstones sedimentary rocks can be found on the surface.

- *Les formations de l´Atacora* which are identified by AFFATON as *l´unité de l`Atacora et ses depressions* is 850 km long from the border of the park "W" in Niger to the Gulf of Guinea. It occupies an irregular 10-50 km wide strip bordered on the west by thrust contacts of the Buem formation, and on the east by thrust contacts with the Dahomeyan basement. It includes the Atakora range in BN, Togo Mountains and the Akwapim range in southern Ghana. According FAURE (1985) three different facies can be identified.
  The light stratified and fine grained quartzites which form the majority of the rugged chains of Atacora with muscovite layers were developed during the Birimian (AFFATON 1975).The mica schist with less compact material and rich in muscovite and mostly present in the plains and thalwegs of the Atacora massif. The granitized mica schist are localised in the north (BF border) and south of the massif and are contact metamorphic rocks with quartz and muscovite. The principal petrographic series of the Atacora and the Buem formations establish similarities between the two formations and leading to retain that the structural Buem unit is a partial and lateral equivalent of the unit of Atacora (AFFATON 1990).

- *Les formations dahomeyennes,* East of the Atacora chain, constitute the granite-gneissic basement which covers a big part of BN. This big panel of metamorphic rocks is heterogeneous but dominated by the presence of muscovite gneiss.

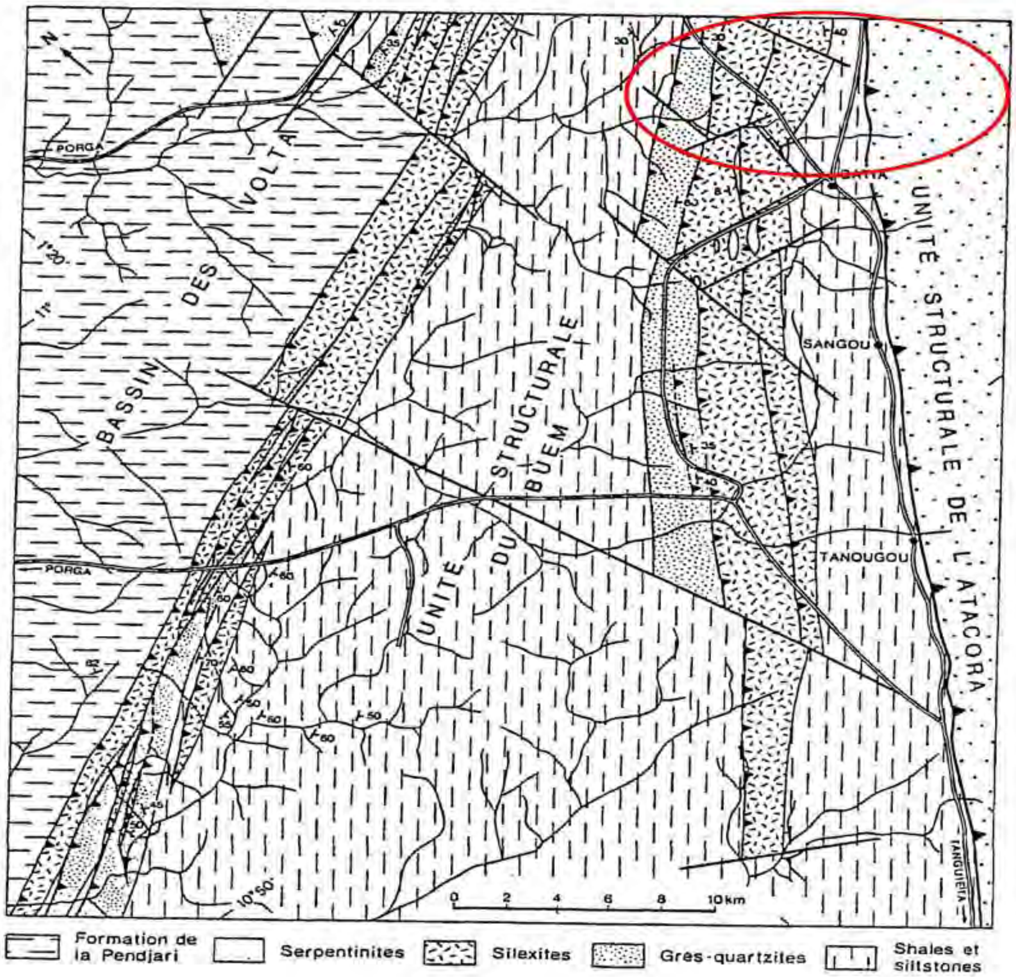

Figure 19: Geological map in the Tanguieta district and in the PNP (red: study areas in the hunting zone and in the central part of the Park) adapted after FAURE, 1977b.

From these basements, landforms in the study are developed mainly through the denudation process (weathering, transportation of the weathered material and deposition) and internal forces (crack, thrust etc).
According to AFFATON (1975) 5 landforms can be identified in South East of BF and North West of BN.

- *La pénéplaine du Gourma* is part of the *dorsale de Leo* (south of the West African craton) with landforms constituted by long *glacis* with low slopes (<1 %) often partly crowned by some residual ferruginous duricrusts (BOULET 1978). These landforms dominate the whole region of BF but a certain modification in the morphology towards the south up to the line Diapaga-Fada Ngourma-Koupela-Pô is visible. Interfluve are undulated and become shorter (transect of Kikideni and Natiabouani see chapter 5), the slopes are more accentuated. In fact, some granite Inselbergs in the near of Pama (photo 7) break the monotony of the northern relief.

- At the northern border of Pendjari basin extend *les plateaux de bordure du basin de la Pendjari* which are not located directly in the study areas. These plateaus are lightly inclined towards the basin with external oriented scarps. The plateau of Gobnangou is one of these geomorphological units.

- *La plaine de Pendjari* an immense zone of 180 m altitude where the Pendjari river flows from the north east to the south west.

- *La zone des collines* limits the plain of Pendjari with a confined band of ridges called *collines du Buem.* Near these Buem units, the plain of Tanguieta is identified scattered by many small hills (photo 8) constitute the geomorphological unit *la zone des collines de Korontières-Manta*.

- The last unit is represented by *la chaine de L´Atakora et ses depressions,* a continuation of the *Monts Togo* and of the Akwapim range in Ghana. It involves large plateaus oriented NNE-SSW and limited by abrupt slopes at the sides. The Atakora chains present 2 bands of mountains range separated by the *Toucountouna* depression where the upper Pendjari River flows in a longitudinal direction.

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Photo 7: View of the Pama hills from the Pama reserve (Mbayngon, E: 2005).

Photo 8: Piste Tanguieta-Batia: scattered hills emerge at the horizon (Anne, Cheikh.A.T. 2006).

3.3. Climate

The climatic conditions of BF belongs to the wet and dry tropical climates which are characterised by the alternation of a dry season between November and April and a wet season between May and October with violent storms in August as well as all the year round high temperatures. Precipitation, which is one of the important factors for the characterisation of the climate, shows temporal and spatial variability. In fact, rainfall amount decreases from the South West (1300 mm/year) to the north (300 mm/year) and is concentrated in the rainy season (6 months in the South and 3 in the North of BF). These rainfalls are characterised by a high intensity in a very short period (more than 60 mm/hour) and can be accompanied by stark winds. The average monthly temperatures are very high (35° Celsius) at the local level and around 29 °C in the Fada Ngourma Station in the study areas. But extreme temperatures

dominate in the northern part of the country where 46°C were measured in 1980 at the station of Markoye. The annual and daily thermal amplitude varies very little globally.
Different climatic zones are identified following a subdivision based on the position of the isohyets related to the sites receiving equal amounts of rainfall. Thereby, the classification involving the rainfall amount and the ecological limit of the vegetation units is mostly used in BF. It subdivides the country in three zones (fig. 20):

- South Sudanian climate zone or Sudanian zone which is delimited to the north by the isohyet
  900 mm extends in the South and South East. This ecological zone is the most humid one with a rainy season that takes about 6 months. Precipitation amount can reach an average of 1300 mm/year and more at times (Gaoua: 1585 mm in 1968). The annual or daily thermal amplitudes are low as well as the potential evapotranspiration.

- North Sudanian zone or Sudano-Sahelian zone covers the central and Eastern regions between the isohyets 900 and 600 mm. This ecological zone which is characterised by a rainy season of 4 or 5 months is the most extensive area and covers more than half of the country.

- Sahelian zone in the north situated above the 600 mm isohyet is a dry region with low and variable precipitation amounts that can strongly decrease to less than 300 mm rainfall distributed in 2 months.

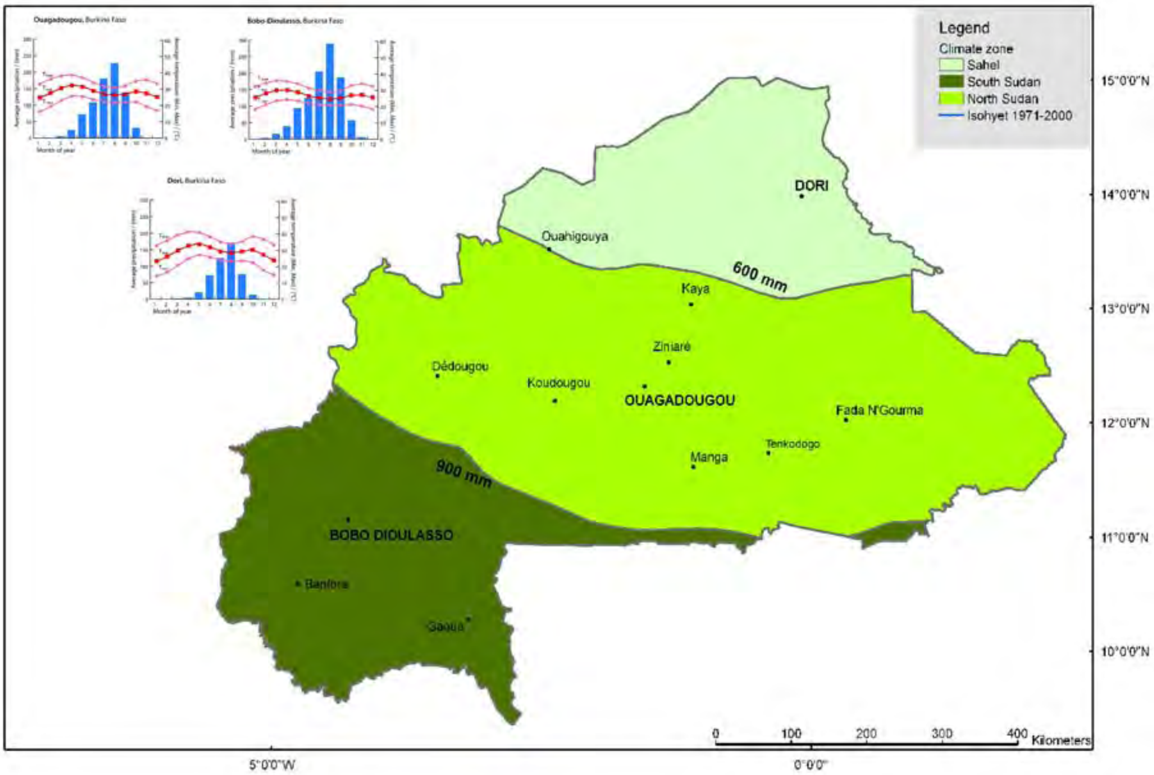


Figure 20: Climate and phytogeographical zones of BF with the climate diagrams of the main cities in each zone (source: *Direction de la Météorologie, Ouagadougou*, BIOTA-Atlas geo data 2010).

The variation of the climate in BF is characterised by a strong inter annual fluctuation of the rainfall and by change assessed through the migration of isohyets (100 to 150 km) in a southward direction (fig. 20). In the land-used site of Kikideni and the partly protected zone of Natiabouani which are located in the Fada Ngourma zone, a mean evaluation of rainfall, mean temperature, humidity and the wind velocity of the last 25 years (from 1981 to 2006) is undertaken (fig. 21). The results show like for the national tendency that the majority of rainfall occurs in the August month with a mean quantity of 187 mm. The mean total annual precipitation for 25 years is 705 mm/year. The percentage of humidity amounts to 48 % but can vary up to 80 % in August and September and the lowest values are measured from January to March. The variation of monthly mean temperature show that the maximum is measured im April with an amount of 30 to 35°C while the lowest temperatures occur mostly in January-December as well as in the rainiest August month. The analysis of the variation of the variation of precipitation amounts from 1981 to 2006 in the rainiest month doesn't show a tendency of decrease or diminution of the mean monthly amounts. Moreover, a variation from year to year can be observed. The variation of wind velocity is relative linear following the different months and the amounts range from 3 to 7 km/h. The densely populated zone as well as the presence of tree and shrub savanna landscapes may explain the relative low wind velocity.

Because of its position Benin has generally a more humid climate than BF and is under the influence of the West African monsoon, particularly in the South. The sub-humid climate in the South is situated between the tropical climate in the South and the arid steppe climatic conditions of the north regions of West Africa. The sub-humid climate of Benin is affected by both the cool and humid monsoon air mass, as well as the hot and dry Saharan air mass. The linear position of the Inter-Tropical Front (ITF) which defines the zone where air mass come together play an important role in the different climatic conditions prevailing from the coastal zone in the South to the north. In general, a decrease of rainfall from the South to the North part of the country can be observed. Three seasonal regimes are identified in Benin (FINK et al. 2008). A bi-modal rainfall distribution between the coast and 7° 30´ North with a first intensive rainy season in May and June and a second in October and November in Cotonou, a bi- or tri modal regime in central Benin (Parakou, Savé) and an uni-modal distribution in the North East region (Kandi). The study areas in the North West and particularly in Natitingou (see fig. 12) one of the synoptic stations of the North West region is under the influence of the Atakora.

Mountain and thus has more rainfall than in the north east part. The analysis of the climate parameters in the station, from 1981 to 2006 (fig. 22), shows a uni-modal regime and the majority of the mean monthly rainfall occurs in August and September with amounts of 200 and respectively 170 mm/year. The mean annual precipitation in the region is 900 mm and is mostly higher in the surrounding areas (Djougou: 1300 mm VOLLMERT et al. 2003). In the Pendjari National Park the annual mean rainfall from the period 1981-1990 is estimated to 1000 mm (Fink et al. 2008 in IMPETUS project 2008). The mean annual temperature in 25 years is estimated around 26°C and is lower than those measured in the Fada station in BF. The relative humidity is higher during the months with the maximum rainfall amounts (August and September with 80 %) while wind velocity has a relative low variation from January to December (4.5 to 7 km/h).

The dynamism of the climate influences the vegetation cover as well as the soil units and properties.

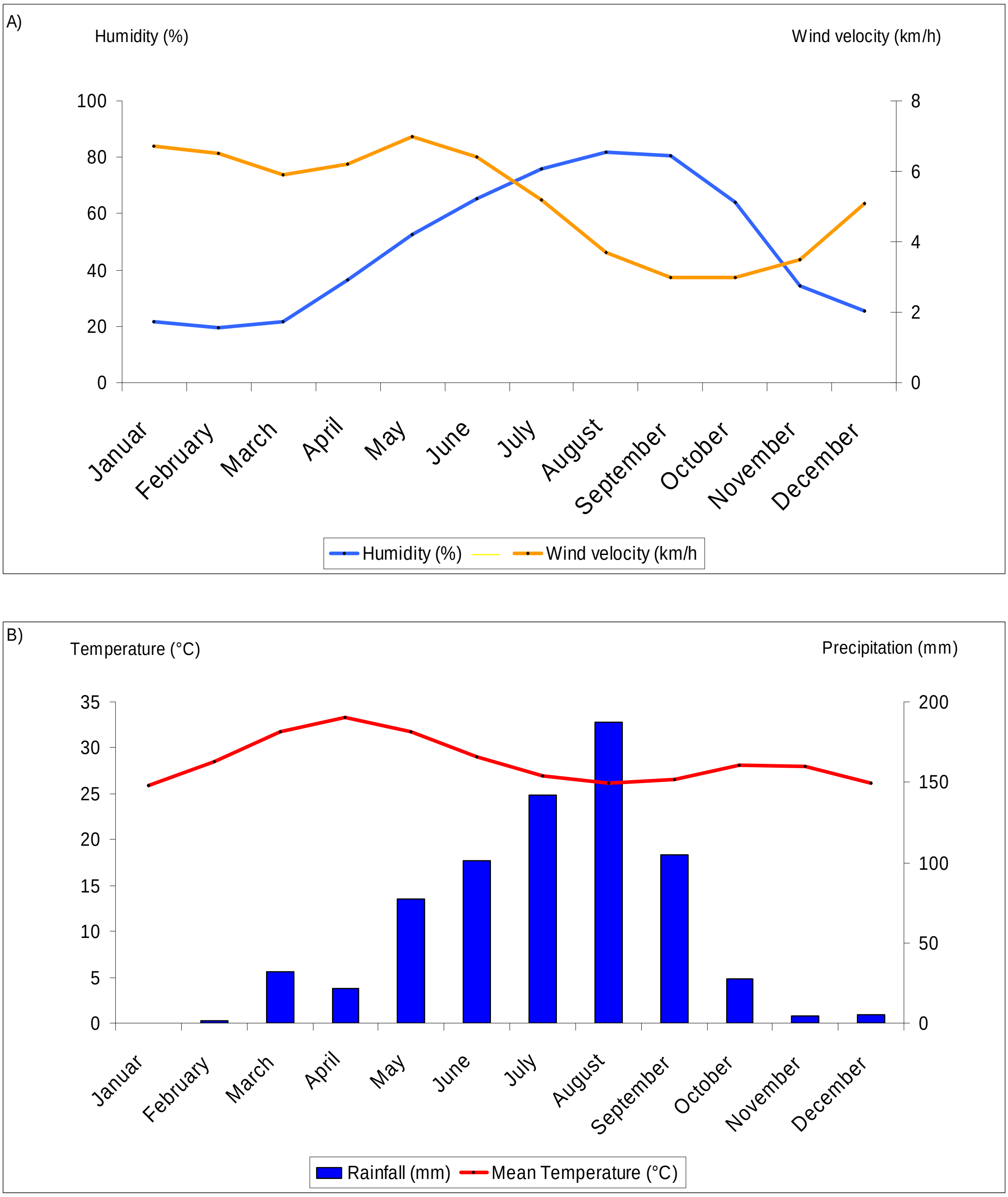


Figure 21: Long term means climatic variability in the station of Fada Ngourma in the South East of BF. The mean monthly precipitation, mean temperature, relative humidity and wind velocity are estimated from the climatic data of 25 years (1981-2006), source: Spanish climate portal: www.tutiempo.net.

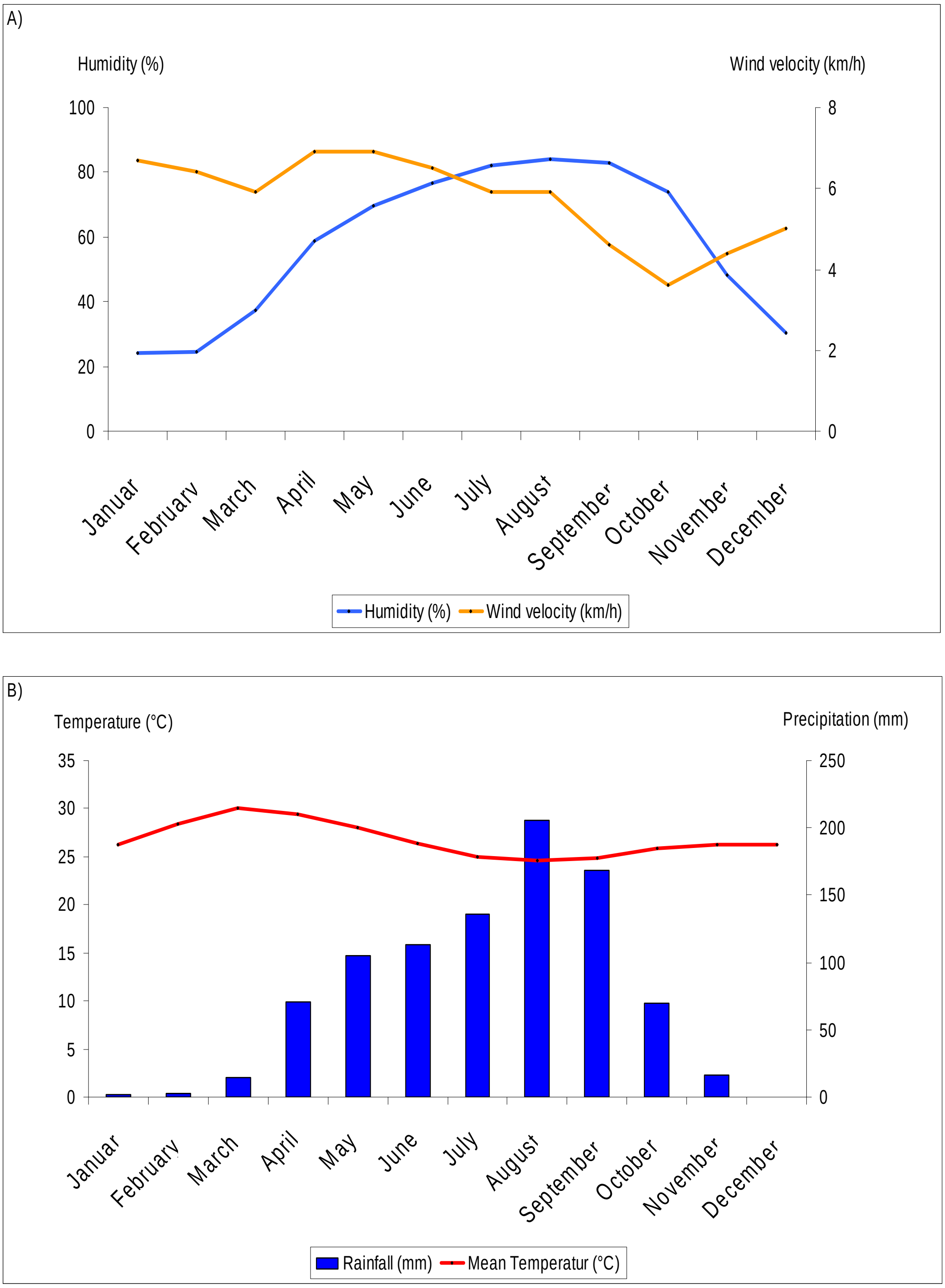


Figure 22: Long term means climatic variability in the station of Natitingou in the North West of BN. The mean monthly precipitation, mean temperature, relative humidity and wind velocity are estimated from the climatic data of 25 years (1981-2006), source: Spanish climate portal: www.tutiempo.net.

3.4. Hydrology

Located in the ecological Soudano-Sahel zone, BF presents a dense water system particularly in the South (Sudanian zone). The rivers are characterised by a tropical flow regime which reflects the precipitation fluctuations (see 3.3) with relative low or even null flow from December/January to July, followed by a dry up from January to June. Consequently, the rivers are temporary in majority except the Mouhoun River and those of the south west of BF. Rivers in BF are connected to 3 main basins: the Comoe Basin in the South West with the upper Comoe river and its affluents, the Niger Basin which is subdivided in two zones; Banafing or Ngorolako basin from the western plateau of Bobo Dioulasso and the real Niger Basin in the East and composed by many confluents (Bonsoaga, Tapoa, Faga, etc) and finally the Volta's Basin which connects the upper drainage of the three Volta rivers (white, black and red Volta) and the Pendjari river which flows in both countries of the study areas (Fig.23). The river system in BN is divided in several basins. Apart from Pendjari Basin, the Niger basin with Mékrou (10 500km^2), Kompa Gourou (1 980 km^2), Alibori (13 740 km^2) and Sota (13 600 km^2); the Oueme basin (*basin de l´Oueme)* and the Mono basin *(basin de la Mono)* in the South represent the other units of the hydrographic system of BN.

The Pendjari River which originates from the Atakora chain and is related to the in situ geological formations, flows in the direction SW-NE and at the BF border the direction of flow changes towards the East, and afterwards to the South West. Several river tributaries to the Pendjari River (Singou, Kompienga and Doudodo with a drainage basin of 21.600 km^2) and flow in the direction South East wards out of the hills of SE BF to join the Pendjari. The Pendjari River as well as the rivers in BF is temporary because of the drying out which takes place every two years. Besides these major rivers, scores of small rivers can be identified in the study areas which contribute to the denudation processes.

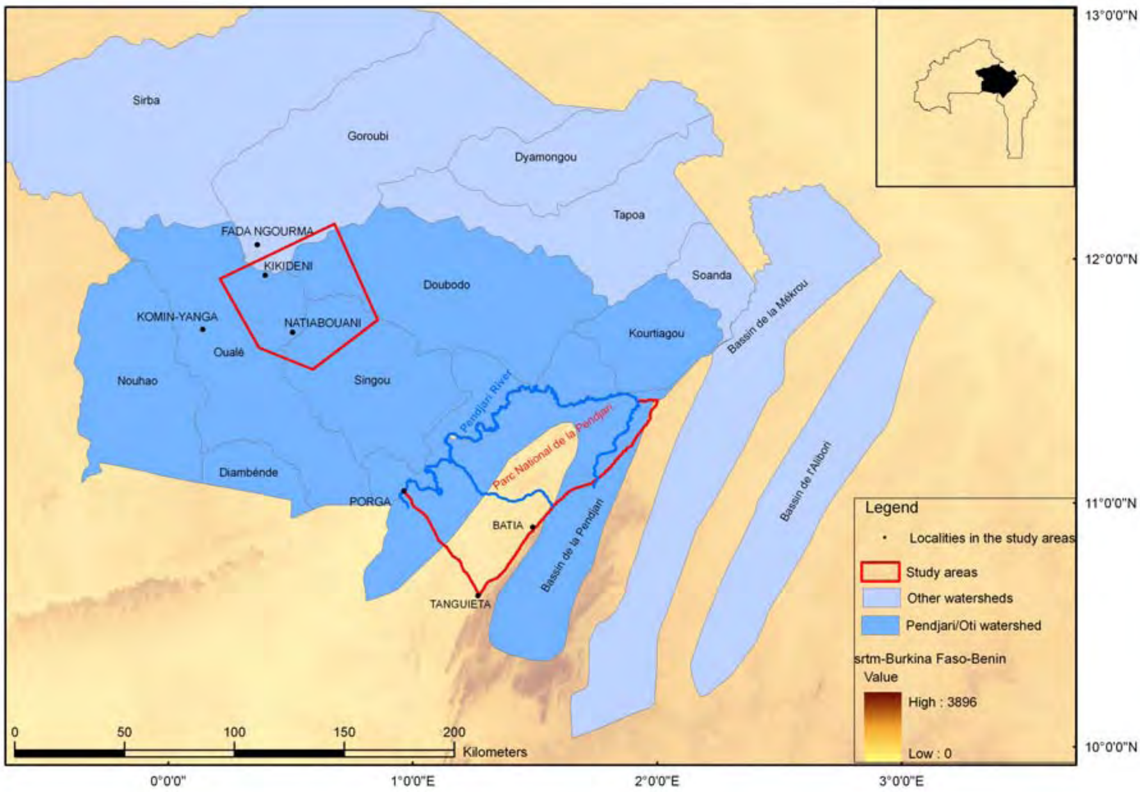


Figure 23: Hydrological Basin in the study areas South East of Burkina Faso and in the Pendjari National Park of Benin (source: Global Lakes and Wetlands Database GLWD adapted).

3.5. Soils

Soil as part of an ecosystem develops and changes under the influence of other ecological compartments (climate, vegetation, relief, human activities). On the national scale, soil resources are classified in major units with a spatial distribution in different regions. But it is important to mention the concurrence of different soil types within a small area as for example in a biodiversity observatory. Thus a strict delimitation of soil units is difficult to establish. However, different soil types are identified in BF (fig. 24):

- Planosols (*Sols ferrugineux tropicaux lessivés pro parte ou peu lessivés)* and Luvisols *(Sols ferrugineux lessivés)* are the most widespread soil types covering more than 45 % of the surface in BF. These soil units are the major components of the tropical ferruginous soils group and comprise the brown-red sub arid soils present mainly in the north and lying on the aeolian sands and the slightly or intensively leached ferruginous soils. The latter are well represented in the central and South Western and Eastern regions. The ferruginous soils are developed on the sandy-clayey and argillaceous-sandy materials characterised by an enrichment of iron manganese hydroxides that can be indurated or non-indurated, and appear in profiles as red or ochre horizon. Leaching processes are related to the amount of rainfall. Consequently, the more leached profiles of ferruginous profiles are found in the centre and in the South while less leached profiles are concentrated in the northern part of BF. These soil units, product of old weathered material, have low calcium, phosphor and potassium contents and are degraded due to the combined action of the traditional crop production system and the physical properties of the soil surface.

- Gleysols (*Sols hydromorphes à gley ou à accumulation de fer en carapace ou cuirasse*) occur in the zones of temporary or permanent excess of water mainly in valleys and in the great axes of drainage (Mouhoun, Nakambé, Pendjari etc). They are mostly associated with other soil types as ferruginous soils. These soils are favourable to the cultivation and growth of rice particularly in the South.

- Ferralsols (*Sols ferraltiques*) and particularly the ferralitic and half desiccated soils can be found in the relative humid South Eastern zone around Bobo Dioulasso and at the Côte d´Ivoire frontier. These soils are basically characterised by the deep and intensive weathering with a residual concentration of quartz and a thick profile.

Apart from these soil units, some marginal soil types as Fluvisols, Lithosols etc. are identified in BF and associated to the above described soil units.
Fluvisols or *sols minéraux bruts d´apport alluvial ou colluvial* are less developed soils which are deposited on outcrops of sandstones and ferruginous cuirasses. They have no agronomic value and mostly occur within and around the massive sandstone of Gobnangou in the South East and the sandstone cliffs of Banfora in the South West region. The soil units deposited on a gravel material, the Lithosols (*sols peu évolués sur matériau gravillonnaire*), are widespread in the centre and East of the country. They are the result of the degraded laterite crust and associated with the ferruginous soils. Their agronomic productivity is limited by the low nutrient content as well as the pedological conditions.
The soil units of BN are characterised by their variability according to their nature, fertility and geographic distribution. Soil types in BN are dominated by the Luvisols or *sols ferrugineux tropicaux lessivés* according to the FAO-UNESCO classification. They represent around 82 % of the country area and are located in the Zou, Borgou and the south of the Atakora regions.

In the study areas in the North West region of BN Luvisols are associated with the less developed soils (Fluvisols) which are strong influenced by erosion and cover the districts of Tanguieta, Boukoumbé and Cobly. They are developed on the granite, gneiss or schist basements. The Luvisols are characterised by their high porosity and high susceptibility to linear erosion as well as limited soil profile development. Gleysols can be found mostly in the temporary or permanent zones of excess water in soils as in the Oueme delta at the borders of the Pendjari and Niger rivers, in the Mono and Couffo valleys as well as in all inlands valleys. Apart from these soil units, Vertisols, Acrisols can be found particularly in the South part of the country.

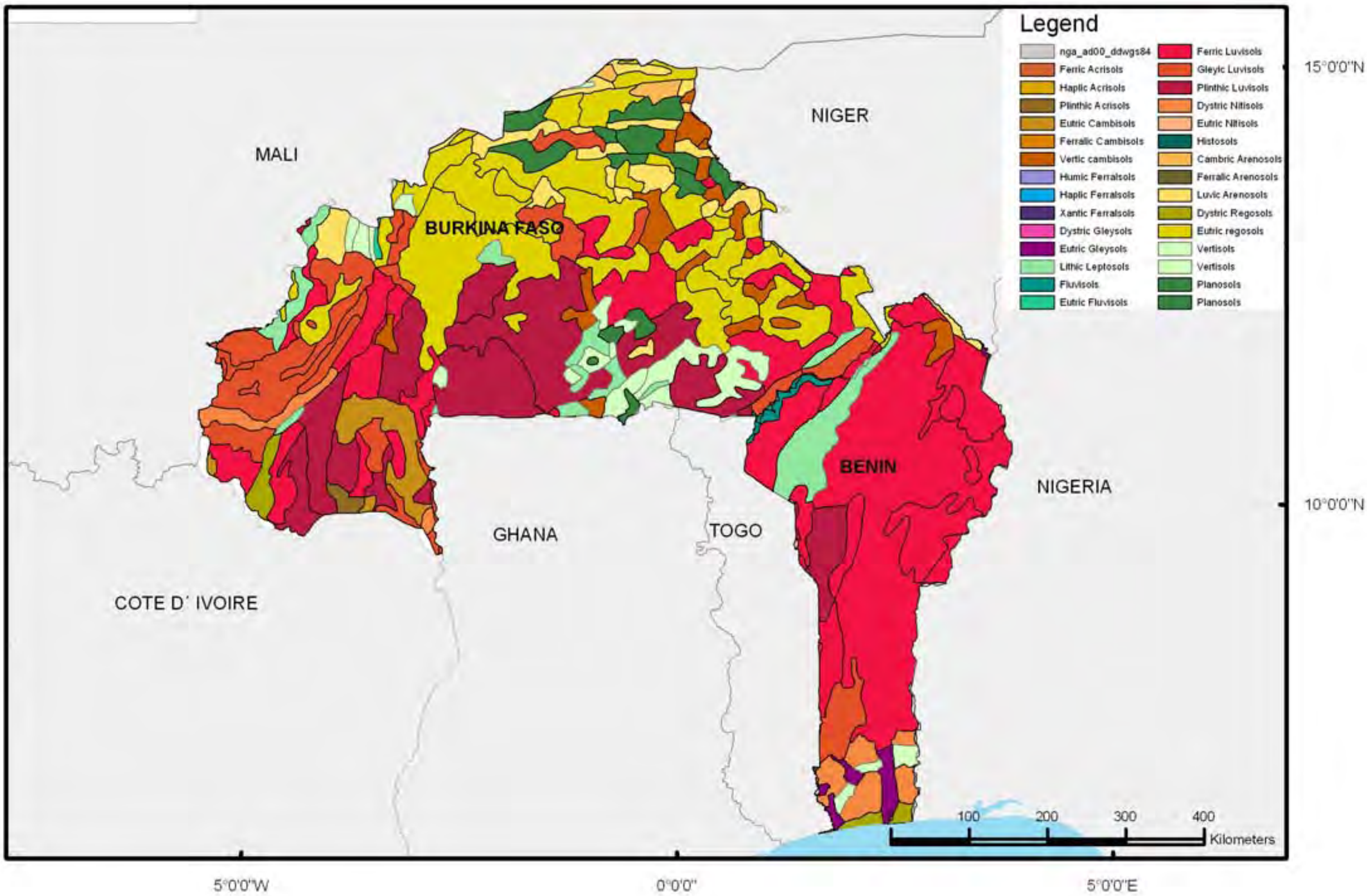


Figure 24: Soil units in BF and BN following the classification and repartition of the World Reference Base for soil resources (FAO 2006 adapted).

3.6. Vegetation units and dynamic

In the study areas vegetation units are closely integrated to the savanna ecosystems of West Africa which are part of the Zambesian-Sudanian domain (DE BIE et al. 1982; WHITE 1986). General characteristics of this domain are that the growth of woody plant species occurs throughout the year but with top growth during the wet season (from March-April to October-November). Vegetation units and dynamic are furthermore influenced by the drought period of at least five or six months (from November-December and March-April). Savannas have been under strong pressure since the severe drought period of the early 1970´s. It should be added that inter-annual fluctuating and recurrent deficit of annual precipitation combined with anthropogenic factors such as fire, shifting cultivation and increase of livestock affect the stability of vegetation communities. Ultimately, the savannas are characterised by the sensitivity of their ecosystem to any changes in the climatic conditions, land-used activities and or in the soil properties. The natural vegetation of BN and BF, and its classification and distribution in vegetation zones, has been object of many investigations over the years. Studies of MONOD (1956) about nomenclature of vegetable formations and recently GUINKO (1984) which divided BF following a phytogeographical approach in ecological zones (fig. 25) based mainly on the climatic zonation and vegetation communities are references in the literature. Many other classifications and mapping have been proposed from different scientists but the climatic factor as principal indicator is omnipresent (AUBREVILLE 1950, WHITE 1986, FONTES 1995). Savannas are present in the Sudan zone in almost all types from the woody savanna and the woodland to the grass savanna.

In and around the open and land used site of Kikideni which is located in the North Sudan-zone, shrub savannah (*savane arbustive*) is the dominant vegetation formation with a ligneous layer (height 3 to 6 meters) composed mainly by *Combretaceae* with species as *Combretum molle*, *Combretum nigricans*, *Combretum glutinosum*. *Cesalpinaceae* family is composed mainly by *Cassia sieberiana* while *Sapotacea* are represented mainly by the usefully shea tree *Vitelllaria paradoxa* (*karité*). Other main species identified in the north Sudanian ecological zone include *Parkia biglobosa*, *Terminalia avicennoides*, *Terminalia macroptera* etc (THIOMBIANO 1996). Apart from the shrub savanna formations, tree savanna could be found in bas-fonds (seasonally flooded valley). The grass cover is dominated by the presence of *Pennisetum pedicellatum* (photo 9); an annual *Gramineae* that covers the eco-zone between the isohyets 600-1250 mm (BARRAULT 1971). Its presence is due to the anthropogenic factors which create favourable conditions for the development of *Pennisetum* through activities as deforestation etc.

Within the protected site of Natiabouani tree savannas are the dominant formation with species characterised by heights between 6 and 15 meters (analysis of vegetation inventories see chapter 5-4). *Rubiaceae* are well developed with dominant species as *Crossopteryx febrifuga*, *Gardenia erubescens* and *Gardenia ternifolia*. *Combretaceae* which are well studied in the East region of BF (THIOMBIANO 2005, OUEDRAOGO 2006) represent an important part of the plant communities in the land-used observatories of Kikideni and Natiabouani of Kikideni mainly with *Terminalia avicennoides*, *Combretum collinum*. Equally, *Mimosaceae,* with *Acacia gourmaensis*, *Acacia hockii* as well as *Cesalpinaceae,* with *Piliostigma thonningii*, *Tamarindus indica L.* can be found. The grass cover is principally characterised by the presence of *Andropogon gayanus* which is a perennial plant with a height of 3 to 4 meters (photo 10).

The most favourable conditions for its prevalence are the region with annual precipitation between 750 and 1300 mm. A particularity of this *Gramineae* lies on the ever green leaves even throughout in the dry season. *Andropogon gayanus* tends to disappear in the sahelo-sudanian zone because of the drought and is present only in depressions (LELOUP et al.1989). The massive presence of *Andropogon* in Natiabouani may be in relation with the protected area status of the site as well as the presence of woodland (*forêt claire*) which is identified in the region mainly within the protected area and moreover in the *forêt classée et réserve partielle de faune de Pama*. The observations and measures are confirmed by many other studies in the same Observatories or in the same zone (THIOMBIANO 2005, OUEDRAOGO 2006, SCHMIDT and MBAYNGONE 2008).

The PNP is identified as part of the agro-ecological south Sudan zone (ADJAKIDJE 1984, ADJANOHOUN 1989). The study areas in the Park and in the hunting zone are characterised by the heterogeneity of the vegetation formations. Indeed, gallery forests are identified mainly along permanent or temporary rivers with tree layers which can reach 20 meters and mainly composed of *Diospyros mespiliformis*, *Khaya senegalensis*, etc (TENTE 2002). The other savanna formations are dominated by shrub savanna and tree savanna. Vegetation dynamic within the Atacora chain and its surroundings are analysed in many studies (WALA 2004). Nevertheless, following the relevés in the park and in the hunting zone, a relative division of the vegetation formation type could be identified. The hills in the park and in the hunting zones are covered by shrub or tree savannas with species such as *Burkea Africana, Detarium microcarpum*, *Entada Africana* (photo 11). In general, independent of relief units, tree savanna is the dominant vegetation formation in the park and in the hunting zone with species like *Vitellaria paradoxa, Dombeya quinqueseta, Crossopteryx febrifuga, Combretum glutinosum*. Vegetation formations in this area are mainly under the influence of fire (park management) and field expansion within and near the hunting zone. The grass cover is characterised by *Andropogon gayanus***,** and *Andropogon***.** *pseudapricus***.**

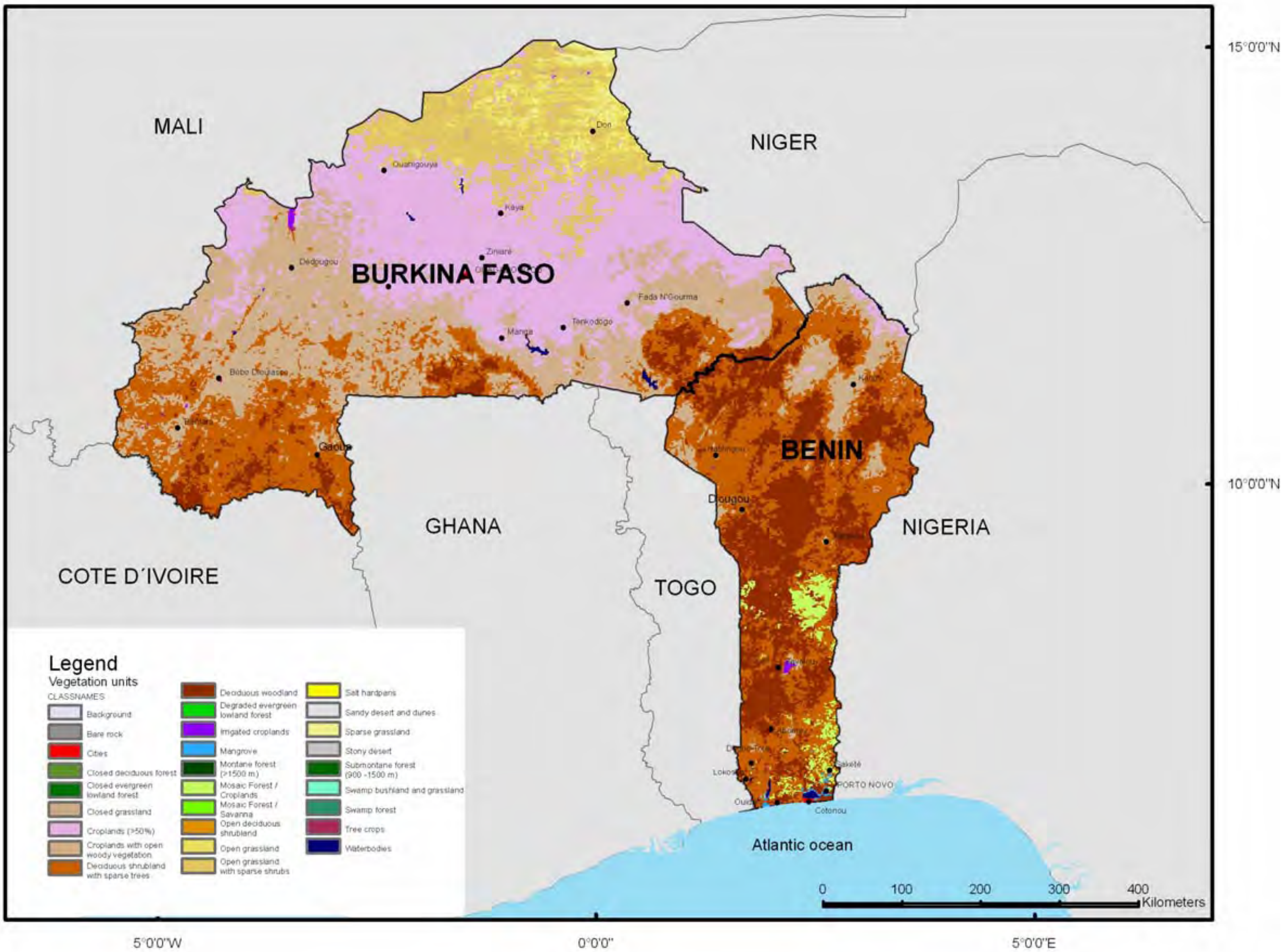


Figure 25: Land cover and vegetation communities in the study areas (source: global land covers 2000).

Photo 9: *Pennisetum pedicellatum* cover in the shrub savanna (BO of Kikideni).
Anne, C. A.T. 23.10.2004.
Photo 10: *Andropogon gayanus* in the tree savanna (BO of Natiabouani), fire influence.
Anne, C. A.T. 14.05.2005
Photo 11: Shrub savanna with *Detarium microcarpum* on the hill (hunting zone Pendjari)
Anne C. A.T. 21.06.2007.

3.7. Population dynamics and land use

BF is a landlocked country with an estimated population of 12.4 Million in a total area of 274,000 square kilometers, and is divided into 45 provinces. The province of Gourma where the transects of Natiabouani and Kikideni are located is one of the 5 provinces of the East Region which covers around 17 % of the national territory area. The ethnical group of *Gourmantché* is dominant and coexists with other groups like *Peuls* and *Mossi* (majority of the population of BF).This region has a relatively low population density compared to the other regions (22 persons per km^2 and 38 persons for the national density average) in spite of the favourable pluvial conditions. The superficies of parks (Arly and W), hunting and protected zones (*forêt classée et réserve partielle de faune de Pama*, *réserve présidentielle*) as well as the undulated relief combined with strong denudation processes may be factors which lead to the low density of the region. However, agriculture and livestock holdings are well developed and are done by 80 % of the local population. The livestock sector takes part in the alimentary and nutritional security of the population and contributes as means of transport, and as soil fertiliser. It brings 10 % of the GDP through export of 213,000 cattle, 304,000 sheep and 254,000 goats (statistics of the *Ministère des resources animales* 2005).In the northern part of the region agricultural activities are based on traditional bush field farming system with cash crop (peanut, sesame and market gardening), millet and sorghum. Because of the decrease of soil fertility, fallows tend to disappear. In the South, where the BO of Natiabouani and Kikideni are located, the farming system is identical to that of the north but with more available cultural spaces. The majority of the farmer's cultivate cotton despite unfavourable price policies and national cotton monopole. Inflow of migrants can be noticed in this zone with an exponential increase of the cultivated areas: 18,000 ha in 2001, 26,000 ha in 2002 and 33,000 ha in 2003 of cotton farms (*Ministère de l´agriculture, de l´hydraulique, et des resources Halieutiques*, 2004).

However, the Eastern region is relatively rich in stabile and well preserved ecosystems due to the parks and the protected areas. The Parks Arly and W, as biosphere reserves, have sub regional importance because lying at the borders of different countries Niger, BF and BN. These ecosystems zones are completed by the national park of Pendjari in northern BN.

With an estimated total population of 8.2 millions (world statistics 2008, http://www.statistiques-mondiales.com/BN.htm) for a total area of 112,622 square kilometers, BN presents a disparate distribution of the population from the South to the North. The South is densely populated (density 500-1000 inhabitants/km^2) because of the climatic conditions that are opportune for the agricultural activities. The north shows densities between 10 to 20 persons /km^2 (fig. 26). The importance of protected areas and hunting zones (zone cynergétique) may be an explanation for the low density in the region as well as the relief with the Atacora chain. The district of Tanguieta, one of the 77 districts in BN is part of the *department de l´Atacora* and is composed mainly of some ethnical groups (*Dendi*, *peuls*, *Bariba, Yorouba and a Gourmantche* minority in the village of Batia) which are peasants in majority. Agriculture is based on the shifting cultivation farming system. These forms of land use increase in relation with the development of cotton cultivation.

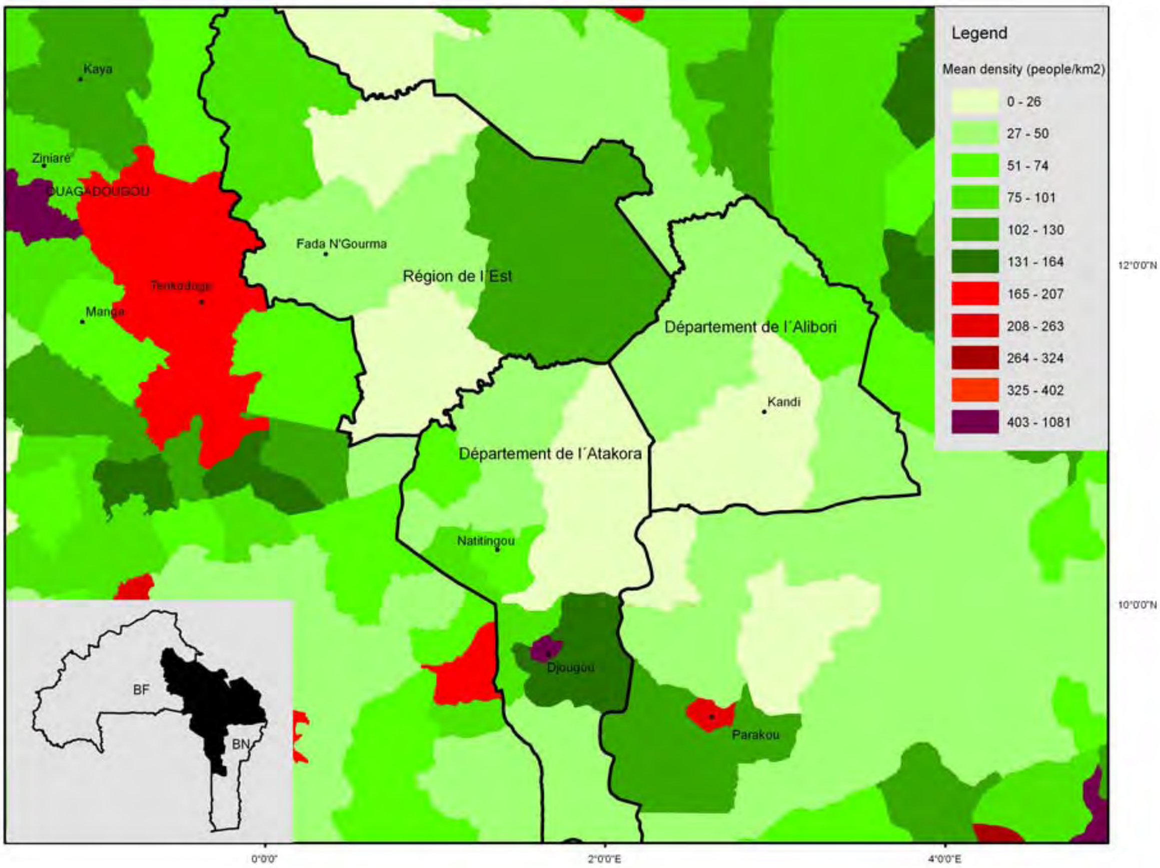


Figure 26: Population density in the study areas of South East BF and North West Benin.

4. METHODS

4.1 Soil sampling

Main focus of the field work which was conducted in South Eastern BF and northern BN in September-November 2004, April-June 2005, April-May 2006 and May-July 2007 consists of soil sampling within the Biodiversity Observatories. The BO which are place-based joint research sites, investigated with standardised methods and standardised spatial and temporal scales were chosen after a climatic gradient from the Sahel to the Sudan zone. However, the observatories were chosen and surveyed mainly from the perspective of investigations into specific diversity (vegetation communities for example) but do not take necessarily into consideration the given relief conditions. Moreover the surfaces of these BO (1 km^2) are relatively marginal and do not permit to apprehend the dynamic of soil profiles along the slopes. Nevertheless, the dynamic and structure of tree layer in the hectare plot of 50 m x 20 m and herb layer 10 m x 10 m are collected by different studies in the zone (THIOMBIANO 1996, OUEDRAOGO 2005).
Considering the restrictions in the choice of these study areas, pedomorphological transects were set up based on pedological maps (IGN feuille de PAMA NC-31-XIX for BF and *feuille Natitingou et Porga* for BN), existing satellite images within BIOTA and direct investigations on the field.
Soils have been surveyed along transects (toposéquences) with a total of 191 soil samples for 69 profiles. Soil profiles which have been collected from inspection pits are a key tool to understand processes that take place in soil development. The analysis of soil profiles is considered as means for the determination of soil types that occur in the study areas and are the basis of soil classification. Some profiles are particularly chosen on the termite mounds and in the direct proximity of these in order to investigate the role of termites through bioturbation in soil characteristics and in composition, distribution and regeneration of plant species.
The gained profiles have mostly a general depth of 80 cm. Fine-grained cover (hill wash) and gravel accumulation are deposited mostly in the first 80 cm except in the valleys where they can be thicker. Material which is either cemented or hardened is located under this layer and therefore a soil sample could hardly be taken. For this reason the standard depth of 80 cm is used in the analyses of soil profiles in this thesis although some variance are given along the pedomorphological transects
Each profile and its surroundings are described. In the field, texture could be assessed through finger probe and the soil colour determined with the “Munsell Soil Colour Charts”. The rooting depth and intensity is described and evaluated in each profile. Rooting system plays an important role of absorption and transport of water and nutrients from the soil to plants.

In order to apprehend the properties soil layers and ecological conditions along transects and their surroundings, several observations and descriptions in the topsoil and surface were done. But previously transects were subdivided in sections of 50 to 100 meters long according to the feature of the landscape to simplify the description of environmental conditions. These observations refer to the texture, structure of soil and presence or not of rock particles, the occurrence and distribution of lateritic and ferruginous crusts and or pisolites on the surface of sections of the transects. (Annex I). Moreover, the inclination of slopes along these sections is

measured with an inclinometer. Dominant plant species are identified and termite mounds specified.
The relicts and particles of rocks and bedrocks were collected on the surface as well as in the profiles and identified in order to determine their origin, their weathering grad and their influence in the local landscape. At least, working hypotheses were formulated at each profile.

4.2 Laboratory processing Laboratory processing

Soil samples are taken from layers or respectively horizons that differ in colour and texture. In order to characterise soil layers, physical and chemical analyses have been carried out in the *laboratoire des sols de la faculté des sciences agronomiques de l´université de Cotonou.*
Soil physical measurements are numerous, depending on the objective of the study. These measurements generally include soil water content, infiltration and hydraulic conductivity, evapotranspiration, heat, temperature, reflectivity, porosity, particle size etc. (KLUTE 1986). However, only a few physical measurements are normally conducted in soil-plants analysis laboratories. In this study, particle size and its distribution in the profiles are studied. For particle size analysis, soil fractions are passed by a 2 mm sieve and the percentage of sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (<0.002 mm) is estimated. This proceeding separates the particles in 5 fractions (fine sand, coarse sand, fine silt, coarse silt and clay) is known as *granulométrie à 5 fractions*. Particle size is an important physical parameter in soil classification and has implication and influence on almost all processes that occur in soils in addition to water availability, ion exchange capacity and on nutrient availability for plants.

Soil pH measurements are made on extracts from soil suspension, which vary from saturated soil pastes to soil suspensions at a ratio of 1:5 soils: dilution medium. The dilution consists of water or diluted solutions of $CaCl_2$ or KCL.
PH water (pH H_2O) is measured in aqueous solution and represents an important parameter in the study of relationship soil-plant and for understanding processes in soil like lixiviation that is responsible for acidification. Measurement of pH in KCl solution is preferred because the concentrations of the test solutions are more representative of the salt concentrations in natural soil solutions, and the values obtained are fewer dependants on the dilution ratio (LANDON et al. 1991). PH (KCl) is considered as the real pH of soils (GOBAT et al., 1998) and identified as potential acidity. This pH takes physical and chemical properties of solid matters of soils into long term consideration.

Organic matter represents the remains of roots, plant material, and soil organisms in various stages of decomposition and synthesis, and is variable in composition. Organic matter (OM) has a major influence on soil aggregation, nutrient reserve and its availability, moisture retention and biological activity. OM is conventionally analysed with the WALKLEY-BLACK dichromate method and adapted by ANNE (AFNOR X31-109) consisting in investigating the organic Carbon. The procedure is based on reduction of potassium dichromate ($K_2Cr_2O_7$) and subsequent determination of the unreduced dichromate by oxidation-reduction titration with ammonium sulphate. The obtained data of organic Carbon are converted to percent organic matter with a conversion factor of 1.72 thus one convention is to assume that organic C is 58 % of the total OM (LANDON et al. 1991).

The primary macronutrient parameters (Nitrogen, Phosphorus and Potassium) are analysed. Nitrogen (N) occurs in the soil in several forms: organic compounds, inorganic phase composed of nitrate (NO_3^-), nitrite anions (NO_2^-), and ammonium ions (NH_4^+). The most common standard method is the KJELDAHL Nitrogen method which involves digestion and distillation. Thereby, soil is digested in concentrated sulphuric acid (H_2SO_4) with a catalyst mixture to raise the boiling temperature and to promote the conversion from organic-N to NH_4-N (BREMNER et al. 1982).
The difference between KJELDAHL-N and Total N, which is measured in this paper, is normally very small, mainly due to the presence of NO_3^- in the total N determination. The procedure, investigating Total N reduces NO_3^- fraction present in soil and subsequently includes that in a distillation unit.

Phosphorus, one of the major plant nutrients occurs in soils in both organic and inorganic forms, the latter usually being the more important for plant nutrition (BUSMAN et al. 2002).Through the BRAY I method for soils with pH < 6.0, total phosphorous and available phosphorous are measured. Total P contains only a small part which is available for plants. The study of its amount and distribution with the depth in different soil profiles is an important parameter. Total P measurement involves digestion of soil samples that are strongly acid (acid fluoride) and the dissolution of insoluble inorganic minerals and organic P forms.

Potassium (K), one of the macronutrients, is an essential nutrient for plant growth because large amounts are absorbed from the root zone in the production of most agronomic crops. Three forms of K (unavailable, slowly available or fixed, readily available or exchangeable) exist in soils. The readily available or exchangeable K is considered readily available for plant growth. Form of K measured by the routine soil testing procedure is an extraction method through ammonium acetate ($NH_4C_2H_3O_2$) and cations dosage in spectrometer.

Cation Exchange Capacity (CEC) measurements are commonly made as part of the overall assessment of the potential fertility of a soil (Booker tropical soil manual 1991) and possible response to fertiliser application. CEC is an extremely important property of soils from both an agricultural and environmental standpoint. It can be defined as the sum of total of the exchangeable cations that the soil can adsorb (KETTERINGS et al. 2005).
CEC is a calculated value that is an estimate of the soil ability to attract, retain and exchange cations elements (Potassium (K^+), Ammonium (NH_4^+), Sodium (Na^+) etc). These cations are held by the negatively charged clay and organic matter particles (clay-humic complex) in soils through electrostatic forces because of the fact that negative soil particles attract positive cations. CEC associated with soil OM is called pH-dependent CEC. This means that the actual CEC of the soil will depend on the pH of the soil.
As a fixed parameter, CEC represents a good indicator of soil fertility and a criterion in the evaluation model of soil vulnerability to loss of nutrients towards the groundwater and clay minerals characterisation (LANDON et al. 1991).

4.3 Botanical inventories

In the framework of relationship soil / vegetation, vegetation *relevés* were carried out according to the BRAUN-BLANQUET (1932) approach of plant communities study and sampling. It aims to provide an analysis of soil / vegetation types as well as structure, dynamic and species distribution of the different sites and to focus on environmental factors that control the species distribution. Around the profiles of the transects, *relevés* sites are identified following on the one hand the same hypothesis which conditioned the choice of soil profile sites and on the other hand according to some environmental factors: degraded zones with small vegetation cover, low human impact areas and seasonally waterlogged conditions. In addition, *relevés* sites are chosen in order to take into account different units of the topography (valleys, plateau, hillside and hilltop). The phyto-sociological approach is based on floristic inventories. The vegetation inventories within the study areas took place in standardised 1000 m^2 plots (50 x 20 m). They were identified and surveyed in consideration of certain homogeneity in vegetation structure and composition. But the size of these plots are modified and adapted to the conditions on the different sites. At top hills (*relevés* in Park Pendjari) for example plots have an outer size of 30 x 20 m or 30 x 30 m (900 m^2). In addition, the different vegetation types are determined. A total of 20 phyto-sociological *relevés* and 44 species are surveyed around the chosen profiles. The sites are chosen taking into consideration the homogenous character of the plot as well as distinctive changes in the vegetation pattern. The data collection concerns tree and shrub layer with Diameter Breast Height (DBH around 1.30 m from the soil) greater or equal than 5 cm. All individual trees with a diameter under this mean DBH are not considered in the 1000 m^2 plot. The circumference and height of each individual tree was measured with a tape measure respectively with a stick. In order to analyse the regeneration potential of woody plants within the plot, 5 small plots of 5 x 5 m were chosen in the different sides of the standard foursquare plot (50 x 20 m; 30 x 30 m) and in the middle of the plot. In this 5 x 5 m plot the number and species of young trees and those with DBH $\leq$5 cm are determined with the aim of evaluating the regeneration and dynamic of vegetation units around different soil profiles (fig. 27). Nevertheless, the surveyed of juvenile species for the regeneration estimation are not sampled with dendrometric properties as height and diameter. They provide basically numerous data of the regeneration ability of the different sites.

Vegetation surveys were realised in June and July (begin of rainy season). Individual trees are identified basically on the field and their family affiliation determined with the collaboration of Botanists from the Universities of Ouagadougou (Dr. Oumarou Ouedraogo) and Abomey Calavy of Cotonou (Dr. Aristide Adomou). Vegetation types and units are identified in the different plots according to the surface cover and density of tree, shrub and grass characteristics

Aside from theses measures within the plots, ecological variables as topography, human or animal activity in each site were registered. Total tree, shrub and grass cover were estimated visually in percentage as perpendicular projection into the plot. Dominant species and vegetation types are identified.

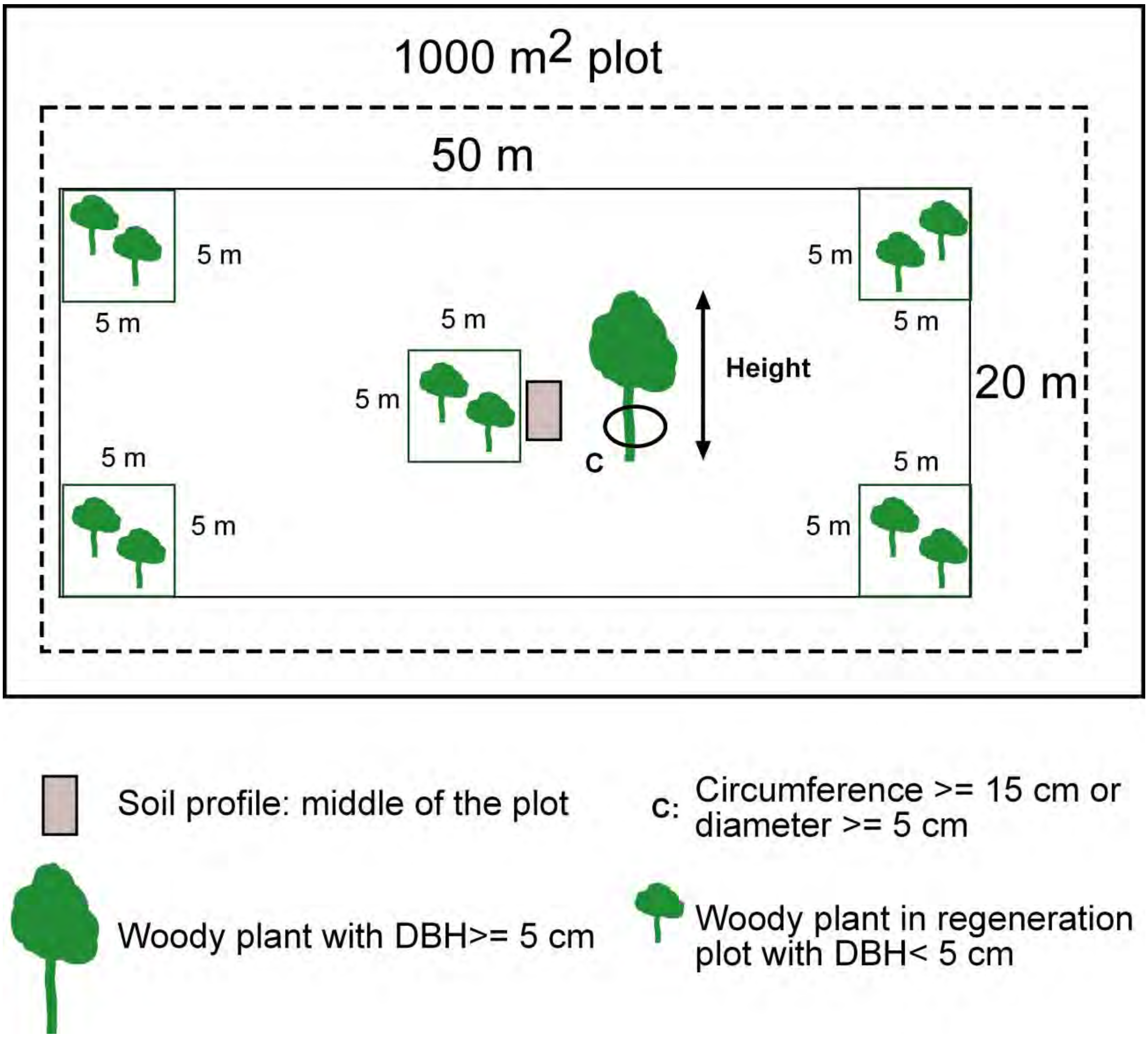


Figure 27: Standard hectare plot around a soil profile; on the field this plot was divided for practical reason in 5 subplots along the 50 m side and all trees and shrubs are identified and measured. In the 5 x 5 m subplot regeneration of the species is assessed, DBH: Diameter at Breast Height (own layout draft).

4.4. Processing of soil and botanical data

4.4.1. Analysis of soil data

Transects are outlined in Macromedia FreeHand graphic software (Version 11.0.2) on the base of field descriptions, measurements and analysis of different profiles. The first level of soil analysis occurs taking into consideration the soil layers (first, second and third layer) as well as the topsoil, on the one hand and subsoil on the other hand. It is important to mention that soil horizons are here conceptualised as soil layer or *couche du sol* in the French literature because taking into consideration the overall superficial processes which occur in the study areas. The soil layer analysis provides information about the lateral and vertical transport of material and nutrients and shows the evolution of physical and chemical parameters from the topsoil to the in situ deposited layers which are resumed under the term subsoil. From this analysis, soil types can be determined and classified of soils in the study area. Soil profiles are classified taking into consideration the prevailing FAO-soil classification in the West African region as well as some aspects of the pedogenetic German soil classification. It is aimed herby to facilitate the correlation between soil and vegetation unit and or composition and dynamic However, the determination of soil types and groups is not important in the scale of analysis in the present thesis and because of the dynamic of the savanna landscapes within pedological transects .

In a second level, parameters are analysed in relation to the surveyed woody plant *relevés* in each site. This analysis allows an interlinkage of specific soil parameters and distribution and composition of the vegetation in consideration to the environmental features as relief and land-used conditions. Along transect points of the sections profiles as well as relicts of lateritic crust are mapped with a Global Positioning System (GPS) and imported and integrated to Arc View GIS 9.2 with other available information in the study areas (vegetation maps, plant cover in BF, etc.). The saved coordinates (decimal degree, date, description and Ellipsoid) are implemented with existing GPS points within BIOTA project database.

4.4.2. Analysis of Botanical data

The vegetation inventories in the land-used and protected areas are classified and analysed according to the status of the sites and to the variation of soil profiles along the transects. Thereby, it is aimed to focus on the dynamic and structure of the vegetation communities.
Phytosociological relevé analyses are based on investigations about the diametric structure of vegetation communities taking into consideration all woody plants (ROLLET 1974). The analysis of diametric structure provides information about the equilibrium of vegetation population. Furthermore, the specific structure of vegetation is highlighted and consists of the classification of diameter classes following the individual species. In addition, the vertical structure presenting the species distribution according to the measured height of species is used. The latter analysis is a good indicator for the assessment of site richness (FAVRICHON et al 1998).
The diversity of vegetation units is analysed through some mathematical measures of species diversity in a community as

- Species richness (**S**) or species density (HURLBERT 1971) which is calculated as the number of species in a sample unit expressed per unit area. In this work we consider the sites with different land use conditions (land-used, partially protected and total protected, respectively Kikideni, Natiabouani and the hunting zone of the Pendjari National Park) as unit areas

- Relative Abundance (**Pi'**) of the 10 dominant species in the protected and land-used sites are calculated as following

Pi’ = ni/N * 100 (ni: number of individual species i; N: total number of all species)

- Shannon Index **H** which accounts for both abundance and evenness of the species present. The proportion of species ***i*** relative to the relative abundance of species (p_i) is calculated, and then multiplied by the natural logarithm of this proportion (**ln*p_i***). The resulting product is summed across species, and multiplied by -1:

$$H = -\sum_{i=1}^{s} Pi(\ln(Pi))$$

p_i: relative abundance of i species.
S: total number of species.

In order to determine the relationship between species distribution and environmental factors, the multivariate analysis method is performed using the default settings of the computer program PC-ORD 4.33 for Windows (MC CUNE et al. 1999) is applied. Soil data are arranged in a vegetation matrix including the 11 sampling locations and the 42 woody plant species identified in the different sites. Ordination techniques like Detendred Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA) were used in this program. DCA is an eigenanalysis (mathematical operation on a square, symmetric matrix) which ordinates both species and samples simultaneously (HILL et al. 1980). DCA performs detrending to counteract the arch effect (a distortion or an artifact in an ordination diagram, in which the second Y axis is an arched function of the first X axis). Sites that are more similar in vegetation structure (species composition and abundance) are depicted as being closer together in the diagram. It can be expected that sites have no species in common and/or similar environmental conditions.

In addition to this DCA ordination technique, CCA is performed. As its name suggests Canonical Correspondence Analysis (CCA) is a correspondence analysis technique which basically consists in arranging species along environmental variables (TER BRAAK 1987). In this study CCA is used because of its ability to seek structure in the main matrix, which contains abundance of the identified species of the *relevés* in a set of sample units, in such a way as to maximize the strength of the relationship with the second matrix (e.g. soil parameters). These parameters (pH KCL, clay, sand, CEC, etc) were chosen in consideration of their possible influence on vegetation distribution and dynamic. CCA permits to gain information about the floristic variability under different environmental and land-used activities. The generated ordination diagram visualizes not only a pattern of community variation (as in the DCA analysis) but also the main features of the distributions of species along the soil and environmental variables.
CCA and DCA ecological analysis are supplementary instruments that establish the relationship between soil relief and phytodiversity under the influence of environmental factors.

5. RESULTS

The results of soil profiles and their chemical and physical properties following the different transects are analysed taking into consideration to the different land use conditions and the variation within the different sites. Thereby, the term layer as homogenous unit with similar textural as well as colour, rooting density is used and corresponds to the well identified horizon succession, term which is more widespread in the framework of the classification of savanna landscapes (A, B and C horizons). Furthermore, the use of layer reflects at best the superficial processes as erosion and or degradation occurring at the surface. The vertical succession of layers in the different soil profiles shows an upper, second and third layer. These layers cover the weathered material or saprolite and the underlying parent material.

5.1. Physical and chemical properties of soils in Kikideni and Natiabouani

5.1.1. Transect sequence and soil profiles in Kikideni

Along the Kikideni transect in the land use site 13 soil profiles are chosen following different relief units. The 2.5 km long transect is represented schematically (fig. 29-A) based on the different identified layers.

Upper layer

The upper layer is characterised by the presence of fine material, mostly a sandy loam texture following the USDA Soil Textural Triangle (fig. 28) mixed with coarse gravel. The gravel materials found within the upper layer represent in some profiles (3, 5 and 10) relicts of the weathered granitic parent material. These relicts are characterised by the omnipresence of quartz and traces of the grained structure of granite. The outcrop of the parent material is found around profile (prof.) 10 of the transect (photo 12).

The thickness of the upper layer is estimated to 20 cm. The inclination along the transect show a generally gentle slope (≤ 2°) representative for the peneplain regions of the savanna landscapes of West Africa. The variation of slope degrees as presented in table 7 reflects the undulated character of landscapes in South East BF.

The rooting density, which indicates the number of fine rooting pro dm^2 (*Bodenkundliche Kartieranleitung 2005*), represents a significant factor for assessment of tree and grass cover as well as for understanding the absorption and transport capacity of water and nutrients in soils. The estimated rooting system shows a relative dense rooting systemThe site where the rooting system is very low (w1) is located in a very strong degraded surface with massive traces of grazing activities (tab. 7).

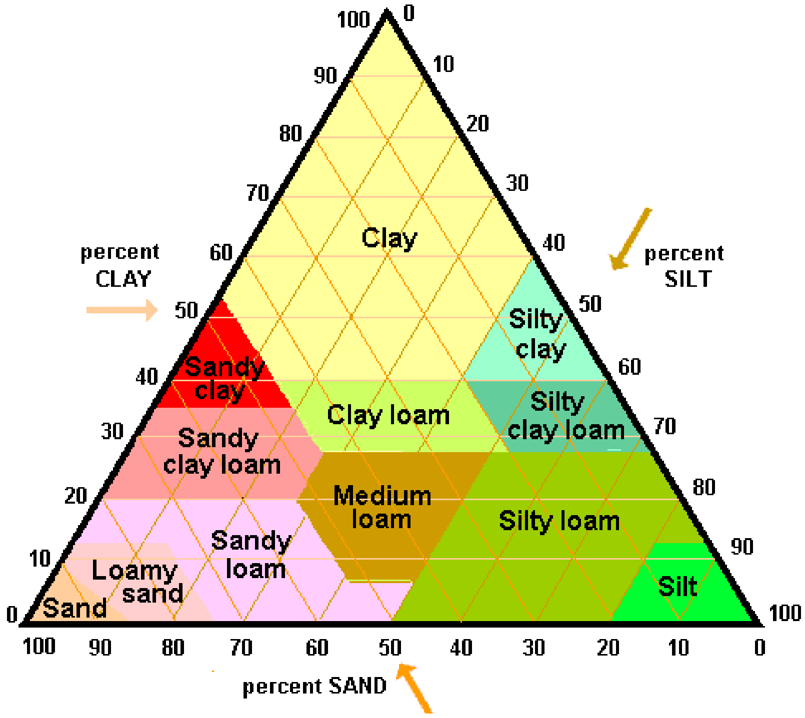


Figure 28: Chart showing the percentage of clay, sand and silt basic textural classes (United States Department of Agriculture, http://soils.usda.gov/education/facts/formation.html) These textural classes served to determine soil texture along transects and in soil profiles.

Soil colour represents a key parameter for identification of soil horizons and for classification of soil in groups (EVANS et al. 1988). Furthermore, soil colour development and distribution in soil profiles as well as along transects reflect an integration of chemical, biological and physical transformations and is indicative of the amount and distribution of organic matter and the state of aeration as well as the weathering type in soils. Thus, soil colour is one of several tools used in evaluating the suitability of a given soil for various uses and determining the kinds of soil modifications that need to be applied (CHESWORTH 2008). The determination of soil colour in the upper layer (tab 7) was carried out during the dry and rainy season. Soil colours are determined in wet and dry conditions and completed in laboratory under the same conditions. Mostly the wet coloured soil sample is considered in this analysis of soil layers.
The predominant colour is brown (Hue 10YR 4/4-4/6 and Hue 7.5 YR 4/3-4/6. The other soil profiles are characterised by variations in the colour composition from dull reddish brown (Hue 5YR 5/4-4/4 in respectively prof. 13 and prof. 1), dark reddish brown (Hue 5YR 3/4: prof. 10, Hue 2.5YR 3/3: prof. 4) to dull yellowish brown (Hue 10YR 5/4: prof. 11) or yellowish brown (Hue 10YR 5/6: prof. 6). Prof. 2, which is situated in a depression, has a particular brownish black colour (Hue 10YR 3/2) indicating a thin humus layer.

Photo 12: Outcrop of granite within the land-used site of Kikideni. Because of the weathering intensity fine material is deposited and grass cover has partly established (photo: Anne, C. A. T. 17.10.2004).

Profiles	Thickness	Colour	Rooting density	Inclination (degree)	Texture	Environmental conditions/observations
1	0-16 cm	Hue5YR 4/4w* and 5YR 6/2 d*	Moderately dense (w3*)	0.5°	sandy loam	profile near a foot path, grazing traces; fine material mixed with coarse material
2	0-20 cm	Hue 10YR 3/2w, Hue 10YR 5/2 d	very dense (w5)	-1°	silty clay	temporary inundated valley with very high tree species; fine material
3	0-15 cm	Hue 7.5YR 4/4w, Hue 10YR 6/4 d	very dense(w5)	2°	sandy clayey loamy	slope related to the previous site (small valley); pisolite (50 %) of the layer
4	0-12 cm	Hue 2.5YR 3/3 w, Hue 2.5YR 5/3 d	dense (w4)	-1.2°	sandy loam	degraded site with arched surface pisolite on the soil surface, outcrop of relict laterite crust
5	0-23 cm	Hue10YR 4/6w, Hue 2.5Y6/3 d	very dense (w5)	1.3°	sandy loam	plateau unit (120 meters long)
6	0-15 cm	Hue 10YR 5/6w,	dense (w4)	2°	sandy loam	plateau, prolongation previous

		Hue 10YR 6/3 d				
7	0-23 cm	Hue 7.5YR 4/4w, Hue 10YR 5/3 d	very low (w1)	0.5	sandy clayey loamy	strong degraded surface, grazing; presence of massive pisolite; weathered blocks
8	0-20 cm	Hue 7.5YR 4/6w, Hue 10YR 7/3 d	low (w2)	0.8°	sandy loam	slope following degraded zone (profile 7); fine and coarse material
9	0-25 cm	Hue 7.5YR 4/6 w, Hue 10YR 6/2 d	dense (w4)	-2°	loamy sand	gully (4 m width and 1.15 m depth), traces of grazing; presence of alluvial horizon; pisolite
10	0-20 cm	Hue 5YR 3/4 w, Hue 7.5YR 6/4 d	dense (w4)	0.5°	sandy loam	plateau, profile located 10 m from bedrock outcrop presence of block of rocks
11	0-20 cm	Hue 10YR 5/4	very dense (w5)	0.5°	sandy loam	profile located by termite mound, grazing; fine material
12	0-37 cm	Hue 10YR 4/6w, Hue 10YR 6/4 d	very low (w1)	0.1°	sandy loam	plane surface with less anthropogenic activities; fine material
13	0-18 cm	Hue 5YR 5/4 w,	low (w2)	0.1°	sandy loam	profile nearby abandoned termite mound; fine material

Table 7: Description of physical and environmental conditions at the surface and in the upper layer of Kikideni transect (*w: colour wet sample, *d: colour dry sample); rooting density based on the German soil science mapping manual (*Bodenkundliche Kartieranleitung*, 2005).

Second layer

The underlying second layer of profiles are characterized by the enrichment and/or accumulation of coarse material identified as non indurated and closely packed round pellets of iron (5-10 mm diameter) recognizable through their purple red coloration, mostly pisolites. Pisolites appear in the layer as discontinuous iron or continuous modules mixed with fine material. The underlying average thickness in the second layer ranges between 20 and 42 cm except in the prof. 6, 10 and 12 where thickness comes up to 80 cm (tab. 8). The thickness of layer 3 in these latter profiles cannot be empirically surveyed because of the hardness of the

cemented material present. In fact they are part of the lateritic crust. Moreover, they are commonly situated around 80 cm within plateau units and up to 2 meters in the valleys.
The rooting system does not show a recognisable trend following relief units or state of degradation in the site. Nevertheless, soil profiles with a very low density of the rooting system are marked by the presence of indurated or partly indurated horizons in the second layer (prof. 10 and 12). The majority of soil profiles are characterised by yellowish brown colour (Hue 10YR 5/8, Hue 10YR 5/6 and Hue 10YR 6/6), which tends to bright yellowish brown (prof. 8) and bright brown (prof. 11). Soil texture in layer 2 is predominantly sandy loam as in the upper layer. For the differentiation of upper and second layers, proportion of coarse material and presence of an indurated horizon are essential factors.

Profiles	Thickness	Colour	Rooting density	Texture	Environmental conditions/Observations
1	16-44cm	Hue 10YR 5/8w* Hue 10YR 7/6 d*	low (w2*)	sandy clayey loamy	fine material mixed with pisolites from the laterite crust
2	20-43 cm	Hue 10YR 4/6w, Hue 2.5 Y 7/2 d	very dense (w5)	silty clay	compact structure with fine material
3	15-44 cm	Hue10YR 5/8w, Hue 2.5 Y 7/4d	dense (w4)	clayey loamy	coarse material from the laterite crust (80 %)
4	12-32 cm	Hue 10YR 5/8 w, Hue 10YR 7/3 d	dense (w4)	sandy loam	presence of coarse material and yellow coloured traces
5	23-42 cm	Hue 10YR 5/6 w, Hue 7.5 YR 6/6 (c. m.*)	dense (w4)	sandy loam	biological activity through presence of ants
6	15-80 cm	Hue 5YR 5/6 w, Hue 5 YR 3/6 (c. m.*).	dense (w4)	sandy loam	indurated fine material
7	23-52 cm	Hue 10 YR 7/3 w,	very low (w1)	sandy clayey loamy	white and yellow coloured traces in a saprolite (weathered material)
8	20-43 cm	Hue10YR 6/6 w, Hue 10 YR 7/4 d	low (w2)	sandy loam	more coarse material than in layer 1
9	25-44 cm	Hue10YR 5/6w, Hue 5 YR 3/6 (c.m.*)	very dense (w5)	loamy sand	massive pisolite in the layer
10	20-80 cm	Hue 7.5 YR 6/6 w, Hue 7.5 YR 7/4 (c. m.*)	low (W2)	sandy loam	laterite crust
11	20-38 cm	Hue 7.5 YR 5/6	very dense (w5)	sandy loam	fine material mixed with coarse material
12	37-80 cm	Hue 5 YR 4/8w, Hue 7.5 YR 6/6d	very low (w1)	sandy clayey loamy	fine material mixed with pisolite
13	18-44 cm	Hue 7.5 YR 7/3	very low (w1	sandy loam	fine material mixed with pisolite

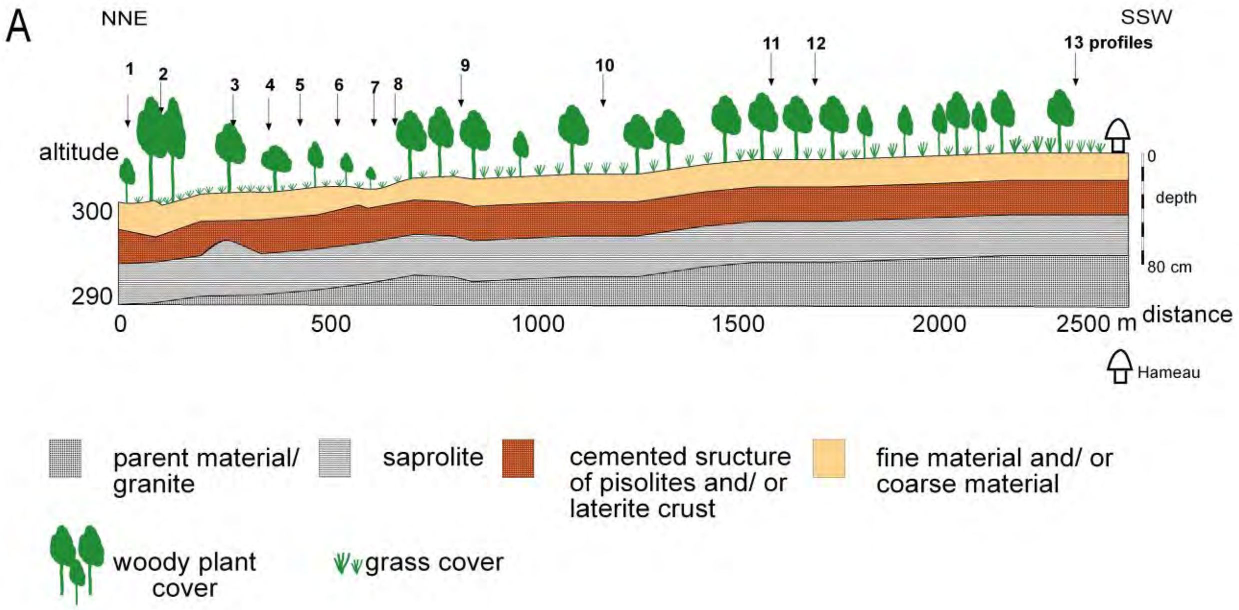
Table 8: Description of physical and environmental conditions of the 2nd layer of the Kikideni transect.
*: this colour is obtained from the crushed coarse material, mainly from pisolites.

Layer 3

Compared to layer 2, the underlying layer 3 is characterised by enrichment of coarse material and massive presence of indurated structures enriched with quartz particles and/or pisolites , which are identified as part of the laterite crust (prof. 4, 5, 8, 9, 10, etc...). The analysis of soil layers, particularly of fine material deposited or developed in the subsoil are carried out within 80 cm depth because of the hardened and cemented structure of underlying horizons. But profiles located in the valley (prof. 2) show a deeper and less indurated profile. The average thickness of the third layer ranges between 44 and 80 cm (table 9). Rooting system is essentially low (w2) to very low (w1). Soil colours in this layer are variable and indicate differences and intensities of weathering processes along the transect. Soil texture of the third layer is principally sandy clayey loamy and clayey loamy.

Profiles	Thickness	Colour	Rooting density	texture	Environmental conditions/Observations
1	44-80 cm	Hue10YR 6/4w* Hue 10YR 6/6 d	very low (w1*)	sandy clayey loamy	indurated layer with presence of fine material; quartz particles
2	43-63 cm	Hue 10R4/6w, Hue 2,5 Y 7/4d*	low (w2)	sandy loam	compact structure; thicker than layer 1 and 2
3	44.80 cm	Hue10YR 6/2	low (w2)	clayey loamy	enrichment of coarse material; quartz particles
4	32-80 cm	Hue10YR 8/2w, Hue 2,5Y8/3 d	very low (w1)	sandy clayey loamy	partly indurated layer with quartz particles; saprolite
5	42-80 cm	Hue 2,5 Y 8/3	very low (w1)	sandy clayey loamy	presence of rock particles, partly indurated: laterite crust
7	52-80 cm	Hue 5 Y 8/3	very low (w1)	sandy clayey loamy	fine material mixed with coarse particles from the bedrock: saprolite
8	43-80 cm	Hue10YR 7/3w, Hue 7,5 YR 8/3d	very low (w1)	clayey loamy	laterite crust
9	44-80 cm	Hue10YR 8/3w, Hue 10YR 5/6 d	low (w2)	sandy clay	indurated layer, presence of coarse material
11	38-57 cm	Hue 5 YR 5/8	dense (w4)	sandy clayey loamy	laterite crust
13	44-80 cm	Hue 7.5 YR 7/3	0	sandy clayey loamy	laterite crust

Table 9: Description of physical and environmental conditions in the third layer of Kikideni.



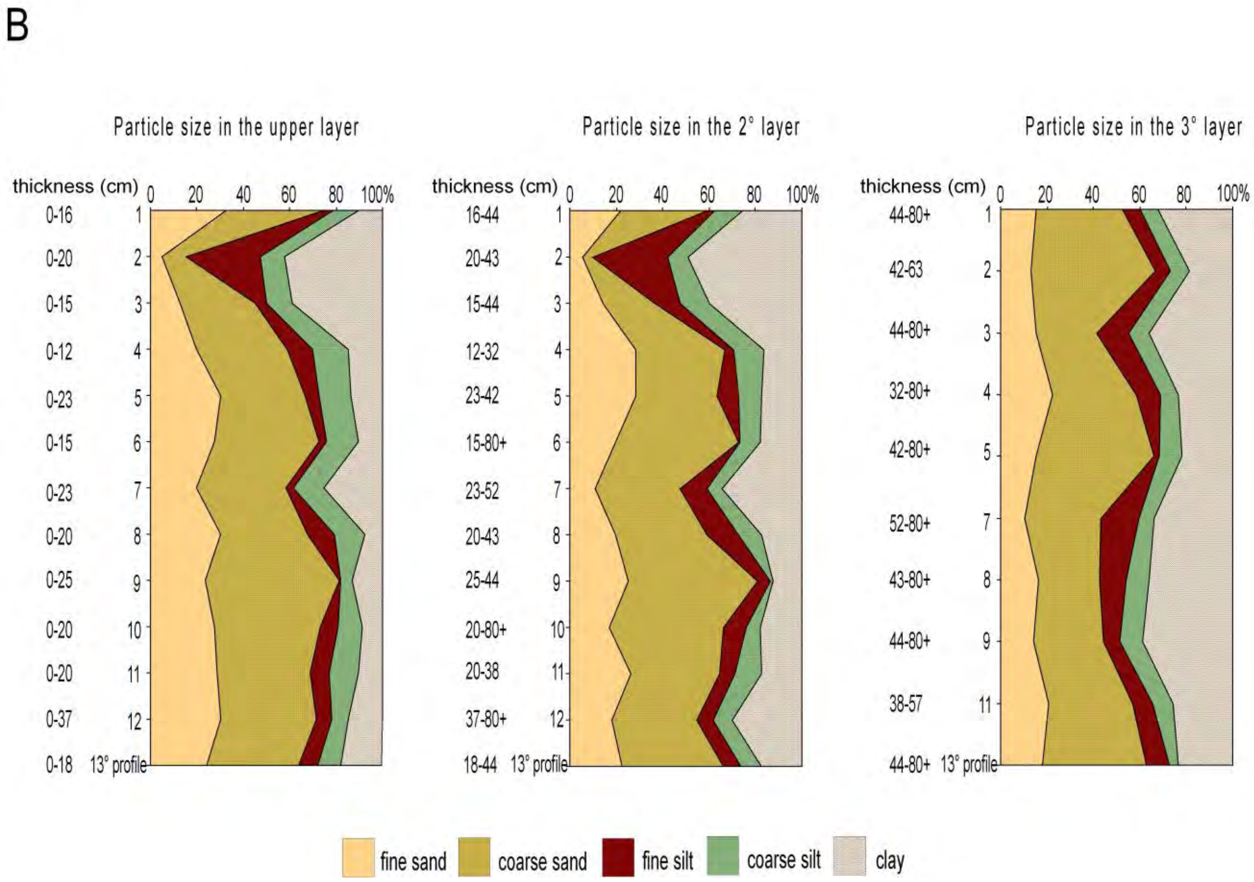


Figure29: A) Schematical representation of the transect and its different layers in the land-used area of Kikideni. B) Particle size distribution in the different layers.

Particle size distribution

Particle size distribution (c) represents a key parameter for soil classification and soil texture, the latter influencing different soils properties as water retention, nutrients availability for plants and fertility (BRABANT, 1998). The variability of 5 fractions of particle size distribution (coarse sand, fine sand, coarse silt, fine silt, and clay) along the Kikideni transect are first analysed following the three identified layers and then graphically visualised (fig. 29-B) in order to assess lateral variation of soil texture in relation with different relief units as well as environmental conditions in the land-used site of Kikideni.

PSD in upper layer

The total sand fraction lies above 50 % in the majority of soil profiles except in prof. 2 and 3 with 15 % and 37 % respectively. The fraction of coarse sand is generally higher than that of fine sand. The analysis of fine and coarse silt shows that in almost all profiles fraction of coarse silt is higher than that of fine silt except in prof. 2. The average amount of clay fraction reaches 13 %. Moreover, high clay content is observed in prof. 2 and 3 (fig. 30-B).

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	16 cm	32.5	41.5	74	5	11	16	10
2	20 cm	5	10.5	15	32	10	42	42
3	15 cm	12.5	32.5	45	5	11.5	16.5	38
4	12 cm	19.5	39	58.5	11	15	26	15
5	23 cm	30	36	66	6.5	14	20.5	13.5
6	15 cm	28	45	73	3.00	14	17	10
7	23 cm	20	38	58	3.50	13	16.5	25
8	20 cm	30	38	68	11.50	13	24.5	7.5
9	25 cm	23.5	57.5	81	1	5	6	13
10	20 cm	27	45.5	73	7.50	11	18.5	9
11	20 cm	28	40	68.5	8	13	21	10
12	37 cm	30	41	71	7	7	14	15
13	18 cm	24	40	64	8	10	18	18

Table 10: Particle size distributions in the upper layer along profiles of Kikideni transect.

PSD in layer 2

Total sand fraction lies clearly above 50 % except in prof. 2 (tab. 9) and decreases generally from the upper to layer 2. The amounts of coarse and fine silt fractions show that in 8 profiles (1, 3, 4, 5, 6, 11, 12, and 13) coarse silt is higher than fine silt.
From the upper to layer 2 an enrichment of clay content can be observed in the different soil profiles. The clay content decreases with depth only in prof. 8, located within a plateau unit.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	16-44cm	22	37	59	3	12	15	26
2	20-43 cm	6	4	10	32	9	41	49
3	15-44 cm	14	22	37	11	12.5	23.5	40
4	12-32 cm	28	38	66	3.5	13	17	16.5
5	23-42 cm	28.5	35	63.5	9	10	19	18
6	15-80 cm	19.5	53	73	0.25	9	9	18
7	23-52 cm	11	36	47	12	6.5	18.5	34
8	20-43 cm	19.5	39	59	14	10	24	17.5
9	25-44 cm	25	56	81	5.5	1	6.5	12.5
10	20-80 cm	17	49	66	10	6	16	18
11	20-38 cm	26.5	38	64.5	7	11	18	17.5
12	37-80 cm	18	36.5	54.5	7	8	15.5	30
13	18-44 cm	22.5	43.5	66	7.5	9	16.5	18

Table 11: Particle size distributions in layer 2 along the profiles Kikideni transect.

PSD in layer 3

The percentage of total sand in this layer decreases essentially compared to percentage of total sand in both overlaying layers. The coarse silt fraction decreases except in prof. 2, 5 and 9. Compared to layer 1 and 2, clay fraction in the third layer increases and confirms the enrichment of clay proportion with depth, which is recognized as one of the properties of the soil units in the study areas (see 5.2). However, an impoverishment with depth is observed only in prof. 2 and is characterised by temporary flooded conditions.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	44-80 cm	15.5	37	52.5	8	7	15	32.5
2	43-63 cm	13	53.5	66.5	7	8	15	18.5
3	44.80 cm	15	26	41	13.5	9	22	36
4	32-80 cm	22	36	58	10	7.5	18	24
5	42-80 cm	15	51	66	2	10	12	22
7	52-80 cm	10	32.5	42.5	17	6	23	34
8	43-80 cm	16	26	42	12	10	21.5	36
9	44-80 cm	14	30.5	44.5	7	10	16.5	39
11	38-57 cm	20.5	36	57	9	9	18	25.5
13	44-80 cm	18	45	63	10	4	14	23

Table 12: Particle size distributions in layer 3 of Kikideni transect.

Chemical properties along the Kikideni transect

Similar to above focussed particle size distribution in the different layers of the Kikideni transect, soil chemical parameters and/or nutrients affecting plant growth are analysed following the same approach of vertical succession in layers in order to apprehend lateral transport and processes of nutrients between profiles and relief units.

PH, organic matter and nutrients in the upper layer

Soil pH (KCL) is considered as the real pH because it determines the potential acidity of soils and represents one of the major factors controlling many processes such as chemical weathering, biological activity, root developing, and plant nutrient availability (CAIN et al., 1999). The variation of pH (KCL), organic matter, cation exchange capacity and macro soil nutrients as available and total phosphorous, nitrogen, and magnesium are visualised in different diagrams following the soil layers in the Kikideni transect (fig. 30).

PH (H_2O) values are higher than pH (KCL) ranges in all profiles (fig. 31) and indicate poor nutrient availability and phosphate fixation following LANDON (1991). However, the pH (KCL) values show that the soils are characterized by their acidity and can range from very strongly acid (5.0-4.5) to moderately acid (6.0-5.5) according to the U.S. Department of Agriculture (1998). At pH values below 5.5, iron and aluminium serve as precipitating agents in the process of phosphate fixation non available for plants.

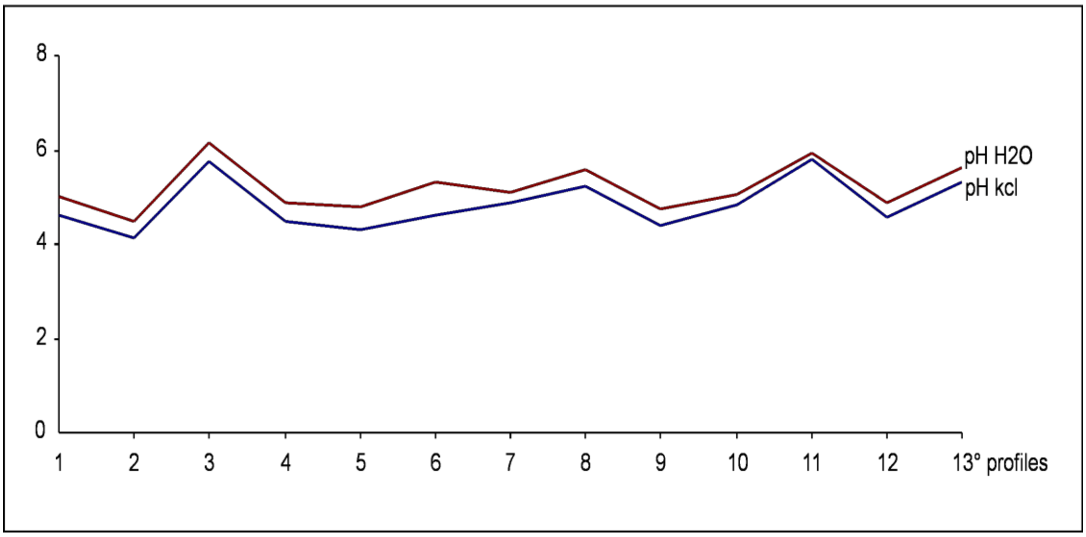


Figure 31: pH (KCL) and pH (H_2O) in the upper layer of soils along the Kikideni transect: in every profile pH (H_2O) < pH (KCL).

Soil organic matter (SOM) is organic material that has undergone decomposition and humification, which determines the process of transforming and converting organic residues to humus (Brady et al. 1999). Commonly defined as amount of organic residue that will pass through a 2-mm sieve, SOM affects soil by improving or maintaining a structure favourable to

plant root system, adding to or maintaining nutrient capacity and availability as well as soil fertility (FABER 1995).
The percentage of soil organic matter is higher in the inundated zone, which is characterised by the presence of dense and high tree species and high clay content (42 % tab. 8). However, organic matter contents in the upper layer are basically low to very low.
The ratio organic carbon and nitrogen (C/N) is an essential factor in the decomposition of organic matter. These two soil parameters determine organic matter type through their degree of humification (LANDON 1991). C/N ratios are generally relatively high (values are almost higher than 20) and indicate a low decomposition of organic matter in soil surfaces or low organic nitrogen content in soils. Optimal values of C/N ratios range from 8 to 10 and indicate good and stabilised humus in soil surface (MILLER et al. 1990).
Nitrogen (N), which occurs in soils in several forms (organic compounds, nitrate and nitrite anions, and ammonium ions) proceeds mainly from the breakdown and humification of organic matter (LANDON 1991). Thereby, the slow decomposition of humus, which can be observed through the ratios of C/N, releases NH_4 which are oxidized to nitrite and nitrate. Total N contents in the upper layer can be considered as very low according to METSON´s (1961) interpretation of soil parameters.
In soil, phosphorus (P) exists mostly in organic and inorganic form, both of which are important sources of P for plant and microbial uptake. The organic form exists mostly in humus and other organic materials. The inorganic form occurs in combination with various forms of aluminium (Al), iron (Fe), magnesium (Mg), calcium (Ca) and other elements, most of which are not soluble and therefore not available for both plant and microbial uptake. Available inorganic P for plant take-up is released in the soil solution in form of phosphate ions ($H_2PO_4^-$).
Comparative to the available P, the highest total P amounts are measured in prof.2 in the inundated zone and in prof. 7 within a strong degraded zone. The high amount of Total P in prof. 2 is related to the high SOM content (3 %).
Levels of available P in nearly all the upper layers of the profiles along the Kikideni transect can be considered as acutely deficient to deficient, with amounts comprised mostly between 2 and 7 ppm according to LANDON (1991) and based on studies on soils phosphorus from the Zimbabwean Ministry of Agriculture.
Potassium (K), as one of the macronutrients in soils plays an important role in plant growth. Nearly all of the potassium in soils (90 to 98 %) is incorporated into soil minerals and is unavailable for plant in short term. However, the minerals represent an important reservoir in long term potassium that is dissolved in soil water (water soluble). The fraction of potassium that held on the exchange sites on clay particles (exchangeable K) is considered readily available for plant growth (REHM 1995).
The amount of available K in this layer can be considered as rich according to the interpretation of measurements in sandy and sandy loam soils in Zimbabwe (LANDON 1991) and to available K values based on Malawi soils by YOUNG et al. (1977). Thereby, amounts of available K > 0.5 meq/100 are categorised as high values or rich and no K enrichment required. However, high amounts of K measured in the land-used site of Kikideni may be related to the transport of soil particles from the previous or ongoing areas marked by agricultural activities, which are normally enriched with potassium in the degraded soil units within the savanna landscapes of West Africa.

Cation Exchange Capacity (CEC), which represents the total amount of exchangeable cations that a soil can adsorb, are measured for the assessment of the soil fertility and used as rough guide for the identification of clay types in soils. CEC amounts are related to the clay and organic matter contents in soils because of their negative ion charge. The majority of soil profiles have low CEC values (6≤CEC≤12 according to HAZELTON et al. (2007). A low CEC means that soil has a low resistance to changes in soil chemistry that are caused by land use. The variation of CEC values at the surface reveal that the clay mineral types in this land-used site of Kikideni is Kaolinite (see 2.2.1.2).

PH, organic matter and nutrients in the 2nd and 3rd layer

Compared to the upper layer, a decrease of pH (KCL) amounts in the second layer can be observed in 10 of the 13 profiles along the Kikideni transect (fig. 30) while from layer 2 to layer 3 pH (KCL) increase lightly in nearly all profiles. As in the upper layer pH (H_2O) values in the second and third layer are higher than pH (KCL) values.
The amounts of SOM decrease from the topsoil to the underlying layers along the Kikideni transect. The SOM contents can be considered as very low in the second and third layer of the soil profiles. Indeed, almost all profiles have a percentage of organic matter lower than 1.5 %.
The majority of C/N values in layer 2 and 3 are greater than 20 and indicate a low decomposition of organic matter like the upper layer. Only within layer 3 profiles located around the temporary inundated valley (prof. 1, 2 and 3) show C/N ratios lower than 20 and consequently good decomposition of the organic matter. The presence of the humus horizon in prof. 2 may be an indication of good organic matter decomposition. C/N values decrease from the upper to the second layer within 8 of the 13 profiles. But from the observation of the different profiles in depth, any trend of C/N variation can be assessed.
Generally, a decrease of total N from the topsoil to the underlying layers can be observed in nearly all soil profiles. N contents in the second third layer are very low.
With regard to the available P amounts from the upper to the underlying layers, there is no visible trend in the vertical variation of P contents. Values of available P are estimated as deficient in layer 2 and 3 like in the upper layer with values comprised generally between 3 and 6.5 ppm. Moreover, an increase of total P from layer 2 to layer 3 can be observed in 8 of the 13 profiles. Generally, there is no visible trend of the total P variations with depth.
The vertical variations of available K tend to decrease from the topsoil to the underlying layers. Profiles, where an increase of available K with depth is observed are characterised by the degradation of the sites (prof. 9 with gully erosion and prof. 7 under influence of sheet erosion).
A comparison of layer 1 and 2 shows an increase of CEC values in 10 of the 13 profiles along the Kikideni transect. Prof. 6, 8 and 9 have very low CEC values (<6), which may be related to lowest clay content (18, 17.5 and 12.5 % respectively). With these unfavourable conditions, soils cannot hold very much water or cation nutrients and plants cannot grow well. These profiles are subject of a visible degradation of the surface with spare vegetation cover.
Generally, CEC amounts measured in the different layers indicate the presence of kaolinite as clay type.

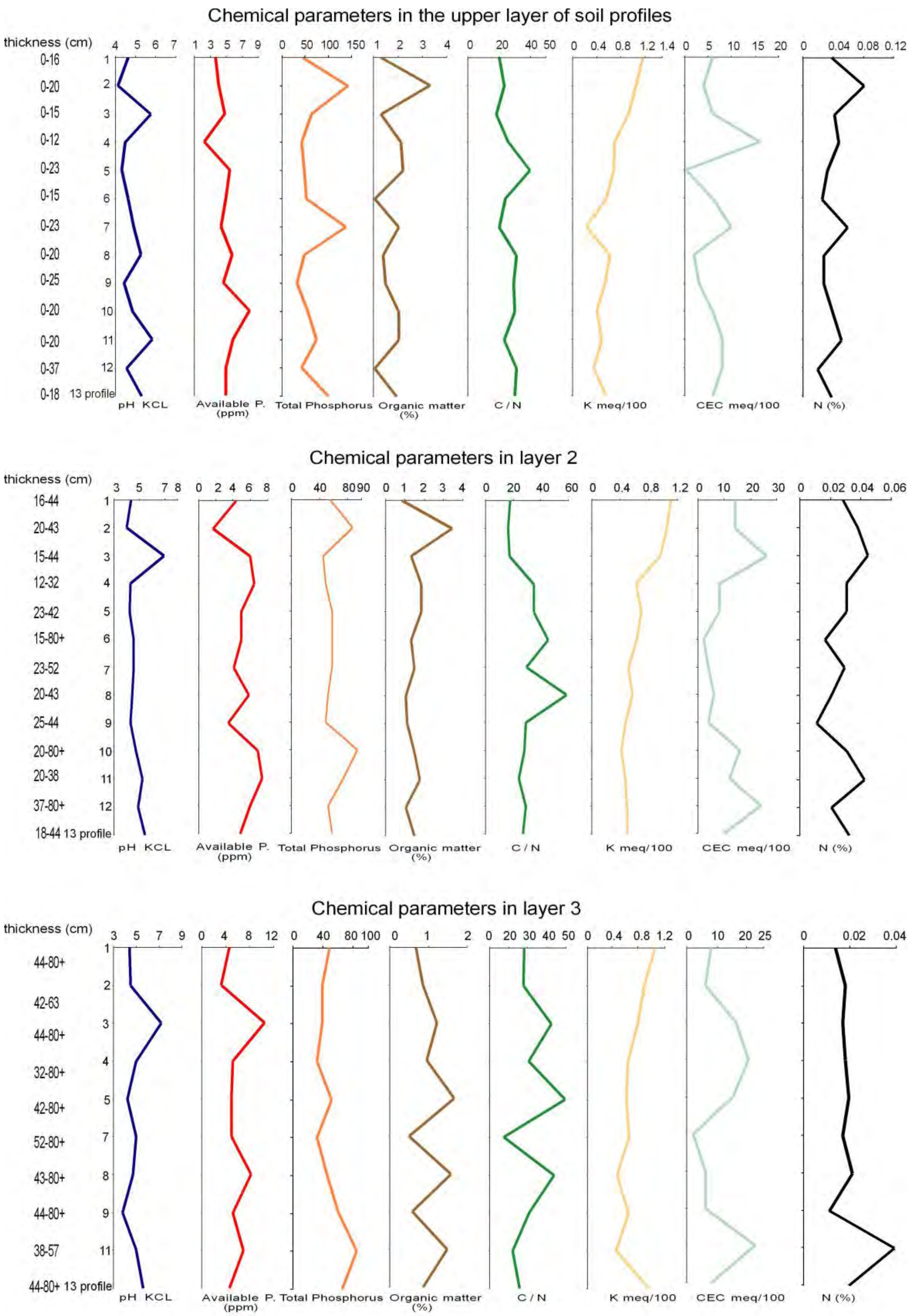


Figure 30: Variation of chemical parameters of soil profiles in the different layers within the land-used transect of Kikideni (South East BF).

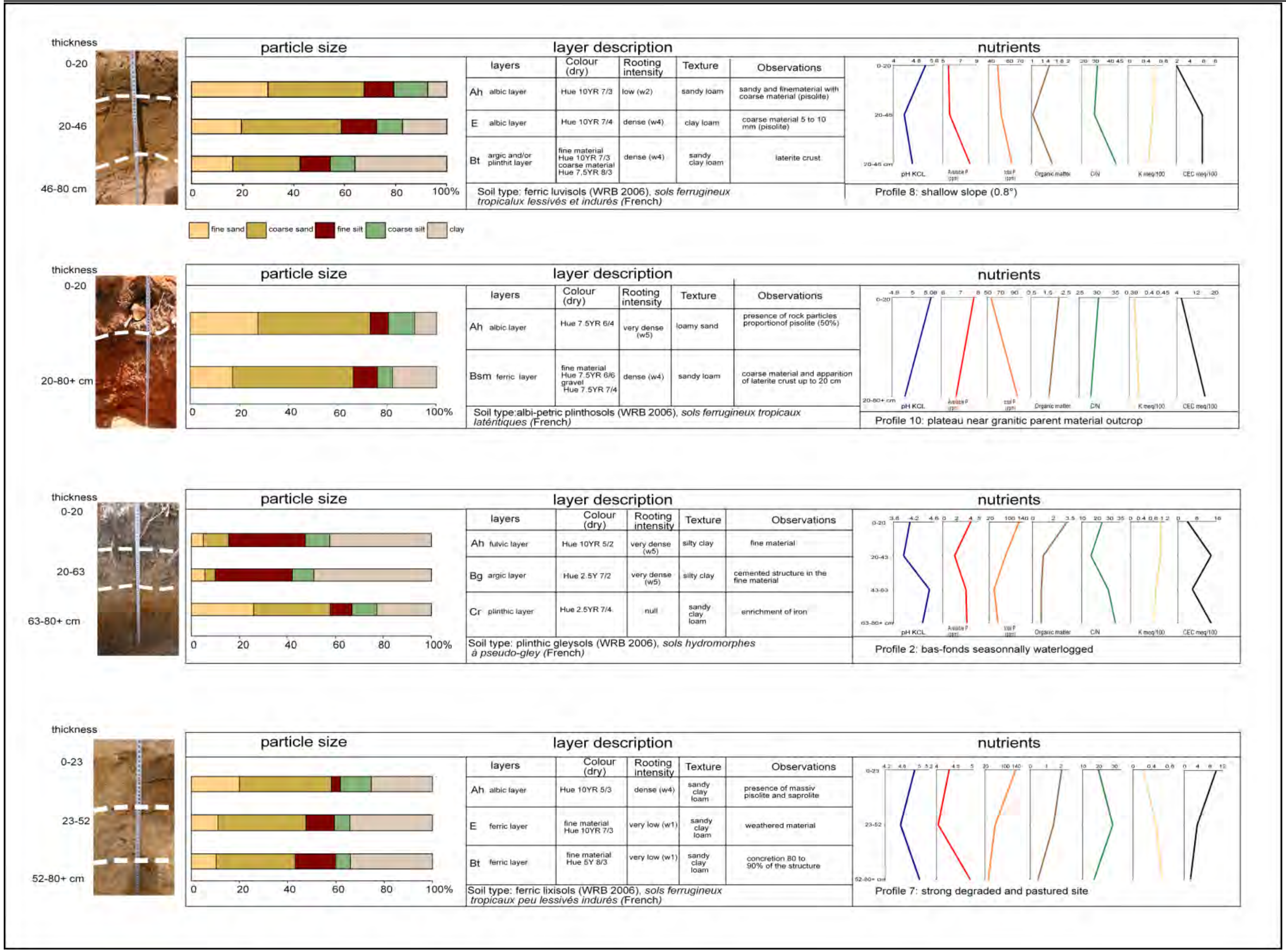


Figure 32: Sample of soil types according to the world reference base for soil resources (WRB 2006), physical, chemical and environmental parameters in the land-used site of Kikideni. These profiles show how variable can be soil types within a small scale study

5.1.2. Transect sequence and soil profiles in Natiabouani

The same analysis model is done for the transect Natiabouani. The Natiabouani transect is situated at the boundary of the partly protected reserve of Pama (*Réserve partielle de Pama*) in the Kompienga province, department of Pama (fig. 33). 11 profiles are chosen in consideration of the different relief units. The site is formed by multiple small hills and abundant small rivers. Agricultural activities are absent in the reserve.

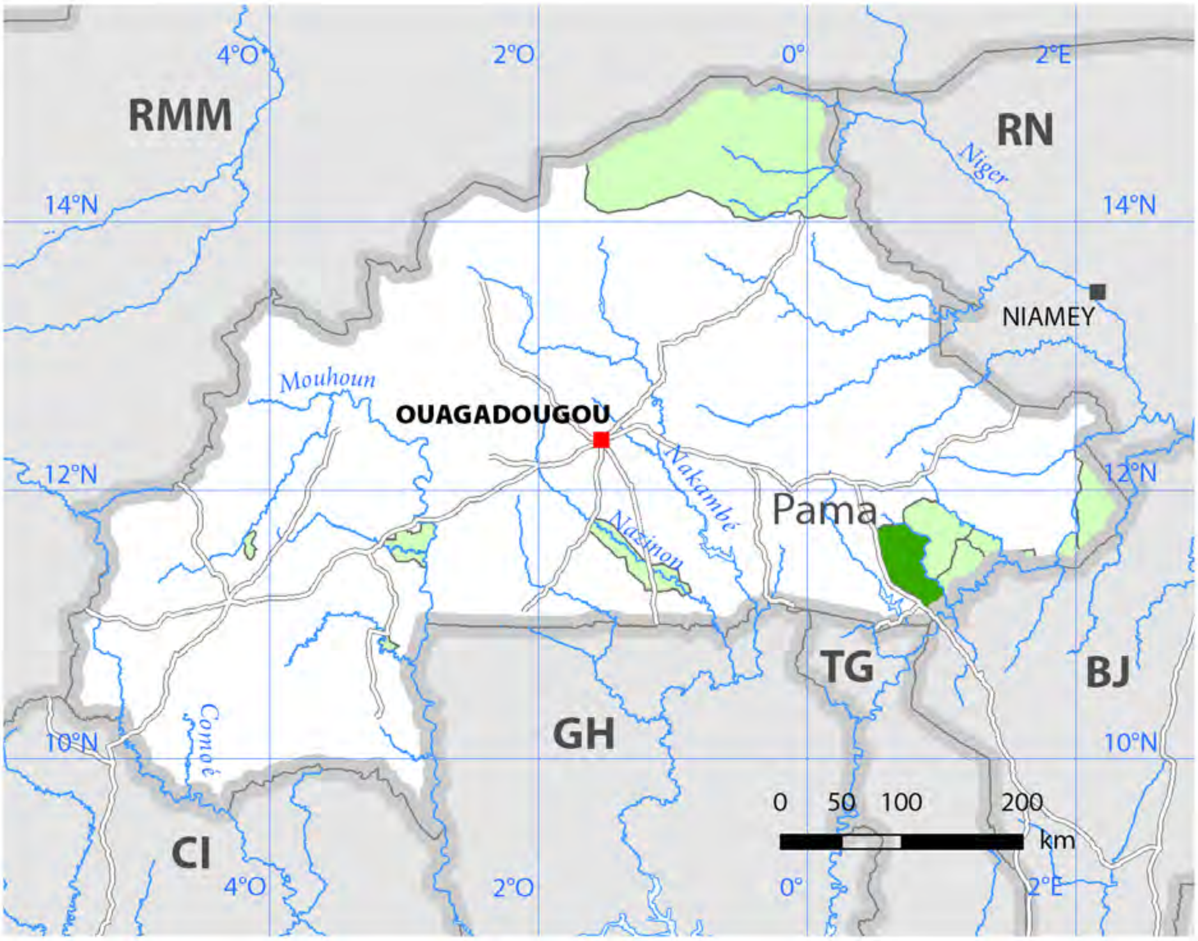


Figure 33: *Reserve partielle de Pama* in South East BF (source: BIOTA-ATLAS Eisenberg, J. 2011).

Upper layer

The upper layer along Natiabouani transect is characterised by the presence of fine and coarse material in the topsoil. Soil textures are mostly sandy loam to sandy clayey loam (tab. 13). Some profiles and their surroundings, which present different relief units and environmental conditions, are highlighted. Prof. 1 around a gully with a sandy loam soil texture and a relative steep slope (+ 9.5°) is characterised by a massive presence of pisolites on the surface and a very hilly relief, while prof. 2, situated within a peneplain section adjoining the main river in the site, presents a very dense grass and tree cover (photo 13).

Photo 13: Dense vegetation cover and stable environmental conditions around a soil profile within a peneplain (gently slope) in the protected site of Natiabouani (photo: Anne, C. A. T., 11.06.2007).

The BO of Natiabouani is characterised by an outcrop of the granitic bedrock like in Kikideni, but here principally situated at the main river (photo 14). Apart of this site, any outcrop of the parent material was not observed along the transect.

The thickness of the upper layer is estimated to 25 cm; representing the average of 10 profiles (except prof. exposure 8 characterised by a very thick layer [50 cm] and lack of topsoil due to gully erosion). Prof. 7, situated around the termite mound is less thick with 13 cm. The thickest layers are measured in profile exposures 3 and 8. Soil profiles within the transect line are less influenced by anthropogenic activities because of the protected status of this reserve. Nevertheless, influences of fire related to the reserve management for a sustainable biodiversity can be observed on the soil surface. Fauna in the reserve is relative rich because of the proximity to the adjoining reserve of Arli and of the Park Pendjari. Elephant traces are observable on the soil structure, particularly around profile 9.

Slope values (tab. 13) reflect the undulated character of the southern Sudan zones landscapes with small peneplains related to valleys units in this case temporary to permanent rivers. In prof. 1 and 3 slope degrees range from -9.5° to -8° respectively. Inclination values and variations along the Natiabouani transect are clearly more accentuated than those measured in the land-used site of Kikideni (see tab. 7).

Rooting system density is principally dense to very dense in nearly all profiles.

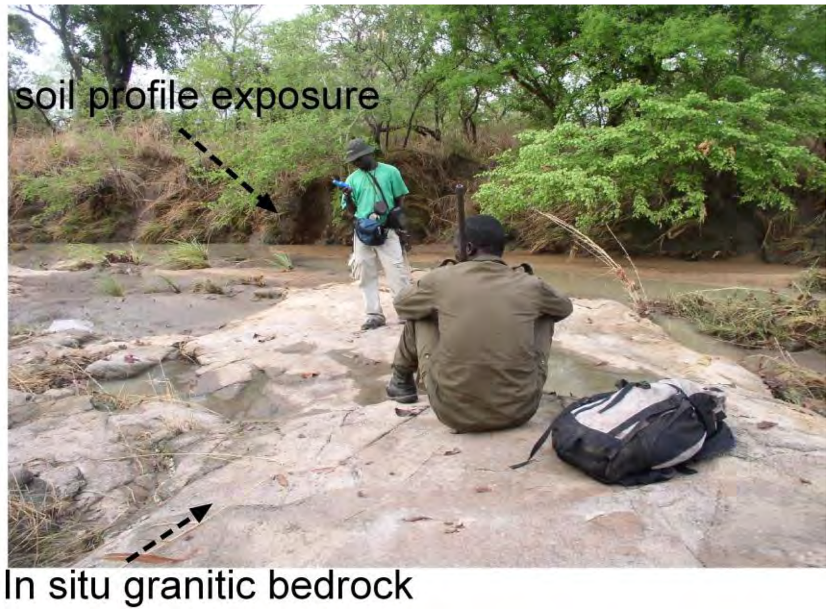


Photo 14: In foreground outcrop of granitic bedrock along the river channel surrounding profile exposure 3 (background) of the Natiabouani transect (photo: Anne, C. A. T., 15. 06. 2006)

The predominant colour in the upper layer is dark brown with Hue 7.5YR 3/4 and Hue 10YR 3/3 respectively within prof. 1, 2, 5, 7 and 10.

Profiles	Thickness	Colour	Rooting density	Inclination (degrees)	Texture	Environmental conditions/observations
1	0-18 cm	Hue 7.5YR 3/4 w*,7.5YR 2/3 d*	very dense (w5*)	-9.5°	sandy loam	profile in a gully (width: 7m, depth: 1.4 m), sandy structure with massive pisolites
2	0-25 cm	Hue 10YR 3/3 w, Hue 10YR 2/2 d	very dense (w5)	0.1°	sandy clay loam	section with a dense tree and grass cover.
3	0-44 cm	Hue 10YR 4/6w, Hue 10YR 5/4 d	dense (w4)	-8°	sand	outcrop of bedrock in the river, at the border soil profile exposure
4	0-38 cm	Hue 10YR 4/6 w, Hue 7.5YR 4/4 d	dense (w4)	4°	sandy loam	plateau within a degraded site near the BIOTA hectare plot, low vegetation cover, anthropogenic influence (old construction work)
5	0-25 cm	Hue 5YR 3/2 w, Hue 7.5YR 3/2 d	very dense (w5)	0.5°	sandy loam	plateau unit with stony structure on the surface, good vegetation cover
6	0-20 cm	Fine material: Hue 2.5YR 4/2 w, coarse particles Hue 2.5YR 3/4 d	dense (w4)	1°	sandy clay loam	eroded site, proportion of pisolite in the structure 70 % and relicts from the bedrock at the surface
7	0-13 cm	Hue 10YR 3/3	dense (w4)	0.5	sandy loam	profile at a termite mound, proportion of pisolite in the structure 70 % and relicts from the bedrock

8	0-50 cm	Hue 7.5YR 5/3 w, Hue 7.5YR 5/8	low (w2)	-5°	clay	soil profile exposure in the gully due to gully erosion (width: 5 m, depth: 1.6 m). The upper layer is eroded
9	0-20 cm	Hue 5YR 2/2 w, Hue 10R2/1 d	very dense (w5)	0°	clay loam	profile within a temporary inundated site with dense grass cover
10	0-25 cm	Hue 10YR 3/3 d	low (w2)	-3°	sandy clay loam	Soil profile at the border of the small river (*Tchecheri* River)
11	0-30 cm	Hue 10YR 5/6	low (w2)	3°	sandy clay loam	soil profile within a eroded plateau

Table 13: Description of physical and environmental conditions at the surface and in the upper layer of Natiabouani transect (*w: colour wet sample, *d: colour dry sample); rooting density based on the German Soil Science Mapping Manual (*Bodenkundliche Kartieranleitung*, 2005).

Second layer

The underlying layer 2 of soil profiles along the Natiabouani transect is characterised by enrichment of coarse material, mostly pisolites, that can reach 90 % of the structure for example in prof. 8. Coarse partly cemented material is associated in all profiles with fine material (tab. 14). Soil texture in this layer is principally sandy loam to sandy clayey loam.
The average thickness in layer 2 ranges from 36 cm (prof. 1) and 80 cm in prof. 6 and 11.
Rooting system density in layer 2 is estimated as dense to very dense. Only prof. 6, 8 and 11 are characterised by low to very low density of rooting system. Soil profile 6 is situated within a degraded site with massive presence of pisolites, partly cemented in the topsoil and in the underlying horizons and consequently unfavourable to strong root penetration. The vegetation clearing around this profile may be related to the latter described soil textural conditions. Soil profile 8, is subject to intensive erosion processes, which cause loss of fine material cover at the surface. The surrounding gully area is characterised by scarce vegetation. Prof. 11 is under influence of sheet erosion. Apparently, soil sediments are transported towards the river (prof. 10).

Soil colour in layer 2 is predominated by brown (Hue 7.5YR 4/3, Hue 10YR 4/4 w, Hue 10YR 4/6 and 10YR 4/6 in prof. 1, 4, 7 and 10 respectively) to bright brown (Hue 7.5YR 5/6, Hue 7.5YR 5/8, Hue 7.5YR 5/6 in prof. 6, 8, and 11).

Following to US soil textural basis, soil texture in layer 2 is dominated by sandy loam to sandy clayey loam.

Profiles	Thickness	Colour	Rooting density	Texture	Environmental conditions/observations
1	18-36 cm	Hue 7.5YR 4/3 w* Hue 10YR 5/6 d*	very dense (w5*)	sandy loam	massive presence of coarse material principally pisolite (3 cm)
2	25-55 cm	Hue 5YR 4/4 w, Hue 10YR 4/4 d	very dense (w5)	sandy clayey loam	fine material with an dense rooting system due to the tree and grass cover
3	44-118 cm	Hue 7.5YR 3/4w, Hue 10YR 5/6 d	very dense (w5)	sandy clayey loam	fine material

4	38-63 cm	Hue 10YR 4/4 w, Hue 2.5Y6/3 d	very dense (w5)	sandy loam	fine material with iron traces
5	25-65 cm	Hue 7.5YR 3/4 w, Hue 7.5YR 4/4 d	very dense (w5)	sandy loam	proportion of coarse material 50 % and increase with depth, coarse material (20 to 20 mm diameter)
6	20-80+ cm	Hue 7.5YR 5/6	low (w2)	sandy loam	presence of cemented and/or compact pisolite (top of the laterite crust)
7	13-29 cm	Hue 10YR 4/6	very dense (w5)	sandy loam	coarse material associated with fine material
8	50-100+ cm	Hue 7.5YR 5/8	very low (w2)	clay	massive presence of pisolite (90 %) associated with fine material
9	20-40 cm	Hue 5YR 2/2 w, Hue 5YR 4/4 d	very dense (w5)	sandy clayey loam	fine material
10	25-85 cm	Hue 10YR 4/6	very dense (w5)	sandy loam	fine material
11	30-80+ cm	Hue 7.5YR 5/6	low (w2)	sandy clayey loam	cemented structure with association of fine and coarse material

Table 14: Description of physical and environmental conditions in layer 2 of Natiabouani transect.

Layer 3

Layer 3 along the Natiabouani transect is characterised by the appearance of the upper part of laterite crust and/or cemented structure with massive presence of pisolite as well as occurrence of fine material (tab. 15) particularly in prof. 2, 3, 9 and 10. These profiles are located within sites adjoining rivers, with gently slope and fine material deposited or maintained providing them an apparently stable structure (photo 13). The presence of fine material in profile exposures at rivers (prof. 10 for example) is related to the sediment deposit in the bed river in spite of the massive transport of material particularly during the rainy season (photo 15).
Soil texture in layer 3 varies from sandy clayey loam to sandy loam. The sandy texture identified in prof. 10 across the river *Tchecheri* originates from the fine material transported and deposited in the bed river (photo 15).

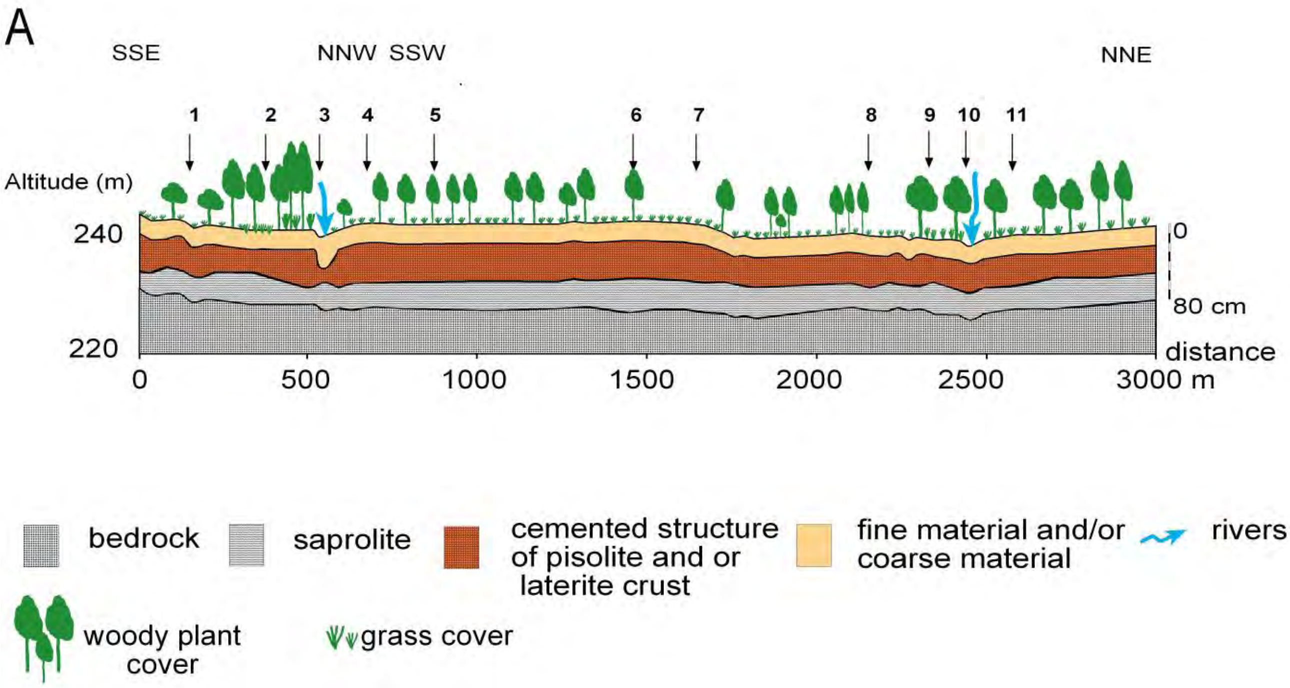
The average thickness of layer 3 varies from 36 to 118 cm. Compared to layer 3 within the land-used site of Kikideni; this layer is generally thicker because of the relative stabile conditions in the sites surrounding the rivers. These facilitate and/or maintain accumulation of fine deposits into the topsoil and the underlying layers.
Across the soil profiles chosen on proximate surfaces, where the tree cover is marginal, rooting system density within layer 3 is essentially low (w2) to very low (w1). Nevertheless, rooting density may be under influence of unfavourable textural conditions such as increase of coarse material in a cemented structure in layer 3. These conditions tend to restrict root penetration in the land-used site as well as in the protected zone.

Soil colour in layer 3 is mainly yellowish brown, bright brown (Hue 10YR 5/6, Hue 2.5YR 5/6, Hue 10YR 5/6) to dull yellowish brown.

Photo 15: Deposited fine and coarse sediments in *Tchecheri* river bed along the Natiabouani transect. Dark particles are pisolites and indicate the strong transport of materials, particularly during rainy season (photo: Anne, C. A. T., 12.06.2007).

Profiles	Thickness	Colour	Rooting density	Texture	Environmental conditions/observations
1	36-53 cm	Hue 7.5YR 5/8w* Hue 10YR 5/6 d*	very low (w1*)	sandy clay	massive presence of coarse material more than in layer 2 and cemented
2	55-80+cm	Hue 10YR 5/4w, Hue 7.5YR 4/4 d	low (w2)	sandy clayey loam	fine material with an dense rooting system due to the tree and grass cover
3	118+ cm	Hue 10 YR 5/6w, Hue 7.5YR 5/4d	very low (w1)	sandy clayey loam	thickest horizon and presence of fine material
4	63-80+cm	Hue 2.5 YR 5/6	low (w2)	sandy clayey loam	cemented structure with presence of coarse material (5 mm)
5	65-80+cm	coarse material Hue 7.5YR 5/4, fine material Hue 7.5YR 4/6	dense (w4)	sandy loam	massive coarse material (80 % of the structure) upper part of the laterite crust
7	29-80+cm	Hue7.5YR 6/4 and /.5YR 6/2	very low (w1)	sandy loam	laterite crust
9	40-80+cm	Hue 10 YR 5/3 and 6/6w, Hue 10YR 4/6 d	very low (w1)	clay loam	cemented and compact structure but with fine material and yellow or bright brown traces
10	85-170+cm	Hue 10YR 5/6	low (w2)	sand	fine material associated with coarse material (10 % of the proportion)

Table 15: Description of physical and environmental conditions in layer 3 of Natiabouani transect.



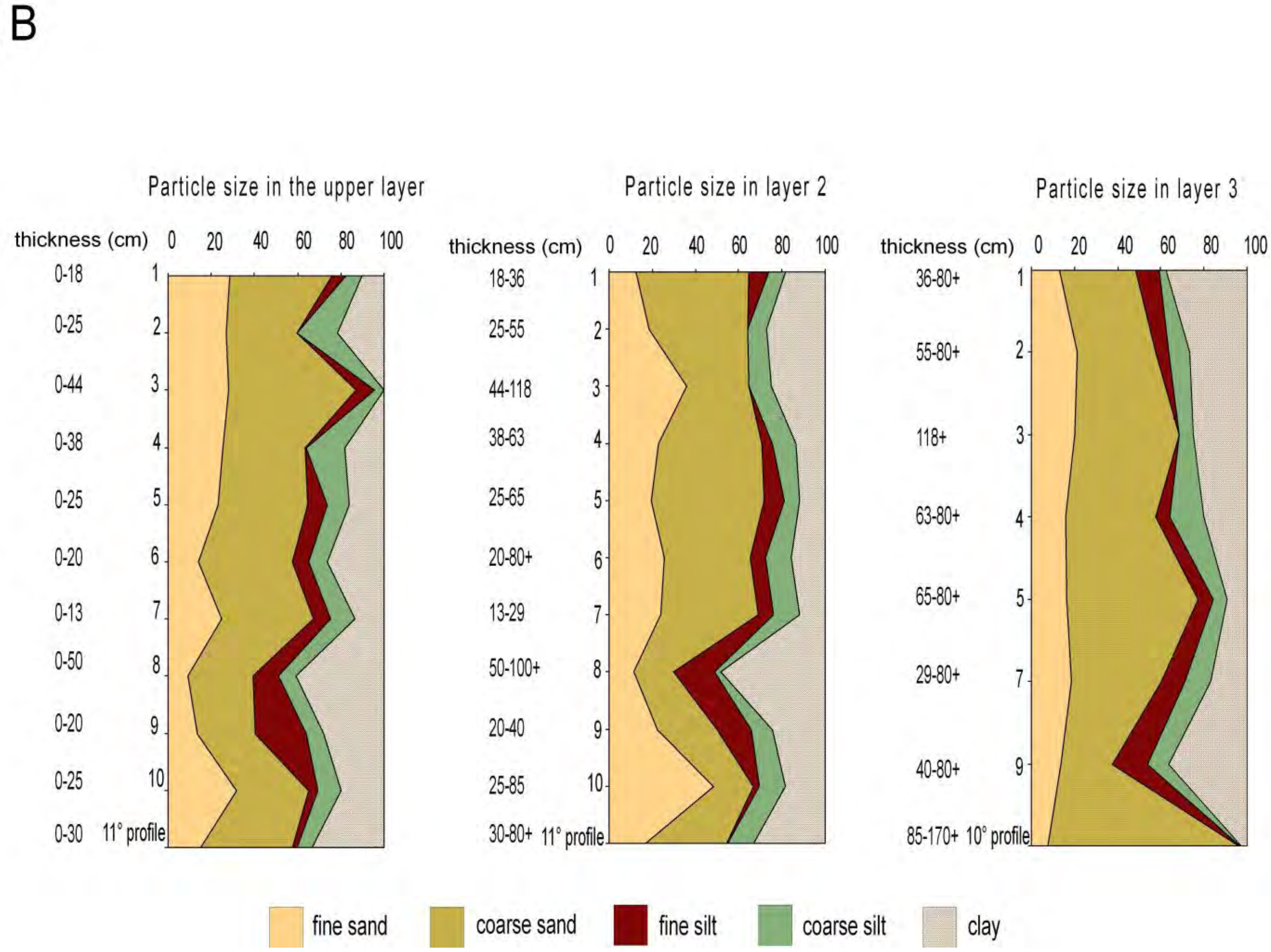


Figure 34: A) Schematical representation of transect and its different layers in the partly protected reserve of Natiabouani. B) Particle size distribution in the different layers.

Particle size distribution

PSD along the Natiabouani transect, which is surveyed following same principles as in Kikideni, completes the environmental observations and analysis of different layers, PSD´s in the different layers in Natiabouani transect are schematically represented (fig. 34 B).

PSD in the upper layer

Total sand percentage dominates particle size distribution, similar as in the upper layer of Kikideni transect. Its values range from 39 % in prof. 8 to 87 % in prof. 3 (tab. 16). According to the above upper layer description, low percentage of total sand in prof. 8 originates from the gully erosion and consequently loss of fine material in the topsoil. The highest total sand proportion in prof. 3 is related to the accumulation of fine and coarse sand at the surface and their maintenance in this layer advantaged by the gently slope and relative density of grass and tree cover (photo 13). Highest fine sand portion characterises profile exposures at the two main rivers along the transect.

Total silt fraction varies from 12.5 % in prof. 3 to 58 % in prof. 11. Coarse silt is in all profiles higher than fine silt. The percentage of fine silt in prof. 2 and 4 are very low. The amounts of clay fraction vary from 42 % at the clay texture of prof. 8 to 0.25 % at the sandy structure of prof. 3. The upper layer of prof. 8 may be part of the subsoil, which is identified as a horizon with enrichment of clay. The upper soil layer is apparently eroded.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	18 cm	28	47.5	75.5	7	7.5	14.5	10
2	25 cm	27	32.5	59.50	0.25	19	19	21
3	44 cm	28	59	87	8.5	4	12.5	0.25
4	38 cm	25	38	63	0.5	18	18.5	18
5	25 cm	23	41	64	9	10.5	19.5	16
6	20 cm	14	44	58	7	8.5	15.5	26.5
7	13 cm	24.5	42	67	8	12	20	13
8	50 cm	9	30	39	12	8	19.5	41
9	20 cm	13	27	40	23	8	31.5	28
10	25 cm	31.5	33.5	65	4	10.5	15	20
11	30 cm	15	43	58	15	43	58	33

Table 16: Particle size distributions in the upper layer of soil profiles along Natiabouani transect.

PSD in layer 2

As in the upper layer, lowest amount of total sand is measured in profile 8, under influence of gully erosion. Nearly in all soil profiles total sand fraction lies above 50 % as in the upper layer (fig. 35 B). Coarse sand percentages are higher than fine sand in all the profiles. Coarse silt amounts are higher than fine silt and the highest values are measured in prof. 11. The sandy clayey loam and sand textures of prof. 2 and 3 are characterised by the absence of fine silt particles in layer 2.

In the majority of profiles (7) along the Natiabouani transect clay percentages decrease from the upper layer to layer 2. This trend is in contrast to the increase of clay contents from the upper layer to layer 2, which is observable along the transect in the land-used site. Nevertheless, an increase of clay mineral is noticeable in prof. 1, 2, 3, and 8. Prof. 1, 3 and 8 can be considered as sites situated in well drained locations and relative gently slopes are measured within these sites (see tab. 13).

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	18-36 cm	13	52	64.5	9.5	7.5	17	18.5
2	25-55 cm	18.5	46	64	0.00	9	9	27
3	44-118 cm	36	29	64.5	0.00	10.5	10.5	25
4	38-63 cm	23	48	71	5	11	16	13.5
5	25-65 cm	20	52	72	9	7.5	16.5	12
6	20-80+ cm	25.5	39.5	65	7	12	19	16
7	13-29 cm	24	45.5	69	7	12	19	12
8	50100+cm	11	19	30	19	3	22	48
9	20-40 cm	22.5	28	50	15	10	25.5	24
10	25-85 cm	48.5	18	67	3	12	20	18
11	30-80+ cm	17	37	54	17	37	54	33

Table 17: Particle size distributions in layer 2 of soil profiles along Natiabouani transect.

PSD in layer 3

The high total sand content in layer 3 (prof. 10 for example) is a confirmation of the importance of sediment accumulation as mentioned and illustrated above (photo 14). Total sand variation from layer 2 to layer 3 reveals no recognisable trend of increase or decrease with the depth.
Coarse sand proportions are higher than fine sand contents in layer 3, compared to other layers. The layered horizons in profile 10 show that percentage of coarse sand fraction grows with the depth in the bed river.
The variations of total silt show a decrease from layer 2 to layer 3, within profiles with favourable drainage conditions (prof. 1, 3 and 10). The variation of coarse silt compared to fine silt shows no obvious trend of decrease or increase.

From the upper layer to layer 3 clay contents increase in 8 of the 11 profiles where layer 3 could be identified and surveyed (prof. 1, 2, 3, 4, 7, 9). Prof. 10, with important sand proportion reveals a drastic diminution of clay content (from 33 % in the upper layer to 2.5 % in layer 3)

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	36-53 cm	13	35	48	11.	3	14	37.5

2	55-80+cm	21	36.5	58	6	10	16	27
3	118+ cm	20	48	68	0.25	6.5	7	25
4	63-80+cm	16	42	57.5	6.5	16	21.5	20
5	65-80+cm	16	61	77	7	6.5	13.5	9.5
7	29-80+cm	18.5	41.5	60	11	12	23	17
9	40-80+cm	13.5	24	38	16	10	26	36
10	85-170+cm	8	88.5	96	0.75	0.5	1.25	2.5

Table 18: Particle size distributions in layer 3 of soil profiles along Natiabouani transect.

Chemical properties along the Natiabouani transect

This analysis occurs in consideration of the different layers identified and described above in a first level and in a second in relation to the different profiles (see 5.4.2.2). Chemical parameter variations are schematically presented following the different layers (fig. 35).

PH, organic matter and nutrients in the upper layer

PH in soils are analysed in a partly protected site, which are different from those prevailing in the land-used conditions. PH (KCL) in the upper layer of profiles along the Natiabouani transect show a lowest value (4.5) in prof. 4 within the BO characterised by indices of anthropogenic influences in former times (laterite crust of the surrounding site was apparently used for road construction and thereby accelerating lateral transport). Highest pH (KCL) is measured in prof. 5, located within a plateau unit with stony structure on the surface and relative good vegetation cover. PH (H_2O) values are higher than those of pH (KCL) in all profiles. PH (KCL) values within the upper layer show that soils are slightly acid to moderate acid ($6.0 \leq$ pH (KCL) ≤ 5.0). Profiles, which can be characterised as strongly acid with pH (KCL) ≤ 5.0, are situated in sites with strong erosion processes
Compared to the values measured in the land-used site, pH (KCL) in this layer are generally higher.

The very low SOM content in prof. 8 is related to the gully erosion conditions and the instable properties of the site, characterised by transport of fine material from soil surface. Relative high organic matter value in prof. 9 (4 %) derives from the temporary inundated conditions combined with the gently slope (0°) of the site and the relative density of grass and tree cover. In all other profiles SOM contents can be considered as very low (1 % $\leq$ SOM $\leq$ 2).

The highest C/N characterises a site with low vegetation cover and apparently important sheet erosion processes (prof. 4). C/N ratios do not confirm the average C/N relationships of 15 in savanna landscapes measured under similar climatic conditions (mean annual rainfall 1000 mm/year) in south west of BF. The majority of soil profiles along the Natiabouani transect have C/N values higher than 20.

The N values in the top soil confirm partly the relationship C/N because lowest N contents are measured in profiles with very high of C/N ratios (prof. 3 and 4). A comparison of N and SOM contents shows like in the top layer in the Kikideni site, that highest SOM are measured at sites with highest total N. Nevertheless, total N values within the partly protected site are generally higher but can be classified as very low according to the interpretation of soil N content after KJELDAHL method (METSON 1961).

According to the soil phosphorus interpretation (LANDON 1991) available P amounts can be considered as marginal ($6.5 \leq$ available $P \leq 13$) to deficient ($3 \leq$ available $P \leq 6.5$). The highest total P content in the upper layer is measured in prof. 9 (332 ppm) and in prof. 5 (248.5 ppm) while the lowest total P value (68).
The available K amounts can be considered as medium to low following studies under similar conditions undertaken in Malawi (YOUNG et al. 1977). All profiles have available K values < 0.5 meq/100 g.
The sites with highest CEC values (prof. 5 for example) are those where highest pH (KCL) and SOM amounts are measured (fig. 36). A relationship between CEC on the one hand and pH (KCL) and SOM on the other hand can be established (CALVET 2003). Profiles with low CEC amounts ($6 \leq CEC \leq 12$) are, according to HAZELTON et al. (2007) characterised by the degradation of the surface through gully erosion (prof. 1) or by sheet erosion (prof. 6 and 11). The CEC values within the protected site are generally higher and more variable than those within the land-used area.

PH, organic matter and nutrients in the layer 2 and 3

pH (KCL) values in layer 2 along the transect vary from 4.5 under acid conditions in prof. 4 to 7.5 under neutral conditions in prof. 8. In layer 3, pH (KCL) measurements show values comprised between 4 (prof. 3) and 7 in prof. 2. As in the upper layer, lowest pH (KCL) values in layer 2 are measured at sites with evident traces of degradation of the soil surface through sheet erosion (prof. 11) and/or through anthropogenic factors (prof. 4) while in layer 3 lowest values are measured at profile exposures. PH (H_2O) values are higher than pH (KCL) values in all profiles as in the upper layer.

The very low SOM content in temporary inundated site (prof. 9 with 1 %) stands out against the organic matter content in the upper layer (4 %) and indicates a concentration of organic matter at the surface and an insignificant vertical migration of organic matter under hydromorphic conditions.
SOM contents layer 3can be classified as very low in all profiles. From the upper to layer 2, SOM contents decrease except in profiles located in the gullies (prof. 1and 8) and profile exposure at the river with good drainage conditions (prof. 3). Compared to layer 2, within the land-used site, SOM contents in layer 2 in Natiabouani are noticeable higher. Its values decrease from layer 2 to layer 3 except in prof. 9, where an increase can be observed.

An increase of C/N ratios from the topsoil to the underlying layer 2 can be noticed in the latter profiles, while C/N ratios decrease generally from layer 2 to layer 3. C/N ratios in layer 3 are generally very high, indicating a low decomposition of organic matter. Only prof. 9, where C/N ratio of 16.5 is estimated, shows nearly ideal conditions for a good rate of organic matter decomposition.

Total N values decrease generally from the topsoil to the underlying layers.
Available P contents in layer 2 and 3 can be classified as deficient (3 ≤ available P ≤ 6.5 ppm) to marginal (6.5 ≤ available P ≤ 13) and they decrease from the top soil to the underlying layers.
Total P proportions like available P tend to decrease from the upper to the following layers.
The values of available K can be considered as medium to low (YOUNG et al. 1977). There is no recognisable trend of decrease or increase of available K contents from the upper to the underlying layers.
CEC values in layer 2 and 3 are generally very low (CEC≤ 5 meq/100 g) to low (5 ≤ CEC ≤ 15) and indicate presence of few nutrient stocks and are characteristic for the kaolinitic clay type similar as in Kikideni. There is no trend in the variation of CEC contents from the upper to the underlying layers.

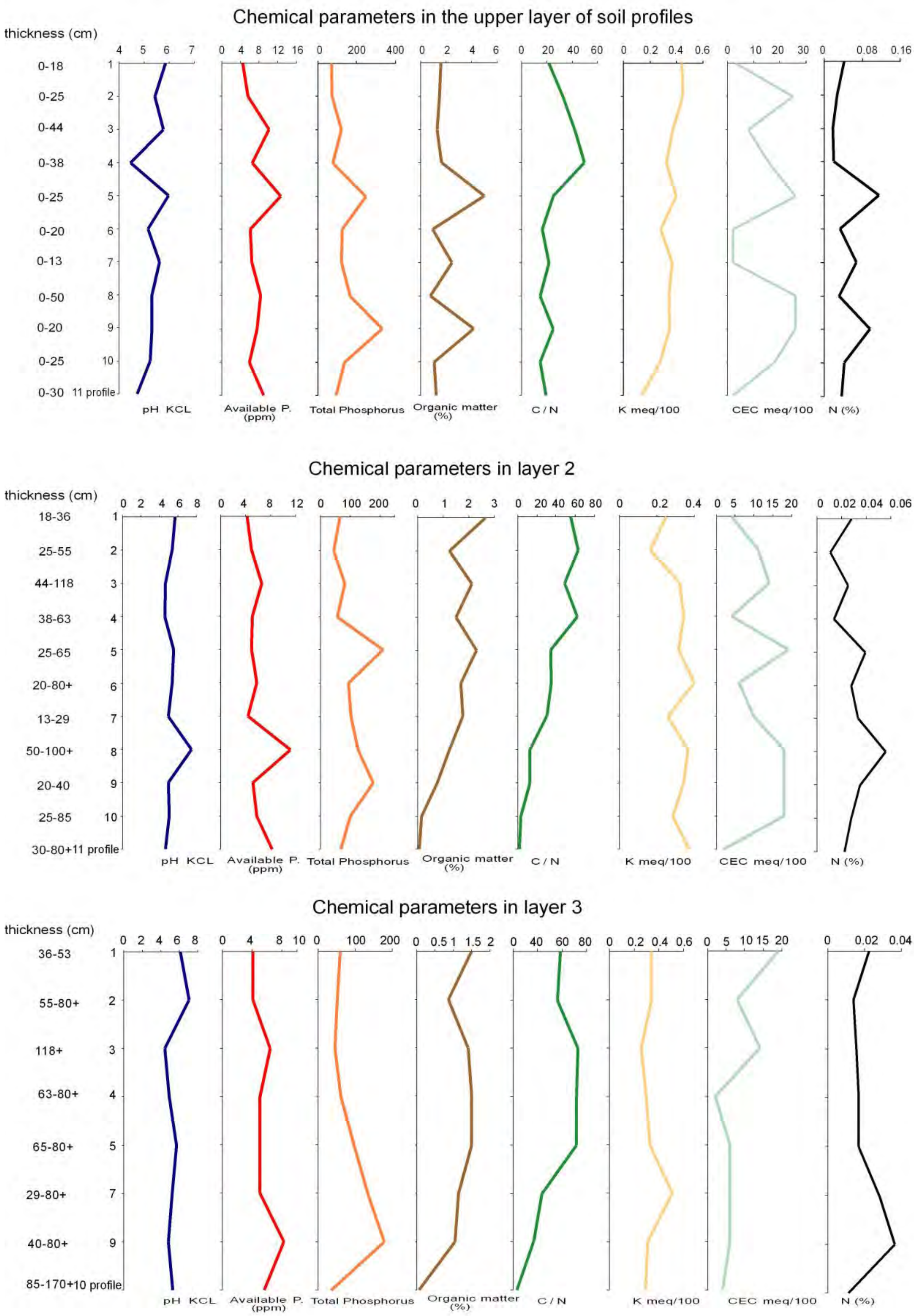


Figure 35: Variations of chemical parameters in the different layers of transect within the partly protected reserve of Natiabouani (North West BN).

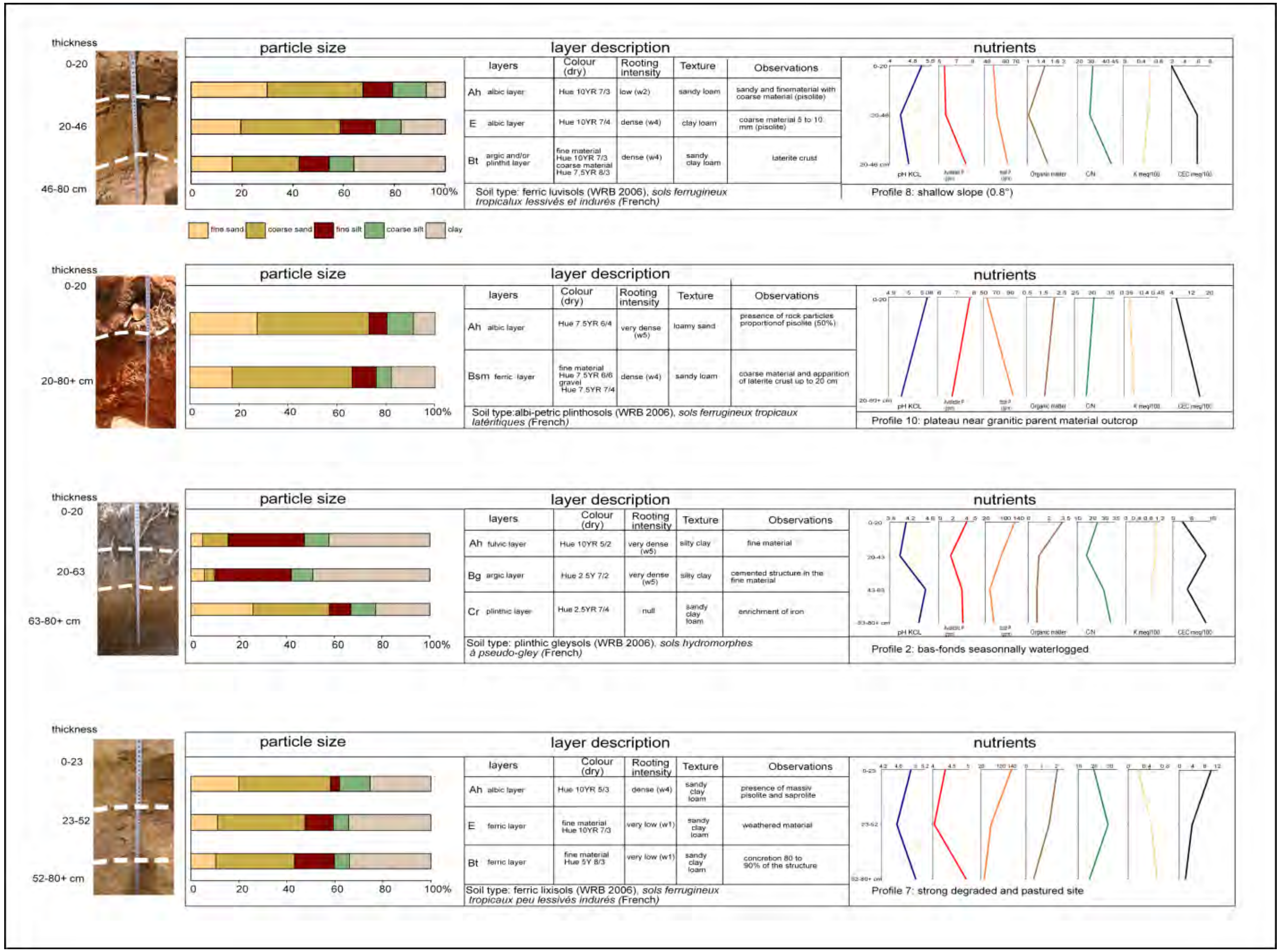


Figure 36: Samples of soil types according to the world reference base for soil resources (WRB 2006), physical chemical properties and environmental parameters in the partly protected site of Natiabouani.

5.2. Physical and chemical properties of soils in Pendjari National Park (PNP)

5.2.1. Transect and soil profiles in the Hunting zone (HZ)

The HZ or *zone cynergétique* as an ecological entity adjoining the PNP is partly under influence of anthropogenic activities. Around the localities of Batia, Koualegou, Porga etc. in North West BN (fig. 15) and the surrounding areas farming is widespread with yam, manioc and cotton crops. The hunting activities are carried out mainly by tourists and partly by local population for their own needs. The BIOTA-BO as common plot for data surveying are chosen essentially in fragments of the HZ where agricultural activities are absent providing them in fact a total protected site status. Nevertheless, illegal pasture activities could be observed during the field works. The National Park management team uses “controlled fire” for achieving primary goal of clearing grass and tree cover to increase wildlife visibility for tourists and secondary for enhancing the biodiversity in these ecosystems. Indeed, fire management may stimulate the regeneration of tree and grass species as observed in the HZ and in the PNP (photo 16).

Photo 16: View of a site within the HZ (BO 3) of National park Pendjari, influence of fire with wood coal residues as well as regeneration of grass and newly growing tree species can be observed. (Anne, C. A. T., 02.06.05).

The transect in the HZ 3 is chosen as representative sample of the BO, which are principally located near earth roads (photo 17) and do not take into account the given relief structural conditions but only vegetation communities. Relief around transect is characterised by the presence of relative steep hills and gently slopes.
8 soil profiles are surveyed along in the *zone cynergétique* 3. Similarly to the transects in South East BF, Particle-size distribution as well as chemical properties are analysed following the different layers. Environmental conditions are described previously.

Photo 17: View of a BIOTA Biodiversity Observatory adjoining the earth road within the HZ of the PNP North West BN (photo: Anne, C. A. T., 17.06.07).

Upper layer

The upper layer of the HZ transect is characterised by the massive presence of gravels and particles of bedrock on the most part of the soil surface. The HZ is dominated geomorphologically by peneplains (glacis) from the Volta Basin and depressions (see 3.2) overlying Ordovician sedimentary formations with argillaceous schist facies and pre-Cambrian metamorphic formations. The latter formations, which include the *Buem* and *Atakora* units, are found along transect in form of gravels, blocks and fragments, which are deeply iron weathered. Extracted particles in the upper layer are identified as quartz schists, folded with a visible schistosity and an argillaceous substratum as well as deeply weathered quartzite and quartz sandstones (photo 18). Outcrop of bedrock is observed mostly at hills adjoining the valleys and/or depressions in prof. 1, 6 and 7. Similarly, profiles situated on plateau units are characterised partly by outcrop of bedrock and presence of blocks from the bedrock like in prof. 5. Slopes are relative steep in some hills along the transect (tab. 19). Hill units at the beginning of the transect adjoining prof. 1 reveals a slope degree of + 15° as well as the highest hill unit adjoining the valley in prof. 8 (fig. 37 A). Slope values and variations along the HZ transect are more accentuated than those measured in the Natiabouani transect. Geological, geomorphological as well as pedological processes (weathering, lateral transport of sediments etc.) in North West BN with the *Atakora* chains and the presence of *Buem* formations and their relicts play an important role in this differentiation.
The measured thickness of this layer is approximately 15 cm in almost all soil profiles.
Traces of anthropogenic activities mainly through fire management can be observed along all profiles of the transect and surrounding sites within the HZ. Rooting system density varies from dense to very dense. Profiles in the valley (prof.2) reveal a dense grass and tree cover in spite of the gravelous structure of topsoil. But generally, tree and grass cover are relatively dense within all relief units including gently slopes of gravelous hill and plateaus units.
Dark brown (prof. 1, 3, 5, 6) and brown (prof. 4, 7) are the dominant soil colour. Soil texture is dominated by sandy loam (prof. 1, 3, 4, 5, 6 and 7) and loam (prof. 2 and 8). The profiles with loamy texture are situated in valleys.



Photo 18: Blocks and fragments from the bedrock within hill adjoining profile 1. Rock sample (right down) is weathered quartz and right top quartzite with deep iron weathering (Anne, C. A. T., 21.06.2007).

Profiles	Thickness	Colour	Rooting density	Inclination (degree)	Texture	Environmental conditions/observations
1	0-15 cm	Hue 7,5 YR 3/4 w*,7.5YR 4/4 d*	dense (w4*)	-15°	sandy loam	profile within valley adjoining a mound with relative steep slope (-15°), presence of fine material, fire traces
2	0-15 cm	Hue 5YR 4/3w, Hue 2,5 3/2d	very dense (w5)	-0.5°	loam	section within temporary flooded plain , massive fine material presence
3	0-15 cm	Hue 7,5 YR 3/4	very dense (w5)	+1°	sandy loam	site near Biota Hectare plot, termite mounds, pisolite at surface, fire effects: clearan-ce of vegetation
4	0-15 cm	Hue 10 YR 4/6	dense (w4)	-1°	sandy loam	profile near termite mound, slightly slope adjoining small depression, presence of coarse particle from bedrock identified as quartz grains, fire traces
5	0-15 cm	Hue 10 YR 3/3	very dense (w5)	+2°	sandy loam	plateau unit with stony structure, outcrop of altered bedrock, good vegetation cover, massive presence of plant seeds at the surface, fire traces
6	0-30 cm	Hue 10 YR 3/4	very dense (w5)	-4°	sandy loam	valley following plateau unit, gravelous structure, newly growing tree
7	0-15 cm	Hue 10 YR 4/4	dense (w4)	-4.5°	sandy loam	section between 2 hills, blocks of granitic material with traces of ferric alteration, fire traces

8	0-13 cm	Hue 5YR 2/4w, Hue 10 YR 2/3d	very dense (w2)	0°	loam	plain adjoining a relative steep hill (+16° inclination), shrub savanna less dense than other sites, dense grass cover

Table 19: Description of physical and environmental conditions at the surface and in the upper layer of transect in the hinting zone of PNP (*w: colour wet sample, *d: colour dry sample); rooting system density based on German Soil Science Mapping Manual (*Bodenkundliche Kartieranleitung*, 2005).

Layer 2

Underlying layer 2 is characterised by enrichment of coarse material presence mostly pisolites and/or debris from bedrock with proportion of more than 50 % of the whole structure in all profiles. Soil structure is in the majority partly cemented or cemented.
The average thickness ranges from 15 cm in almost all profiles to 68 cm in prof. 5. Rooting system density is very dense compared to layer 2 within the partly protected transect of Natiabouani. Soil colour is dominated by brown (Hue 7.5YR 4/4) in prof. 1, 2, 3 and 4) and yellowish brown or dull yellowish brown (respectively Hue 10 YR 5/6 in prof. 6 and Hue 10YR 5/4 in prof. 7). Coarse material e.g. pisolites are reddish brown (Hue 5YR4/8) to bright reddish brown (Hue 5YR 5/8) coloured, while fine material combined with pisolites, indicating iron influences, shows brown to dull orange colours.
Soil texture varies from sandy loam (prof. 1, 5) to sandy clayey loam (prof. 3, 6, and 7). This loamy soil texture was not present in any profile and layer along transects in South East BF.

Profiles	Thickness (upper layer)	Colour	Rooting density	Texture	Environmental conditions/observations
1	15-49 cm	Hue 7.5YR 5/8w* Hue 10YR 6/6d*	very dense (w5*)	sandy loam	more coarse material, residues of bedrock (size= 4 cm), partly cemented structure
2	15-34 cm	Hue 7.5YR 4/4w. Hue 2.5YR 5/4d	very dense (w5)	clay loam	enrichment of coarse material (70 % structure) pisolite or part of laterite crust
3	15-30 cm	Hue 7.5YR 4/4w Hue 7.5YR 4/6d	very dense (w5)	sandy clay loam	enrichment of coarse material (50 % of structure) more pisolite proportion
4	15-55 cm	Hue 10 YR 6/6	very dense (w4)	loam	presence of thick roots in the layer good grass and tree on surface
5	15-68 cm	coarse material Hue 5YR 5/8 and Hue 5 YR 7/3. fine material Hue 5YR 6/3	very dense (w5)	sandy loam	enrichment of coarse material (70 % of structure)
6	30-55 cm	Hue 10 YR 5/6	dense (w4)	sandy clay loam	cemented structure, relicts of altered bedrock
7	15-34 cm	Hue 10YR 5/4	dense (w4)	sandy clay loam	cemented structure
8	13-47 cm	coarse material Hue 5YR 4/8 Fine material	very dense (w2)	clay loam	upper part of laterite crust,

		Hue 7.5YR 4/6			

Table 20: Description of physical and environmental conditions in layer 2 of the HZ transect.

Layer 3

An upper part of a laterite crust as well as partly cemented structures dominate in this layer. These particles may derive from the outcrop bedrock at relative steep hill adjoining this profile through hill wash. The average thickness varies from 30 cm in prof. 3 to 80 cm in almost all soil profiles. Soil colour is red to orange (Hue 10R 4/8and Hue 7.5YR 5/6) by the pisolites and yellowish, bright yellowish brown and dull yellow orange by the fine material. Soil texture is marked by clay enrichment with clay soil texture (prof. 2, 3 and 8) to clay loam (pro.1 and prof. 6). The clayey texture characterises mainly profiles situated in valleys. In prof. 4 the loamy texture doesn't change from the topsoil to the underlying layers.

Profiles	Thickness	Colour	Rooting density	Texture	Environmental conditions/observations
1	49-80+ cm	coarse material Hue 10R 4/8. Hue 7.5YR 8/4	low (w2*)	clay loam	more coarse material, weathered residues of bedrock (quartzite),cemented structure, laterite crust
2	34-80+ cm	coarse material Hue 7.5YR 5/6 fine material Hue 10YR 5/6.	low (w2)	clay	Part of the laterite crust, cemented structure
3	30-80+cm	coarse material Hue 7.5YR 7/6 fine material Hue 7.5YR 6/6	dense (w4)	clay	enrichment of coarse material 80 %), cemented structure
4	55-50+ cm	fine material Hue 10YR 7/4	very low (w1)	loam	enrichment of coarse material (80 % pisolites), cemented structure
5	68-80+ cm	coarse material Hue 7.5YR 7/6 fine material Hue5YR6/4	very low (1)	sandy loam	weathered coarse material (50 % of structure), cemented structure
6	55-80+ cm	Hue 10YR 6/6	low (w2)	clay loam	enrichment of coarse material (90 %), cemented structure
7	34-80+cm	coarse material Hue 5YR 3/62/2 fine material Hue 7.5YR 5/6	very low (w1)	clay	laterite crust, compact structure
8	47-80+ cm	Hue 10YR 5/6	very low (w1)	clay loam	enrichment of coarse material, laterite crust

Table 21: Description of physical and environmental conditions in layer 3 of the HZ transect.

The following simplified transect illustration doesn´t take into account the local differentiation and the complexity of variation according to the environmental and pedological processes

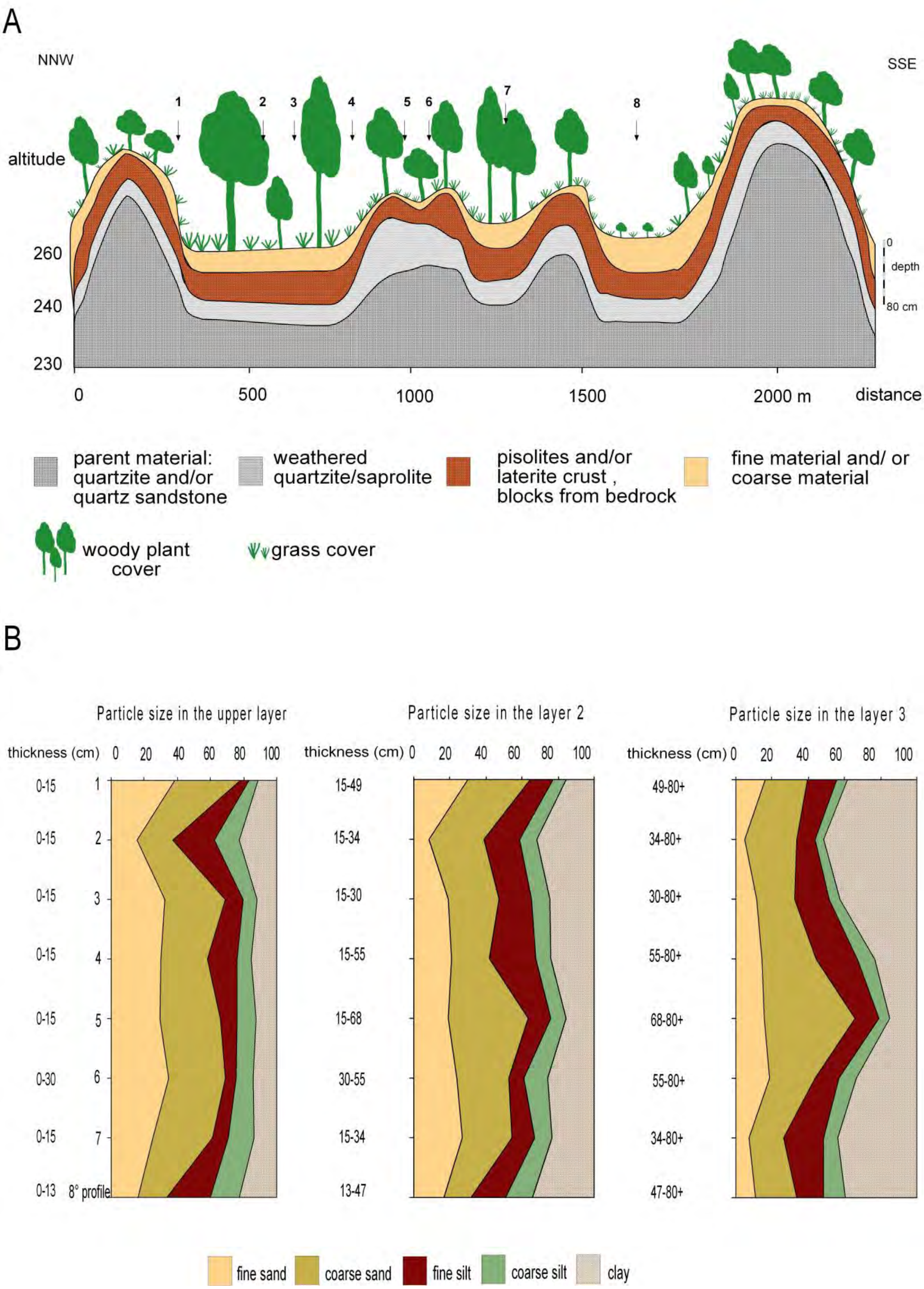


Figure 37: A) Schematical representation of the transect and its different layers in the HZ of PNP. B) Particle-size distribution in the different layers.

Particle-size distribution (PSD)

PSD following the different layers are schematically represented (fig. 37-B).

PSD in the upper layer

Proportions of total sand are principally greater than 50 % in the profiles (tab. 22). Sites where total sand content ≤ 50 % are temporary inundated valley (prof. 2 with 37 %) and plain (prof. 8) adjoining the steepest hill. High total sand content in prof. 1 may be related to lateral transport of sand from the steep slope, which is characterised by the presence of blocks and fragments from the bedrock (photo 18). Normally, the same situation might be expected in prof. 8. But it is conceivable that transport of sand particles towards valley is inhibited by dense grass and tree cover on the slope (photo 19). Coarse sand proportion is higher than fine sand in 6 of 8 profiles. In contrast to the above analysed transects within Natiabouani and Kikideni, fine silt proportions are higher than coarse silt in 5 of the 8 profiles in the HZ transect. The highest clay fractions are measured in profiles located in valleys.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	0-15 cm	38.5	39	77.5	6	5	11	11.5
2	0-15 cm	16	21.5	37.5	25	15.5	40.5	22.5
3	0-15 cm	32	36.5	69	11	8	19	12
4	0-15 cm	30	28	58	18	8	26	16
5	0-15 cm	30	36	66	10	12	22	12.5
6	0-30 cm	34.5	34	69	7	10	17	14
7	0-15 cm	25.5	35.5	61	10	15.5	25.5	14
8	0-13 cm	16	17	33.5	26.5	17	44	23

Table 22: Particle size distributions in the upper layer of soil profiles along the HZ transect.

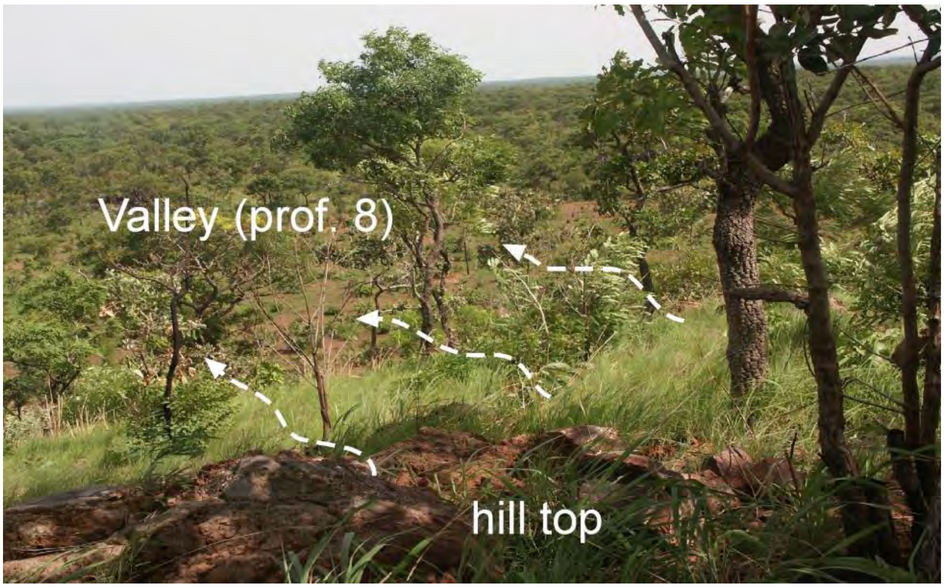


Photo 19: View from steep hill unit adjoining soil prof. 8. Grass, tree cover and fragments of bedrock on the slope (foreground) might inhibit fine material transport to the valley (photo: Anne, C. A. T., 21.06.2007).

PSD in layer 2

Fraction of total sand is higher than 50 % in only 4 of the 8 profiles. The variations of total sand proportion from the upper layer to layer 2 show a decrease in nearby all soil profiles. In 5 of the 8 profiles coarse sand fraction is higher than fine sand.
Fine silt fractions in layer 2 are generally higher than coarse silt fractions.
An increase of clay proportion from the upper layer to layer 2 can be observed in all profiles. Similar as in layer 1, profiles located within valleys have the highest clay contents.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	15-49 cm	30	35	65	12.5	7	19.5	16
2	15-34 cm	8.5	30	39	20	9.5	29	32
3	15-30 cm	19.5	28	47.5	18	10.5	28.5	24.5
4	15-55 cm	21	21	42	23	8	34	24
5	15- 68cm	19	44.5	63.5	12	8	20.5	16
6	30-55 cm	23.5	29	52.5	8	13	21	26
7	15-34 cm	27	27.5	54.5	13	9.5	22.5	23
8	13-67 cm	17	15	32	19	15	34	34

Table 23: Particle-size distributions in layer 2 of soil profiles along HZ transect.

PSD in layer 3

As in layer 2 proportion of total sand is higher than 50 % in 4 of 8 profiles. Coarse sand fraction is higher than fine sand in all profiles. Similarly to layer 2 fine silt fractions are higher than coarse silt. An increase of clay proportion from the upper to layer 3 can be clearly observed. Profiles located within depressions (2 and 8) contain more clay.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine Silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	49-80+ cm	16	23.5	40	16	6	2	38.5
2	34-80+ cm	5	28.5	33.5	10	5	15	51
3	30-80+ cm	11	21	32.5	19	6.5	25	42
4	55-80+ cm	14.5	30	44	23	9.5	32	23.5
5	68-80+ cm	15.5	50.5	66	13	6	19	15
6	55-80+ cm	19	25	44	13	10	23	33
7	34-80+ cm	7.36	19	26.5	22	7.5	29.5	44
8	67-80+ cm	10.5	22.5	33	15	12	27	39.5

Table 24: Particle-size distributions in layer 3 of soil profiles along the HZ transect.

Chemical properties along transect within the HZ of PNP

Comparable to the South East BF transects, chemical parameters are analysed within transect in the HZ of PNP in North West BN. Anthropogenic factors are at this site reduced to fire management strategies. The influence of fire as well as accentuated relief units may act on the variations of chemical parameters in the different layers.

PH, organic matter and nutrients in the upper layer

Compared to pH (KCL) values in upper layer of Natiabouani transect, average amounts of pH (KCL) within the HZ are higher and can be considered as slightly acid ($6.0 \leq$ pH (KCL) ≤ 5.0) to neutral (pH (KCL) = 7). High pH (KCL) are measured in the near of termite mounds in the upper layer of the HZ transect as well as within the Natiabouani transect in (prof. 7 see above). SOM values can be considered generally as low ($2 \leq$ SOM ≤ 3).
C/N values are higher than 20 in profiles, which are located in valleys or depressions (prof. 6, 7 and 8). As in the transect within the partly protected site of Natiabouani, SOM contents may be related to the amount of total N. Profiles with highest organic matter content show highest total N contents.
Available P for plant up-take can be considered as deficient ($3 \leq$ Available P≤ 6.5).
Apart of prof. 2 all other soil profiles have available K contents ≤ 0.5 meq/100 g and can be considered as medium to low. Soil profiles with the highest total P and available K contents show highest CEC contents. Variation of CEC contents reveals essentially the presence of kaolinite as clay type (CEC ≤ 10 meq/100 g).

PH, organic matter and nutrients in layer 2 and 3

PH (KCL) amounts decrease from upper to layer 2 in all profiles, while a decrease from layer 2 to layer 3 in prof. 1, 2, 3, 4 and an increase in the remaining profiles can be observed. Interpretation of pH (KCL) in layer 2 and 3 shows that the majority of soil profiles characterised by an enrichment of coarse material proportion and partly cemented structure can be considered as slightly acid ($6.0 \leq$ pH (KCL) ≤ 5.0).
From the topsoil to the underlying layers, organic matter contents decrease and can be considered as very low along the HZ transect.
The majority of soil profiles (5) have C/N ratios higher than 20 and indicate a low decomposition of organic matter. Total N amounts decrease generally from the soil surface to the underlying layers.
Available P values in layer 2 and 3 can be considered as deficient ($3 \leq$ available P ≤ 6.5) to marginal ($6.5 \leq$ available P ≤ 13). The contents decrease from topsoil to the underlying layers in 6 soil profiles. However, an increase of available P is observed in soil profiles located in inundated valley (prof.2) and depression (prof. 8).
Available K decreases generally from layer 1 to layer 2 and increase from layer 2 to layer 3 in 5 of the 8 profiles. There is no recognisable trend of variation with depth in consideration to specific environmental conditions.
CEC amounts in layer 2 and 3 indicate a predominance of kaolinite as clay type. The variation of CEC amounts from the topsoil to the underlying layers shows no trend of decrease with the depth.

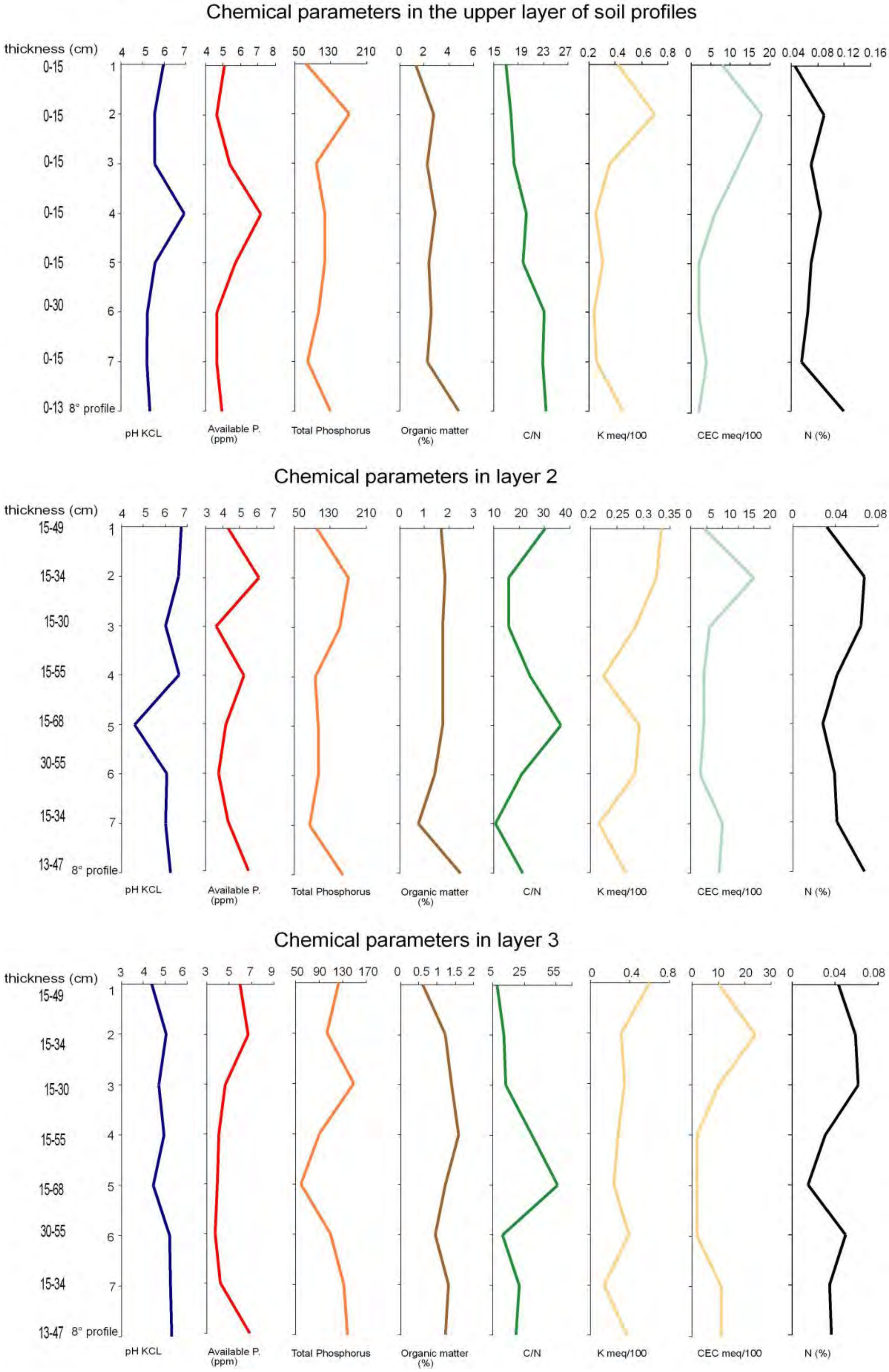


Figure 38: Variation of chemical parameters in the different soil profiles along the HZ transect of PNP.

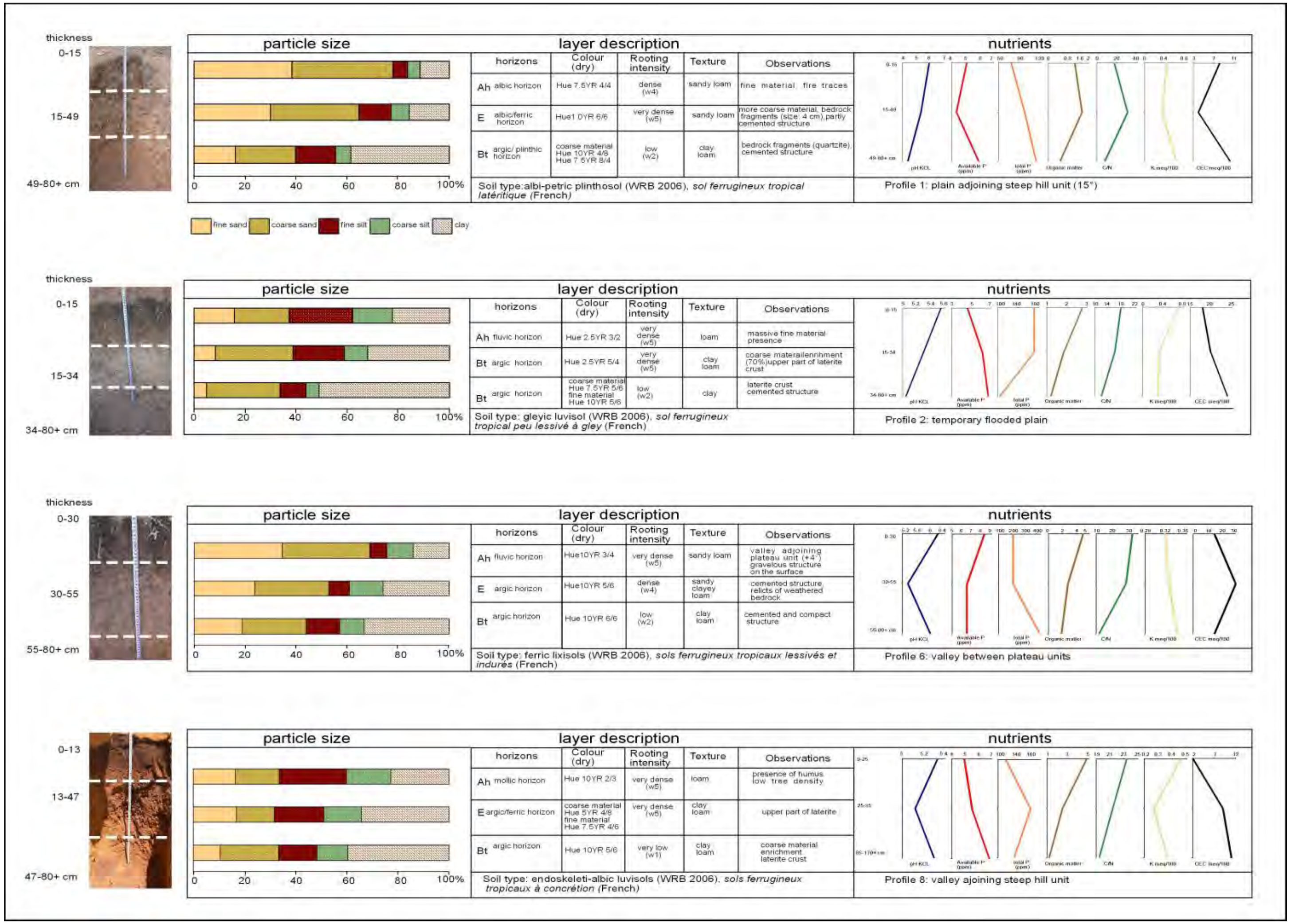


Figure 39: Samples of soil types according to the world reference base for soil resources (WRB 2006), physical, chemical and environmental parameters in the hunting zone of the PNP.

5.2.2. Transect sequences and soil profiles in PNP

5 transects are surveyed within the PNP. Pedomorphological transects take into account different relief units and are partly located in BO, where botanical and zoological studies have being gathered. 1 transect is analysed *in extenso* in this chapter. The chosen transects involve different relief units (peneplains, valleys and hills) and reflect the lateral transport of soil materials and particles as well as different vegetation communities.

Transect in the central zone of PNP

8 soil profiles are identified and analysed along a 1700 m long transect. Anthropogenic activities are limited to fire management tools with "controlled fire" for regeneration of tree and grass cover. Wild fauna population is very dense and diverse with amphibians, bats, carnivores (cheetah, lion, hyena, etc.), mammals (elephants, hippopotamus etc.). Traces of elephants are observable on the soil surface in parts of the transect.

Upper layer

Transect within PNP stretches from a steep hill at the border of the Atakora chain to the main earth road through the Park. The upper layer is characterised by a large peneplain where fine material at the surface dominates in the majority of soil profiles (fig.40 A). Apart of the hill unit, outcrop of bedrock is observed, under the thin layer of prof. 1 with 10 cm and prof. 2 with 25 cm thickness (photo 20). Hill units at the beginning of the transect are characterised by a relative steep slope with a slope degrees between 25 to 30°. Slope degrees are gentle (around 0°) in almost all profiles (tab. 25).
The monotony of relief along may let believe that soil parameters from prof. 3 to prof. 8 are similar. In opposition to the upper layer of HZ transect, the upper layer of the transect is characterised by the predominance of fine material partly associated with pisolites. Blocks from the weathered bedrock or gravels are visible in profiles adjoining the steep hill units (photo. 20). Nevertheless, the analysis of the transects in PNP provides basis for comparison of soil properties and dynamic of the lateral transport of sediments in the HZ and in PNP.
The average thickness in the upper layer is around 14 cm and nearby similar to those measured in the HZ transect.
Rooting system density is essentially dense to very dense. Tree and vegetation cover are less dense than within the HZ. The vegetation is identified as tree savanna with species as *Acacia seyal*, *Acacia gourmaensis*, *Combretum glutinosum* and *Terminalia avicennoides*.
The prevailing textures are different to those identified in the HZ transect of PNP as well as in the South East BF transects (Natiabouani and Kikideni). In the latter transects sandy loam soil texture is widespread.
Soil colour in the upper layer of the transect is predominated by dark brown (Hue 10YR 3/3) in prof. 2, 3, 6 and 8 to greyish yellow brown (Hue 10YR 4/2) in prof. 4, 5 and 7. The dullish reddish brown in the thin upper layer of prof. 1 may be related to the direct underlying and partly weathered laterite crust and/or iron weathered bedrock.

Profiles	Thickness	Colour	Rooting density	Inclination (degree)	Texture	Environmental conditions/observations
1	0-10 cm	Hue 5YR 4/4	dense (w4*)	-10°	loam	plain adjoining steep hill (+30°), thin fine and coarse material, outcrop of bedrock up to 10 cm, vegetation: *Acacia seyal*, and *gourmaensis*, *Combretum*

2	0-25 cm	Hue 10YR 3/3w, Hue 10YR 5/4d	very dense (w5)	-1°	loam	thin fine and coarse material layer, laterite crust up to 25 cm, fire traces, sparse vegetation with *Terminalia avicennoides*
3	0-10 cm	Hue 10YR 3/3w, Hue 10Y 6/4d	dense (w4)	+0°	sandy loam	temporary inundated valley, fine and coarse material, fire traces
4	0-16 cm	Hue 10YR 4/2w, Hue 10YR 6/2d	very dense (w5)	0°	silt loam	part of temporary inundated valley, fine material, traces of elephants on soil structure
5	0-16 cm	Hue 10YR 4/2w Hue 10YR 6/2d	dense (w4)	0°	loam	plain unit, profile near termite mound, fine material, fire traces, *Terminalia* and *Combretum*
6	0-13 cm	Hue 10YR 3/3w Hue 10YR 6/2d	very dense (w5)	0°	silt loam	plain unit par of the previous section, fine material, fire traces, presence of *Terminalia* and *Combretum*
7	0-10 cm	Hue 10YR 4/2w Hue 10YR 6/3d	dense (w4)	0°	loam	section near the common BIOTA plot, fine material
8	0-14 cm	Hue 10YR 3/3w, Hue 10YR 5/3d	dense (w4)	0°	loam	section within BIOTA hectare plot, fine material

Table 25: Description of physical and environmental conditions at the surface and in the upper layer of the transect in the central part of PNP (*w: colour wet sample, *d: colour dry sample); rooting system density based *Bodenkundliche Kartieranleitung* 2005.

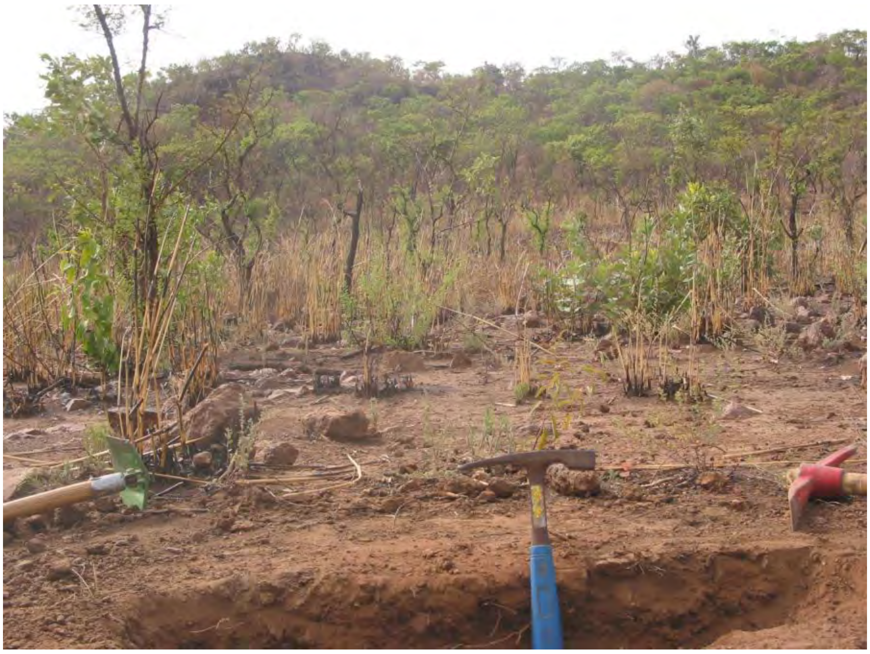


Photo 20: Profile 1 with a thin layer of fine material adjoining steep hill units (+ 30°) in background; in foreground, blocks of bedrock are scattered on the surface (photo: Anne, C. A. T., 18.04.06).

Layer 2

Layer 2, prof. 1 and 2 could not be sampled because of the laterite crust underlying the fine material of layer 1 with respectively 10 and 25 cm thickness (see photo 20). The slope steepness of hill units at the beginning of the transect may intensify lateral transport of fine material across these soil profiles.

The enrichment of coarse material mixed with fine material can be observed in nearly all profiles. Soil structure is cemented only in the clayey loam texture of prof. 5 and 6 in opposition to layer 2 along the HZ transect of PNP, where the cemented structure dominates in all profiles. The thickness in layer 2 varies from 10 cm in prof. 3, 7 to an average of 39 cm. Prof. 5 is characterised by a thick layer. For this reason underlying layer 3 in prof. 5 could not be sampled. Rooting system density in is low in prof. 3, 5 and 7 to dense in prof. 4, 6, 8 (tab. 26). Rooting densities in layer 2 within the HZ transect are very dense contrary to those estimated in transect in PNP. Presence of coarse material and/or weathered blocks from bedrock is not limiting factor for root penetration and fine material in a cemented structure seems to restrict root penetration as observed within transect. Soils in layer 2 are generally brown coloured (Hue 10YR 4/4) to bright brown (Hue 7.5YR 5/6, prof. 8).
Soil texture in layer 2 varies essentially from clayey loam to loam. The clayey loam texture in layer 2 indicates an enrichment of clay particles.

Profiles	Thickness (layer 2)	Colour	Rooting density	Texture	Environmental conditions/observations
3	10-35 cm	Hue 10YR 4/4w, Hue 10YR 6/6d	low (w2)	clay loam	enrichment of coarse material proportion: pisolite
4	16-45 cm	Hue 10YR 5/4w, Hue 10YR 7/4d	dense (w4)	loam	enrichment of coarse material proportion, iron mottle
5	16-80+cm	Hue 10 YR 4/6w Hue 10YR 6/4d	low (w2)	clay loam	cemented structure, fine material
6	13-40 cm	Hue 10 YR4/6w Hue 10YR 6/6d	dense (w4)	clay loam	enrichment of coarse material
7	10-34 cm	Hue 10 YR4/6w Hue 10YR 6/6d	low (w2)	loam	enrichment of coarse material (pisolite), fine material
8	14-43 cm	Hue 7.5YR 5/6w, Hue 10 YR 5/3d	dense (w4)	clay loam	enrichment of coarse material (20 % of the structure), fine material

Table 26: Description of physical and environmental conditions in layer 2 of transect within the central part of the PNP.

Layer 3

Layer 3 is surveyed in only 5 of the 8 profiles and is characterised by an enrichment of pisolite proportions in soil structure (80 up to 90 %) and is identified as part of the laterite crust. The Thickness of layers reach 80 cm in all profiles along transect because of the hardness of soil structure (tab. 27).
The rooting system is low in the clayey texture of prof. 6 and in the clayey loam texture of prof. 8 to very low in clayey loam and silty clayey loam texture of prof. 3, 4 and 7. Soil colour is dominated by brown (Hue 7.5YR 4/6, Hue 10 YR 4/6) in prof. 3, 7 and 8 to yellowish brown (Hue 10YR 6/6-5/6) in prof. 4 and 6. Soil texture is characterised as in layer 2 by the omnipresence of clayey loam texture. It is noticeable that clayey texture mostly dominates in layer 3 within transect as well as in the HZ. From the topsoil to the underlying layers, primary loamy textures are substituted progressively by clayey textures.

Profiles	Thickness	Colour	Rooting density	Texture	Environmental conditions/observations
3	35-80+ cm	Hue 7.5YR 4/6w, Hue 7.5YR 5/6	very low (w1)	clay loam	enrichment of coarse material, partly cemented structure
4	45-80+ cm	Hue 10YR 6/6w, Hue 10YR 7/4	very low (w1)	silty clay loam	fine and coarse material, iron mottled,
6	40-80+ cm	Hue 10 YR 5/6w Hue 10YR 6/6d	low (w2)	clay	upper part of laterite crust, cemented structure with pisolite (80 % of the proportion)
7	34-80+ cm	Hue 10 YR 4/6w Hue 10YR 6/6d	very low (w1)	clay loam	upper part of laterite crust, 90 % of pisolite. partly cemented
8	43-80+ cm	Hue 10YR 4/6w, Hue 10 YR 6/6d Laterite Hue 7.5YR 4/4	low (w2)	clay loam	upper part of laterite crust

Table 27: Description of physical and environmental conditions in layer 3 of transect within the central part of the PNP.

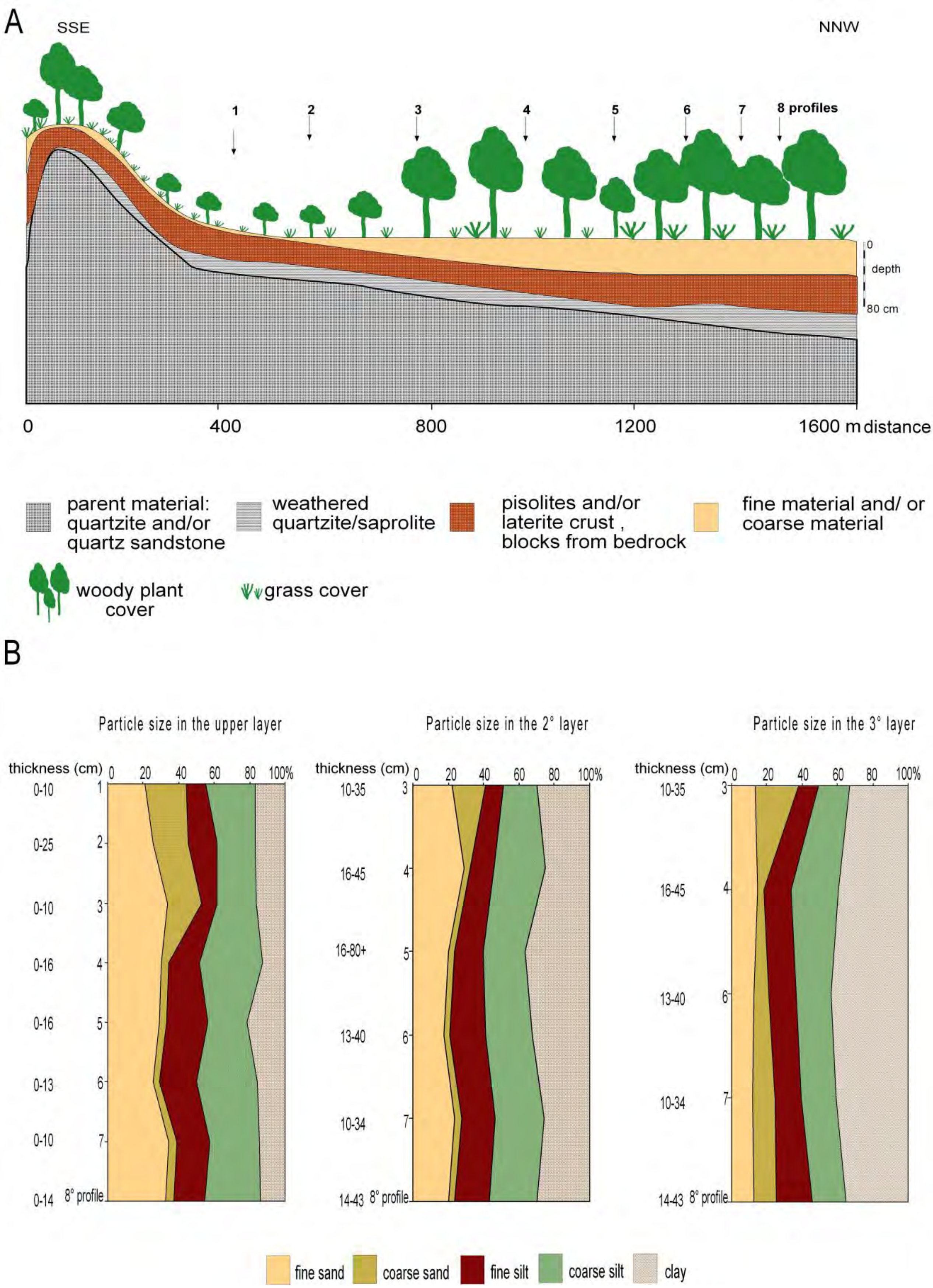


Fig 40: A) Schematical representation of the transect and its different layers of the transect within PNP. B) Particle-size distribution in the different layers.

Particle-size distribution (PSD)

PSD in the different layers along transect is schematically represented (fig. 40B).

PSD in the upper layer

The majority of profiles have a total sand proportion less than 50 % unlike other surveyed transects (in Kikideni, Natiabouani as well as in the HZ of PNP). Fine sand proportions are higher than coarse sand in nearly all profiles within transect (except in prof. 1). The transects studied above were characterised by a higher coarse sand portion in the upper layer. As within transects in South East BF, coarse silt proportions are generally higher than fine silt.
Clay content in the upper layer does not vary a lot because the soil profiles are located in the same low glacis.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
1	0-10 cm	21	23	44	11	27.5	39	17
2	0-25 cm	25.5	20	45.5	16	22	38	17
3	0-10 cm	33.5	195	53	8	22	30.5	16
4	0-16 cm	30.5	4	34.5	17.5	35	53	13
5	0-16 cm	29	4	33	23	22.5	45.5	21
6	0-13 cm	25	4	29	21	34	55	16
7	0-10 cm	34.5	4.5	39	18	28	46.5	14.5
8	0-14 cm	32	5	37	17	31.5	48.5	14

Table 28: Particle-size distributions in the upper layer of soil profiles along transect in the central part PNP.

PSD in layer 2

Total sand fraction decreases from the topsoil to layer 2. Fine sand contents are higher than coarse sand in all profiles within layer 2 as observed in the upper layer. The coarse sand proportions in layer 2 are generally very low (≤ 5 %).
Total silt amounts decrease generally from the upper to the layer 2. Like in the upper layer, coarse silt proportions are higher than fine silt in all profiles along transect. Clay fractions increase from the upper to layer 2 in all profiles and sites with seasonally waterlogged conditions have highest clay content.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
3	10-35 cm	22	19	41	10	19	29	30

4	16-45 cm	29	3	32	14	29	43	25
5	16-80+cm	20.5	3	23.5	16	24	40	36
6	13-40 cm	18	3	21	20	26	46	33
7	10-34 cm	23	4	27	19	28	47	25.5
8	14-43 cm	20	4	24	19.5	26.5	46	30

Table 29: Particle-size distributions in layer 2 of soil profiles along transect in the PNP.

PSD in layer 3

As in layer 2, total sand fractions in all profiles are less than 50 % and decrease from the topsoil to the underlying layers. In opposite, fine sand contents are higher than coarse sand in 2 soil profiles (4 and 6). Proportions of total silt decrease from layer 2 to 3 and coarse silt fractions are generally higher than fine silt. Clay portion increases from layer 2 to 3 in all profiles. It is noticeable that clay contents always increase from the topsoil to the underlying layers.

Profiles	Thickness	Fine sand (%)	Coarse sand (%)	Total sand (%)	Fine silt (%)	Coarse silt (%)	Total silt (%)	Clay (%)
3	35-80+ cm	13	25	38	11.5	18	29	33
4	45-80+ cm	15	3	18	15.5	27	42.5	39
6	40-80+ cm	13	8	21	15.5	19.5	35	44
7	34-80+ cm	12	12	24.5	15	19.5	34.5	41
8	43-80+ cm	13	12	25	20.5	19.5	40	35

Table 30: Particle-size distributions in layer 3 of soil profiles along transect in PNP.

Chemical properties along transect within central zone of the PNP

PH, organic matter and nutrients in the upper layer

The amounts of pH (KCL) are generally lower than those measured in the upper layer of the HZ transect. PH (KCL) values can be considered as strongly acid ($4.5 \leq$ pH (KCL) ≤ 5.0).
Soil organic matter contents which are relative homogeneous, can be considered as low in all profiles ($2 \leq$ SOM ≤ 3). The soil profile adjoining steep hill unit with the highest pH (KCL) contains more SOM in the upper layer. The majority of C/N values are lower than 20 and may indicate good requirement for organic matter decomposition in the upper layer.
The highest total N along the transect coincides with soil profiles, where highest organic matter content and lowest C/N ratios are measured (prof. 1 with 0.13 %).
Highest value of available P is measured in the site with the highest SOM content (fig. 43). Available P amounts for plant take-up measured in transect are clearly higher than those in the upper layer of the HZ transect. They can be considered as adequate ($13 \leq$ available P ≤ 22 ppm).

The available P for plant take-up is generally higher in the upper layer of the transect in the central part than in the HZ transect of the PNP, in different environmental and relief units.
The amounts of available K within transect are clearly lower than those measured within the HZ transect and can be evaluated as very low.
CEC amounts in almost all soil profiles indicate illite as clay type (15 ≤ CEC ≤ 40) and reserve of potassium in the layer (LANDON 1991). CEC amounts in the upper layer of the transect are the highest measured values from the previous chemical parameter analyses within transects in land-used site of Kikideni, partly protected reserve of Natiabouani and HZ on Pendjari.

PH, organic matter and nutrients in layer 2 and 3

PH (KCL) values decrease from the topsoil to the underlying layer 2 and increase from layer 2 to 3. PH (KCL) values in layers 2 and 3 can be evaluated as strongly acid in nearly all profiles with values ≤ 5.0.
From the surveyed layer 3 along transect, lowest SOM is measured in the clayey texture of the upper part of the laterite crust (prof. 6), while highest SOM is observed in the clayey loam texture of prof. 3. SOM decreases from the topsoil to the underlying layers along transect and can be estimated in layer 2 and 3 as very low (1 ≤ SOM ≤ 2).
High C/N ratios are correlated to the lowest amounts of total Nitrogen measured (0.007 % in layer 2 and 0.003 % in layer 3) in all previously analysed transects. Generally, total N contents in layer 2 and 3 are very low and decrease from the topsoil to the subsoil.
Available P values can be considered as adequate in all profiles in layer 2 and 3.
According to total P and available P for plant take-up, an increase of the contents from the topsoil to the underlying layers can generally be observed. In addition, it is important to mention that the average of available P measured in the whole soil profiles along transect are higher than those measured so far in previous transects.
Available K contents in layer 2 increase only at sites presenting hydromorphic conditions.
Amounts of available K increase from layer 2 to 3 in all surveyed soil profiles. Generally, amounts of available K can be considered as low (YOUNG et al. 1977).
Similarly as in to layer 1, illite can be identified as widespread clay types in the surveyed profiles within layer 2 and 3. Prof. 8 near a termite mound shows kaolinite as clay type in the whole soil profile according to CEC values.

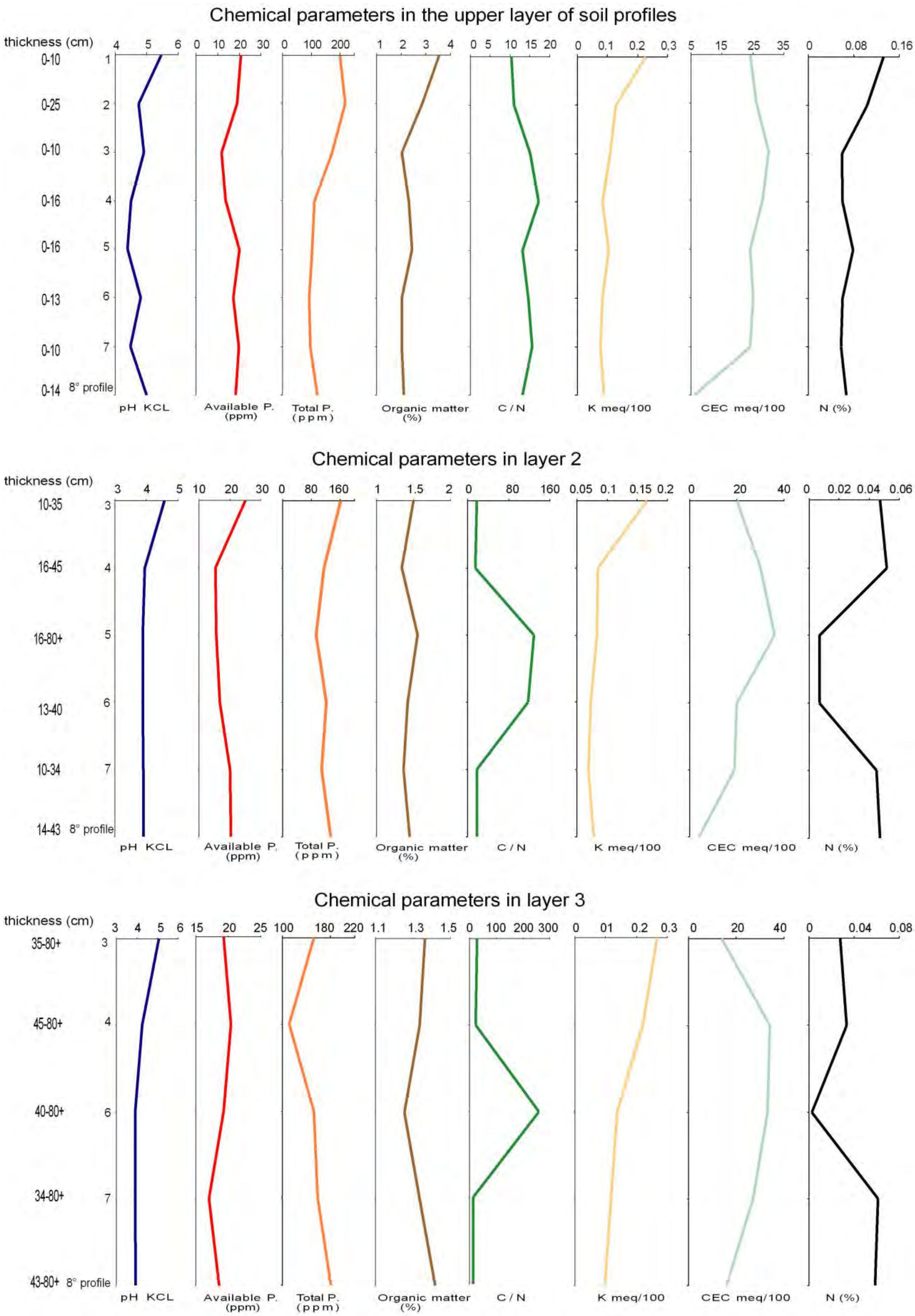


Figure 41: Chemical parameter variations within the different layers along transect in the PNP.

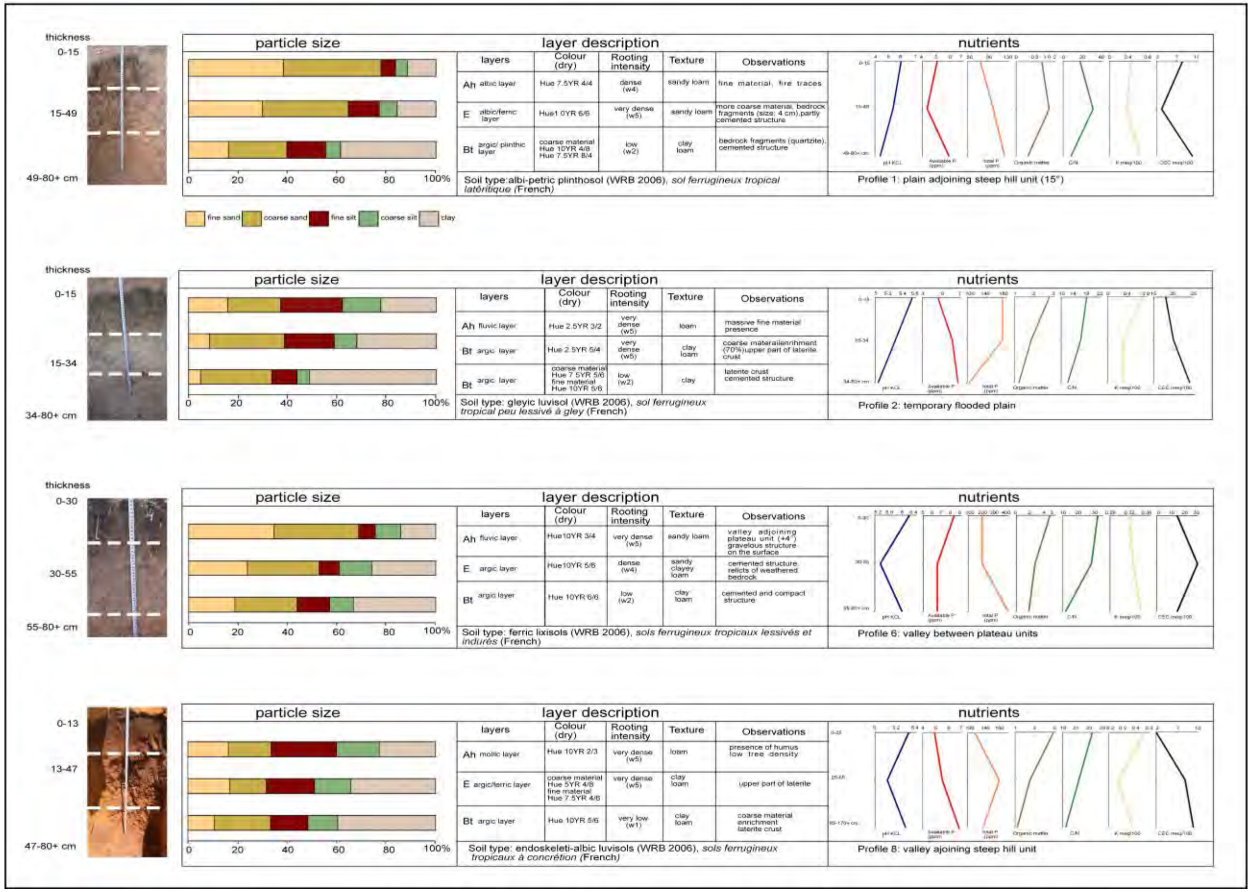


Figure 42: Sample of soil types according to the world reference base for soil resources (WRB 2006), physical, chemical and environmental parameters in the transect in the central part of the PNP.

5.3. Discussion on soil properties in protected and land-used areas

The variations of soil properties following the different layers, which are presented and analysed in the previous chapters, are discussed with the objective of finding out soil features and environmental factors that differentiate soil profiles at a local scale and explaining the dynamic of this differentiation. Furthermore, the influences of lateral and vertical transport of fine material and nutrients as well as the influence of different pedogenesis processes on soil profiles are focused. This happens in consideration to the characteristics of the topsoil in the protected and respectively land-used status of the pedomorphological transects in South East BF and North West BN as shown in the following table summary.

TOPSOIL	**LAND-USED SITE**	**PARTLY PROTECTED SITE**	**TOTAL PROTECTED SITE PARK PENDJARI**	
	Kikideni transect	**Natiabouani transect**	**HZ transects**	**Park Pendjari transects**
Relief units	low peneplains	large peneplains, valleys	steep hill units, short peneplains	steep hill units, short peneplains
Physical aspects				
Thickness (cm)	~ 20 cm	~ 25 cm	~ 15 cm	15-20 cm
Slope (degree)	< 2°	0-8°	0-15°	0-30°
Soil colour	**brown*** (Hue 10YR-7.5YR 4/3-4/6), reddish brown (Hue 5YR 5/4-4/4) and brownish black (seasonally waterlogged site)	**dark brown** (Hue 7.5YR 3/4-Hue 10YR 3/3); dull brown in degraded zone and brownish black in flooded plains	**dark brown** (Hue 10YR 3/3-4) and brown 4/4-6),dull reddish brown in waterlogged site	**dark brown** (Hue 10YR 3/3-7.5YR 3/4) to brownish grey (Hue 10YR 4/1) and/ or greyish yellow brown (Hue 10YR 4/2)
Rooting density	**- dense*** - very dense: hydromorphic conditions - low: strong degraded sites	**- very dense** * - low: strong degraded through sheet wash erosion	**dense to very dense***	**dense to very dense***
Texture	**- sandy loam*** - sandy clayey loam: strong degraded site - silty clay: seasonally flooded site	**- sandy loam, sandy clay loam*** - sand: profile exposure at river - clay loam: seasonally flooded site	**- sandy loam** - loam/silty loam: in valley seasonally flooded or not	**- loam** - sandy loam
Texture class^{+}	moderately coarse	moderately	moderately coarse	medium

		coarse		
Permeability class+	moderately rapid	moderately rapid	moderately rapid	moderate
Permeability rate + (inf/hr)	2.00-6.00	2.00-6.00	2.00-6.00	0.60-2.00
Chemical aspects				
pH (KCL)	4-6	4.5-6	5-7	4.5-6
SOM (%)	1-3	1-5	1-5	1-3.5
C/N	18-40	14.5-49.5	13-23.5	14-22
Available P (ppm)	2-8	4.5-13	4.5-14	9-20
Total P (ppm)	32-142	68-332	74-171	80-218
CEC (meq/100g)	0.2-16	2-26	2-29	2-30

Table 31: Summary and comparison of physical and chemical properties in topsoil within land-used and protected areas; +: classification of texture and permeability adapted from RAMOS (1998); * bold: prevailing property.

Topsoil properties in land-used and protected observatories

The Kikideni transect in the land-used area and Natiabouani in the partial protected site are both under influence of similar climatic conditions, which are specific for the north Sudan climatic zone and characterised by a mean annual rainfall of 900 mm. The transects in the HZ and in the Park Pendjari are part of the South Sudan zone with an average annual rainfall of 1000 mm. It emerges from the results of soil upper layer properties as summarised above (tabl. 31) that some similarities as well as disparities can be established in the topsoil of Kikideni on the one hand and in those located in the protected areas of Natiabouani, HZ and Park Pendjari on the other hand. Indeed, relief units in Kikideni aredominated by the low and well identified peneplains of the savanna landscapes influenced in this case by sheet wash erosion and anthropogenic activities. These conditions lead to the formation of gullies and small, seasonally waterlogged valleys as well as outcrop of the parent material and / or saprolite. The reliefs along the Kikideni transect reveal a gentle inclined slope varying between 0 and 2°.The soil textures are mainly sandy loam. But it change to silty clay in the temporary flooded valley in Kikideni (prof. 2 see fig. 32) and to clay loam in Natiabouani. Such temporary flooded valleys indicate imperfectly to poorly drained site with high organic matter content and low leaching processes in the depth (LAL 2006). Sites under strong degraded conditions show a sandy clay loam texture in the topsoil. In the partial protected transect of Natiabouani (classified as partial protected fauna reserve since 1955) soil texture is more diversified and reflects the variations of relief with slope degrees comprised between 0 and 8 degrees and thus different environmental conditions. Sandy loam and sandy clay loam are the predominant topsoil texture in Natiabouani and are developed respectively in plateau and gully units with a relative dense vegetation and in degraded sites, mainly through sheet erosion. Profile exposure adjoining the river (prof. 9 or prof. 3 see fig. 36) for example is characterised by sandy texture. There is no significant difference in the prevailing topsoil texture (sandy loam) from the land-used site to the total protected areas of Natiabouani and of the hunting zone. However, a change to loamy texture can be identified in topsoil of valleys adjoining steep hill units within the hunting zone. The presence of hill units is a typical relief of the areas situated in the HZ and in the central part of the Pendjari Park (Photo 19). The topsoil within transects in the central part of the Park has principally a loamy texture. In addition, the relief is characterised by steep slopes (between 0 and 30°) followed by long and low peneplains in the Pendjari national Park and by short and low one in the hunting zone.

The thickness of the topsoil is affected by different erosion processes as well as human activities. It varies slightly from an average of 20 cm in Kikideni to 25 cm in Natiabouani and in the Park Pendjari transects. This is related to the fact that the same erosion processes like sheet and gully erosion occur within the peneplains of Kikideni and Natiabouani. It is apparent from the results that the protected status of Natiabouani doesn't seem to play an important role, at least, in the differentiation of the topsoil thickness. Erosion processes in the HZ are rather different to those prevailing along the peneplains in SE BF. They are, in fact, dominated by sheet wash erosion but erosion forms like gullies fail to appear in all transects in PNP. The topsoil thickness in the HZ shows a relative uniformity compared to the more accentuated lateral differentiation in the other sites. Hence, the stony soil surface structure in the HZ seems to be a limiting factor for important lateral differentiation of soil thickness. Among the physical properties of soils the colour represents one of the important differentiation factors and involves the texture as well as organic matter, moisture and iron oxide contents (PEVERILL et al. 2001). Soil colour in the land-used site is dominated by brown (Hue 10YR-7.5YR 4/3-4/6) with some variations like reddish brown and dark reddish brown and changes to dark brown in the protected areas. This variation may be advantaged by the density of the vegetation cover (see next chapter) and thus release of more organic matter. The red component in soil colour may be related to the high presence of iron residual nodules/ and or pisolites on the surface. The reddish and yellowish brown coloured topsoil reflect well oxidation conditions, the latter exist when aeration of soils is good. Between soil profiles, variations of topsoil colour can be observed and are characteristic for many West African catenas as mentioned in many studies about soil changes within catenas (GERRARD 1992). Indeed, lowest and seasonally waterlogged part of the slopes in Kikideni and Natiabouani are characterised by the brownish black colour (Hue 10YR 3/2) which is an indication of imperfectly to poorly drainage conditions and high organic matter content and thus low leaching processes in the depth (LAL 2006). The imperfectly drained sites in the HZ and in the Park Pendjari are then characterised by dull reddish brown. Rooting density is one of the topsoil characteristic which better reflects the differences between land-used sites, on the one side, and protected zones on the other side. The rooting system penetration is generally dense in Kikideni and very dense in the other sites. The upper layer of soils shows low density of the rooting system in strong degraded areas characterised by the instability of soil surface through massive sheet wash and gully erosion, leading to loss of fine material and nutrients and hence to unfavourable conditions for the establishment and growth of vegetation cover.

The chemical aspects prevailing in the topsoil reflect the similar differentiation of physical aspects in the study sites and their lateral variation within the slopes as observed above. Some important chemical parameters are highlighted. PH (KCL) values in the Kikideni site show fewer variations between profiles and are characteristics for moderately to strong acid soils with pH (KCL) comprised between 4 and 6. These low pH values may be related to the high leaching resulting from the high intensity of the rainfall (soil profiles were surveyed at the beginning of the rainy season). In these latter conditions phosphates become less available through interaction with iron and aluminium compounds (LAL 2004). In the sites of Natiabouani and Park Pendjari, pH (KCL) ranges are almost the same as those measured in Kikideni. But the majority of the topsoil in Natiabouani and in the HZ reveals slightly acid soil conditions (6 ≤ pH (KCL) ≤ 5.0) or neutral and seem to better promote the most readily availability of plant nutrients. The proportion of available Phosphorus in the topsoil shows that highest amounts are measured in the protected sites. The differences of Available P are particularly sharp between Kikideni and Natiabouani. The availability of P for the plant take up in Kikideni is affected by the land-used conditions and can be considered as very deficient to deficient in all profiles, according to the measured amounts. Available P contents in Kikideni confirm the studies undertaken in comparable soil types like Luvisols and Gleysols in land-used systems of West Africa (DABIN 1988). Nevertheless, soil P contents decrease mostly in the poorly drained sites as valley and depressions. Available P within the Park Pendjari transects are generally higher in accordance to the total P measured in the topsoil of the different sites.

The results of organic matter contents in the topsoil show very low values between 1 and 3% within the Kikideni transect and those of the PNP. However, SOM contents in Natiabouani and in the HZ are generally higher (1 ≤ SOM ≤ 5). It is important to mention that lateral variations of SOM along the HZ and in the park Pendjari transects are insignificant. The variations of SOM in Kikideni and Natiabouani show an increase in waterlogged sites while a decrease of SOM is observed at sites where denudation processes are widespread and degradation of the topsoil structure visible. CEC contents, which determine clay type in the soils, follow the same tendency as clay contents. The lowest CEC values are measured in the land-used site while highest values are found in the protected areas. CEC amounts reveal the presence of two clay types: Kaolinite in Kikideni, Natiabouani, in the HZ as well and illite in the transect 1 of the central part of Pendjari Park.

Conclusion

It emerges from this discussion that topsoil in land-used and protected sites in south east Burkina Faso and North West BN is characterised by a physical and chemical differentiation through different factors and pedological processes. This differentiation, which occurs within slopes in a first level, is essentially determined by the prevailing erosion processes. In the sites of Kikideni and Natiabouani, located in the same climatic zones, sheet wash, rill and gully erosion are identified as the most important processes leading to the formation and development of relief units. The differences in drainage conditions combined with erosion processes determine thus varying topsoil texture, colour and thickness. The results of topsoil's surveying show occurrence of four main soil surface units: combination of sandy loam-sandy clay loam soils in the land-used sites as well as in the protected zones and loamy soil surfaces, particularly in the central part of the Pendjari National Park. In addition, the classification of soil profiles following the world reference base for soil resources (WRB 2006) reflects the variations of pedological processes in the profiles within this small scale study of the pedomorphological transects. Indeed, in all sites different soil types are identified following the environmental and pedological processes. However, the land-used activities and /or protected status do not lead generally to significant changes in soil surface physical and chemical parameters, however chemical properties as available P along transects suggest differences between the two land use conditions. Apart of the erosion processes, the steepness as well as the length of the slopes combined to soil structure seems to be a limiting factor for the development of erosion types like gully, as observed in the HZ and in the central Part of Pendjari Park. Indeed, in the latter sites a slightly variation of topsoil properties can be noticed and confirms the thesis attesting that soil properties have been found to reasonably constant over slopes of greatly variable forms (GERRARD, 1992) like in the case of the PNP transects. In addition, it is important to mention that differences in the rooting density of the topsoil, from the land-used sites to the protected ones, seem to reflect the status of the studies areas.

Properties of Subsoil in land-used and protected areas

The underlying layers in the different profiles, which are analysed in the previous chapter, are termed as subsoil. The physical and chemical properties of the subsoil, which are important for the characterisation and thus classification of soil units, give precious indication about pedological processes. The subsoil is divided in two layers following the structure and hardness of the material in presence: non indurated or partly indurated layer and indurated layer (tabl. 32).

SUBSOIL	**LAND-USED SITE**	**PARTLY PROTECTED SITE**	**TOTAL PROTECTED SITE PARK PENDJARI**	
	Kikideni transect	**Natiabouani transect**	**HZ transects**	**Park Pendjari transects**
Non-or partly indurated layer				
Thickness (cm)	20-42 cm	25-85cm	15-68 cm	18-45 cm
Structure	combination of fine and coarse material (pisolite; up to 60% content)	enrichment of pisolite portion (up to 60%) mixed with fine material	enrichment of coarse material (pisolite and weathered bedrock residues (up to 70%)	enrichment of pisolite proportion (up to 50%)
Soil colour	**yellow brown*** (Hue 10YR 5/6-5/8), reddish/bright reddish brown (Hue 5YR 4-5/8); brown (seasonally flooded site)	**brown;** **bright brown** (Hue 7.5YR 5/6- Hue 10YR 4/4-6); brownish black (seasonally waterlogged site)	**brown; dull yellowish brown** (Hue 10YR; 7.5YR4/4)	**brown** (Hue 10YR 4/4); orange (Hue 7.5YR 6/6); yellowish orange (Hue 10YR6/3)
Rooting density	**low/very low;** - dense, very dense (seasonally waterlogged site)	**- very dense *** - low: cemented structure	**very dense to dense***	**dense** **- low/ very low** (cemented structure)
Texture	**- sandy loam*** - sandy clayey	**- sandy loam, sandy clay loam***	**- sandy clayey loam,** - clay loam: in valley	**- clay loam** - loam

	loam (strong degraded site) - silty clay (valley)		seasonally flooded or not	
pH (KCL)	4-7	4.5-6	4-5	4-4.5
SOM (%)	1-3.5	0.5-2.5	1-2.5	0.5-1.5
C/N	16-58	1.5-63	9-36	12-128
Available P (ppm)	1.5-7	4-11	3.5-12.5	10-25
Total P (ppm)	45-94	45-209	63-177	71-162
CEC (meq/100g)	2-26-	2-19-	2-20	4-36
Clay content (%)	12-49	11-48	15-34	17-37
Indurated layer				
Thickness (cm)	42-80+ cm	36-118+cm	68-80+ cm	45-80+ cm
Structure	indurated/ laterite crust; quartz and saprolite	more coarse material, cemented; laterite crust	weathered coarse material (residues of bedrock), laterite crust,	upper part of laterite crust, cemented, iron mottled,
Soil colour	- **Orange** (dull, dull yellowish Hue 10YR 7/3-7.5YR 7/3), - pale yellow (degraded sites)	- **dull yellowish brown** (yellowish brown Hue 10YR 5/3-4-6)	- **dark reddish brown**, **orange** (coarse material) - yellowish /dull orange, (fine material)	- **brown**, yellowish/ dull yellowish brown
Rooting density	low to very low	very low to low	very low to low	very low to low
Texture	**sandy clayey loam,** clayey loam	**sandy clayey loam,** sandy loam (profile at termite mound)	**clay, clay loam**	**clay loam**
pH (KCL)	4-7	4.5-6	4-5	4-5
SOM (%)	0.5-2	0.05-1.5	1-1.5	1-1.5
C/N	17.5-49.5	3-56	8-46	13-260
Available P (ppm)	3-10.5	4-8	3.5-14	11-27
Total P (ppm)	32.5-84	35-177	58-148	90-180
CEC (meq/100g)	2-22	2-19	2-24	4-34
Clay content	18-39	2.5-37.5	15-51	29-44

Table 32: Summary and comparison of physical and chemical properties in the subsoil within land-used and protected areas; * bold: prevailing property.

From the summing up of physical and some chemical parameters in the subsoil, it emerges that the non- or partly indurated layer is characterised in all sites by an enrichment of the coarse material, which consists of pisolite, quartz residues as well as weathered relicts from the parent material. However, the proportion of coarse material in the subsoil of the HZ transects is higher (70% of the structure) and reflects the gravelous structure of the soil surfaces in this zone. The thickness of the non-indurated layer varies from 20 to 45 cm in the land-used site and from 25 to 85 cm in the partly protected site of Natiabouani. This differentiation in the upper layer of the subsoil thickness is related to the different environmental conditions within Natiabouani, around profiles adjoining, for example, the rivers where thick soil horizons are found and in sites where relative stable conditions (well drainage, gentle slope and dense vegetation cover) are observed. Apart of this slight variation, the thickness of this layer does not reveal great differences following the different sites. Soil texture in the non-indurated layer of Kikideni and Natiabouani doesn't differ from those in the topsoil. Within transects in the protected areas of the PNP, the prevailing sandy loam texture in topsoil changes to sandy clayey loam and loam to clay loam. The density of rooting penetration in the land-used site of Kikideni is low and/ or very low in the underlying subsoil. In the protected zones, there is no significant change in the prevailing rooting system from the topsoil to the underlying layers. Nevertheless, the low to very low rooting density in some sites of the latter zones is related to the presence of a cemented or partly cemented structure and not to the vegetation cover density at soil surface. Soil colour in the land-used site changes from brown to yellow brown essentially and indicate iron oxides accumulation as well as presence of well drained conditions in the subsoil. The prevailing dark brown topsoil colour in the protected site yields to brown in the non indurated layer and indicates too well drained soils and thus occurrence of leaching processes in this layer.

Soil pH (KCL) values in the non-indurated and indurated layers don't reveal important variations following the different sites. But a generally slight decrease of its values from the topsoil to the underlying non inundated subsoil can be observed. PH (KCL) as well as CEC values are constant in the different layers of the subsoil as observed in the previous table. However, the land-used site of Kikideni is characterised by an increase of the CEC values in the non-indurated layer followed by a decrease in the indurated and cemented structure. The Sites with lowest values are characterised by strong degradation of the soil surface. In the protected sites of Natiabouani and in the hunting zones a trend in the variation of CEC contents in the subsoil cannot clearly be established. However, CEC values in the subsoil reveal generally a presence of Kaolinite as clay type similarly to the topsoil. SOM contents in the subsoil are lower than those measured in the topsoil in all sites. A decrease of SOM from the topsoil to the underlying layers can be observed.

The subsoil of the different sites is characterised generally by an enrichment of clay. But some variations in clay contents from the topsoil to the underlying layers in the different sites and following the drainage conditions can be observed. Indeed, within the transects in the hunting zones and in the central part of Pendjari, clay proportion increases clearly with the depth and indicate the presence of an illuvial horizon in the subsoil, principally through a vertical transport of clay. The highest clay percentages are measured in the indurated layer of the subsoil. In the land-used site of Kikideni, it is noticeable that the presence of the illuviated subsoil horizon is related to the drainage conditions and to the texture of the topsoil. In fact, in soil profiles with poorly or imperfectly drainage conditions (seasonally waterlogged sites) and those, which are result of gully erosion, clay contents decrease from the topsoil to the underlying layers. In the partly protected site of Natiabouani the same trend of clay decrease in the subsoil is observed. The sites in which clay contents decrease are under the influence of intensive sheet wash erosion at the soil surface. Clay particles are laterally transported by rain wash. The surveyed soil profiles with seasonally waterlogged conditions reveal a decrease of clay contents in the subsoil like in the Kikideni site.

Apart of the illuviated property of the indurated layer, it is noticeable that this layer is characterised by the cemented structure in all sites with a low to very low density of the rooting system. The prevailing soil texture reflects broadly an enrichment of clay. Within the non-indurated layer, the predominated sandy loam texture in the land-used and partly protected sites changes to sandy clayey loam in the indurated layer, while sandy clayey loam texture in the HZ turns to clay or clay loam. Soil colour in the indurated layer shows differences from the land-used to the protected status of the sites. Indeed, in the land-used area orange and pale-yellow dominate and indicate the presence of hydrated iron oxides and moderately good to bad drainage conditions (AHN 1970), in the partly protected site brown and yellowish brown in the central part of Pendjari and dark reddish brown in the hunting zone. The reddish and yellowish brown colours in the indurated layer are characteristics for the laterite crust and indicate presence of oxidised forms of the iron into good drainage conditions.

According to the different studies about the characterisation of lateritisation processes and lateritic soil profiles in West Africa (BOCQUIER 1984, MARTINI 1992 and OUANGRAWA et al. 2001 see chapter 2), the non indurated and/ or partly indurated layer in the subsoil of the different sites is identified as the upper and soft part of the laterite formations characterised by a sandy loam and sandy clayey loam texture and accumulation of quartz particles as well as discontinuous ferruginous nodules or pisolites. The indurated layer represents the middle part of lateritic profiles, which is an illuviated horizon with accumulation of indurated and discontinuous iron and/ or aluminium (ferruginous nodules) as well as clay minerals within a cemented and hardened structure

Conclusion

At the scale of small pedomorphological transects within different land use conditions, it is noticeable that soil profiles are marked by a lateral and vertical differentiation of physical and chemical parameters in accordance with the occurring erosion processes and drainage conditions prevailing in the sites. Thereby, the protected and/ or land-used status of the study areas seems to be a differentiation factor of much less significance, at least in the subsoil of the different sites. Indeed, the subsoil, identified as the lateritic weathering product rich in iron and aluminium hard or subject to hardening is developed from the similar granitic parent material and under comparable climatic conditions in the partly protected and land-used site of Natiabouani and Kikideni. In the PNP parent material is obviously quartzites and quartz sandstones, deeply weathered in an argillaceous substratum with presence of relicts at the surface and in the underlying layers and leading to differences in the soil texture. In addition, the subsoil is identified as an illuviated layer, particularly with an enrichment of clay particles. But variations in the illuviation processes can be noticed in the sites where sheet wash and gully erosions are the leading topsoil processes impeding, in fact, the vertical transport of nutrients.

Hence it is apparent from this discussion that processes leading to the differentiation of soil profiles within a slope are so various that any typology of soil units in this scale is irrelevant. Furthermore, the trend of minor variations of soil physical and chemical parameters in protected and land-used sites requires a correlation with the vegetation communities (see 5.4) in different environmental conditions as well as status site to find out how important are soil parameters changes for the vegetation dynamic.

5.4. Diversity of plants and soil properties

The dynamic and variations of soil profiles are under influence of different processes as sheet wash and gully erosion, relief and land-used conditions as shown above. In addition, studies about vegetation structures at a global level are necessary to apprehend the vegetation classes and zones as well as phytosociological dynamics. But in the framework of this study, dealing with soil properties within transects in different land-used status, the focus is on local processes influencing soil properties and vegetation changes. These latter processes are important factors for the assessment of the fertility or the degradation of soils and their relation to vegetation units. In this chapter, botanical inventories around the soil profiles are analysed and discussed, following the status of the sites, on the one hand, and the different soil characteristics prevailing within transects, on the other hand. Before, the relationship soil-vegetation in the savanna landscapes is focussed on

5.4.1. Influence of soil properties on the diversity of woody plants

Detailed studies about relationship soil-vegetation within savanna landscapes of West Africa, taking into consideration in equal profundity the two entities are not widespread in the literature. Indeed, either the studies are undertaken by soil scientists and are focussed on soil formation and processes, although referring to the well known vegetation units of different studies or by botanists, which deal basically with vegetation units, dynamic and structure and thereby mention the soil types and groups (OUEDRAOGO 2006, WALA 2004, ZOMBRE 1984, BOULET 1978 etc.). The relationship soil-vegetation is approached taking into consideration both soil properties and vegetation dynamic. The tree and grass cover of the savanna landscapes play an important role in soil development and dynamic. A dense vegetation cover can prevent the propagation of erosion processes like sheet and gully erosion by breaking the impact of raindrop splash on topsoil. Through the rooting system which draw up necessary water, the vegetation cover influences soil humidity and through leafs, soil organic matter. Soil formations under strong erosion processes affect in equal measure the vegetation cover and soil fertility (AUBREVILLE 1947, ROOSE 1973, LEVÊQUE 1979, SCHUSTER 1996). At a global scale, there is ample evidence that species distribution and communities are determined by soil properties and/ or variations and habitat factors of a given landscape (JOHN et al. 2007). At a local scale, like within the transects in South East BF and North West Benin, habitat factors and species distribution may show minor variations and thus difficult to disentangle the importance of individual soil parameters. Nevertheless, vegetation structure and dynamic are investigated through some parameters as diametric structure (analysis of all species in diameter classes), specific structure (diameter classes following the individual species), and vertical structure involving the height of species (see 4.4.2) in the different sites. For the relationship soil-vegetation, the multivariate method of analysis involving the different species and mean soil parameters of the topsoil are used. This method is composed mainly in this study of ordination techniques as Detendred Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA). Like in the analysis of soil properties (see above), sites with the soil properties in the topsoil and important parameters of vegetation structure and diversity are summarised in the discussion, in order to compare the vegetation structure and dynamic following the different land-used status in relation to the soil nutrients in the upper layer.

5.4.2. Vegetation structure in the land-used and protected sites

5.4.2.1 Characteristics of the phytosociological relevés

In the study areas, phytosociological relevés are surveyed around soil profiles. Furthermore, not all soil profiles are concerned. Based on the homogeneity and/ or changes in the vegetation structure (clearance and or density of the sites), 7 relevés (R) are identified in the land-used site of Kikideni, 5 in the partly protected site of Natiabouani and 7 in the protected hunting zone of the PNP. In each relevé, vegetation type, anthropogenic activities as well as prevailing environmental conditions that are similar to those determined at corresponding soil profiles are described (see Index description card of relevés). Like in previous chapter, plant communities are analysed, first, with a direct comparison of the land-used site of Kikideni and the partly protected zone of Natiabouani, which are located in the same bio geographical entity. In addition, the vegetation structure and dynamic in the hunting zone of PNP are focussed and compared with the Natiabouani and Kikideni sites.

The summary of phytosociological relevés in the land-used site (tab. 38) reveals the presence of shrub savanna as vegetation type dominated by *Combretaceae* family with species as *Combretum molle, Combretum glutinosum* and *Combretum nigricans, Caesalpiniaceae with Piliostigma thonningii, and Cassia sieberiana*. Species as *Combretum molle* are omnipresent in all relevés following the transect in Kikideni. This trend is confirmed by the graphical representation of relative abundance of the species in the site (fig.48). Thereby, it emerges that *Combretum molle* is the most abundant specie with 34% followed by *Combretum nigricans* with 18%. A total of 18 species with a relative abundance between 1 and 34% are found. However, the prevailing shrub savanna changes to tree Savanna in R2. In this seasonally flooded valley individual trees are marked by their mean height (9 meters) which is greater than all other measured values in the site. The modification in the vegetation type in this relevé coincides with the highest measured SOM and CEC values and thus change in soil type along the transect. The estimated shrub cover varies from 10% in R5 corresponding to the soil profile 8 and characterised by an intensive sheet wash erosion to 55% in R7 (prof. 11). The tree cover is principally concentrated in R 2 and the surrounding R 1 with respectively 45 and 40% of the woody cover.

In the partly protected site of Natiabouani, relevés analysis shows that tree savanna is the prevailing vegetation types (tab. 39). The presence of shrub savanna in R3 is apparently related to the relative degraded conditions prevailing at the surface. Like in the site of Kikideni, *Combretaceae* family with species as *Terminalia avicennioides*, *Combretum glutinosum*, *Combretum nigricans, Combretum collinum and Combretum nigricans* as well as *Rubiaceae with Crossopteryx febrifuga* and *Mimosaceae* with *Acacia gourmaensis* are the major components of the savanna units. The relative abundance of the Natiabouani site (fig. 49) shows that *Acacia gourmaensis* is the most abundant specie in the relevés. Nearby the same number of species are identified in Natiabouani but the distribution of the relative abundance of individual species reveals more variations than in the Kikideni site dominated clearly by *Combretum molle*. Indeed, near *Acacia gourmaensis, Combretum nigricans* and *Crossopteryx febrifuga* are characterised by their relative high abundance. The tree cover in Natiabouani ranges from 20% in the site with intense sheet wash erosion (R5/ prof. 11) to 70% in a site characterised by a 100% grass cover, mainly *Andropogon gayanus* (R1) with more than 3 m height. The highest trees in the whole site are measures in this section. Contrary to the land-used site, human activities are here obviously limited to fire traces in all sites, resulting from the ecological management of this protected zone

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Figure 48: Relative abundance of woody population in the land-used site

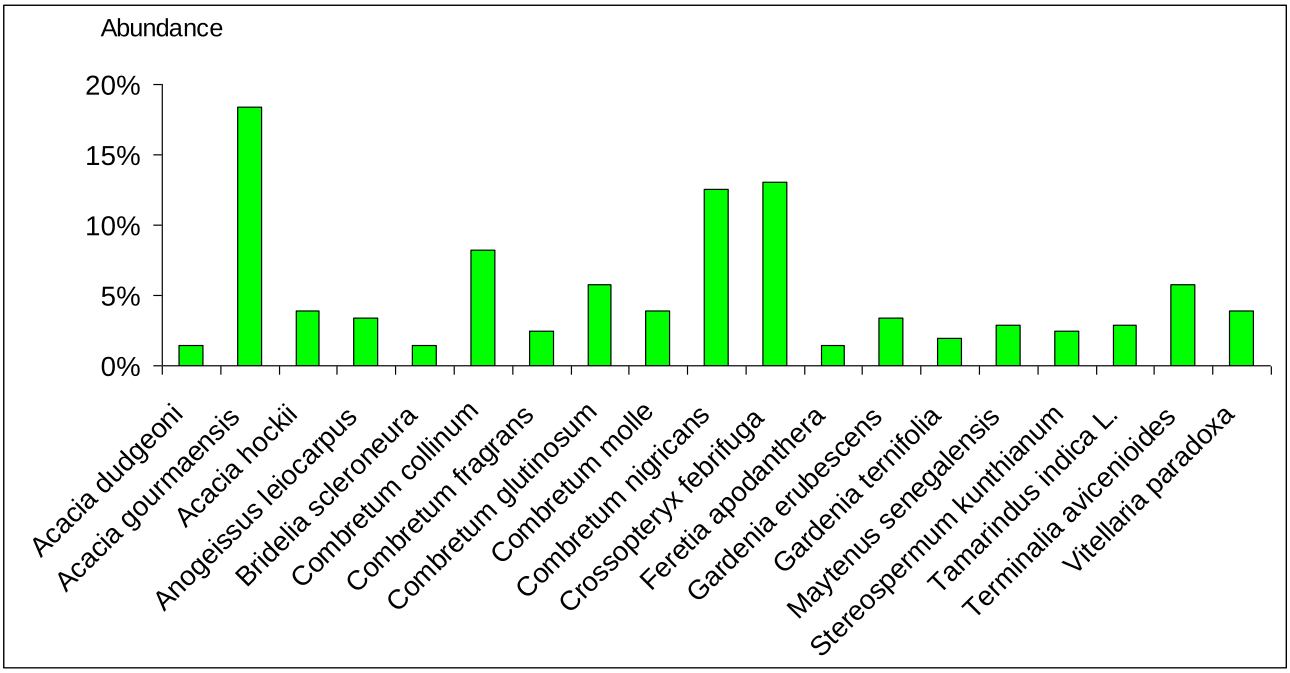


Figure 49: Relative abundance of woody population in the partly protected site of Natiabouani

Relevés/ soil profile	Relevés properties			Woody cover				Topsoil parameters					
	plot surface (m^2)	vegetation type	anthropogenic influence	tree cover (%)	shrub cover (%)	shrub mean height	tree mean height	texture	pH (KCL)	SOM (%)	Avail. P (ppm)	CEC	Clay (%)
1 prof. 1	1000	shrub savanna (*Combretum glutinosum* and *Combretum molle*)	fire	40	20	3.5 m	-	sandy loam	4.5	1.5	3.5	6	10
2 prof. 2	1000	tree savanna (*Piliostigma thonningii* and *Combretum molle*)	fire	45	20	5 m	9 m	silty clay	4	3	4	4	42
3 prof. 3	1000	shrub savanna (*Combretum molle* and *Combretum nigricans*)	fire	-	30	3 m	-	sandy clayey loam	6	1.5	5	6	39
4 prof. 5	1000	shrub savanna (*Combretum glutinosum* and *Combretum molle*)	pasture, firewood	-	20	3 m	-	sandy loam	4.5	2	5.5	0.2	13.5
5 prof. 8	1000	shrub savanna (*Combretum molle* and *Cassia sieberiana*)	pasture, firewood	-	10	3 m	-	sandy loam	5	1.5	5.5	2	7.5
6 prof. 10	1000	shrub savanna (*Combretum molle* and *Combretum nigricans*)	pasture, firewood	5	25	5 m	8 m	loamy sand	5	2	8	6	9
7 prof. 11	1000	shrub savanna (*Combretum molle* and *Combretum nigricans*)	fire, pasture, firewood	5	55	5 m	8 m	sandy loam	6	2	6	8	10

Table 38: Description of surveyed relevés, vegetation structure and types in the land-used site of Kikideni with some topsoil parameters

Relevés/ soil profiles	Relevés properties			Woody cover					Topsoil parameters					
	plots (m^2)	vegetation type	anthropogenic influence	tree cover (%)	grass cover (%)	shrub cover (%)	shrub mean height	tree mean height	texture	pH (KCL)	SOM (%)	Avail. P (ppm)	CEC	Clay (%)
1 prof. 2	1000	tree savanna (*Terminalia avicenioides* and *Crossopteryx febrifuga*)	fire	70	100	-	3 m	6 m	sandy clay loam	5,42	1.5	5,5	25	21
2 prof. 4	1000	shrub savanna (*Acacia gourmaensis* and *Combretum glutinosum*)	fire	-	30	20	3 m	-	sandy loam	4,5	1.5	6,56	16	18
3 prof. 7	1000	tree savanna (*Crossopteryx febrifuga* and *Combretum nigricans*)	fire	25	-	30	4 m	8 m	sandy loam	5.5	2.5	6.5	2	13
4 prof. 9	1000	tree/shrub savanna (*Terminalia avicennioides* and *Combretum collinum*)	fire	25	20	-	4 m	8 m	clay loam	5	4	7.5	26	28
5 prof. 11	1000	tree savanna (*Combretum nigricans* and *Combretum collinum*)	fire	20	50	-	4 m	6 m	sandy clay loam	5	1	6	18	20

Table 39: Description of surveyed relevés, vegetation structure and types in the partly protected site of Natiabouani with some corresponding topsoil parameters

Within the hunting zone of the PNP tree savanna as vegetation type is obviously the dominant vegetation unit (tab.40). However, shrub savanna units are found in the zones adjoining the hill units (R2 and R6) where intensive sheet wash erosion is supposed. *Caesalpiniaceae* is the dominant vegetation family in the tree savannas, with species as *Detarium microcarpum*, *Burkea africana* followed by *Sterculiaceae* with *Dombeya quinqueseta* and *Mimosaceae* with *Acacia gourmaensis*. Contrary to Natiabouani and Kikideni, the relative abundance in the hunting zone reveals a greater number of species along the surveyed relevés (fig. 50). The woody cover is generally very dense in this site as in R1, characterised by a 50% tree cover, 50% grass cover as well as almost 30 % shrub cover. The relevés show generally a dense grass cover despite the omnipresence of fire traces in all sites. The latter, which is part of the techniques of Park management, affects primarily the grass cover and individual young tree. It is important to mention that fire management seems to promote a good regeneration and development of grass cover as observed in the field (see photo 16). The trees mean heights don't show a great difference in comparison to the other sites because being ranged between 5 and 8 meters like in the other sites. The topsoil of site with the highest organic matter and clay contents (R6) is not characteristic for a dense woody cover as observed in Natiabouani and Kikideni. Indeed, R6 is marked by the presence of sparse tree and shrub cover. Nevertheless, the analysis of site richness and vegetation structure may provide more elements of comparison for the different sites. Thereby, a classification of individual species from the entire relevés of a plot in diameter and height classes might be useful as well as the evaluation of species richness and regeneration ability in the different sites.

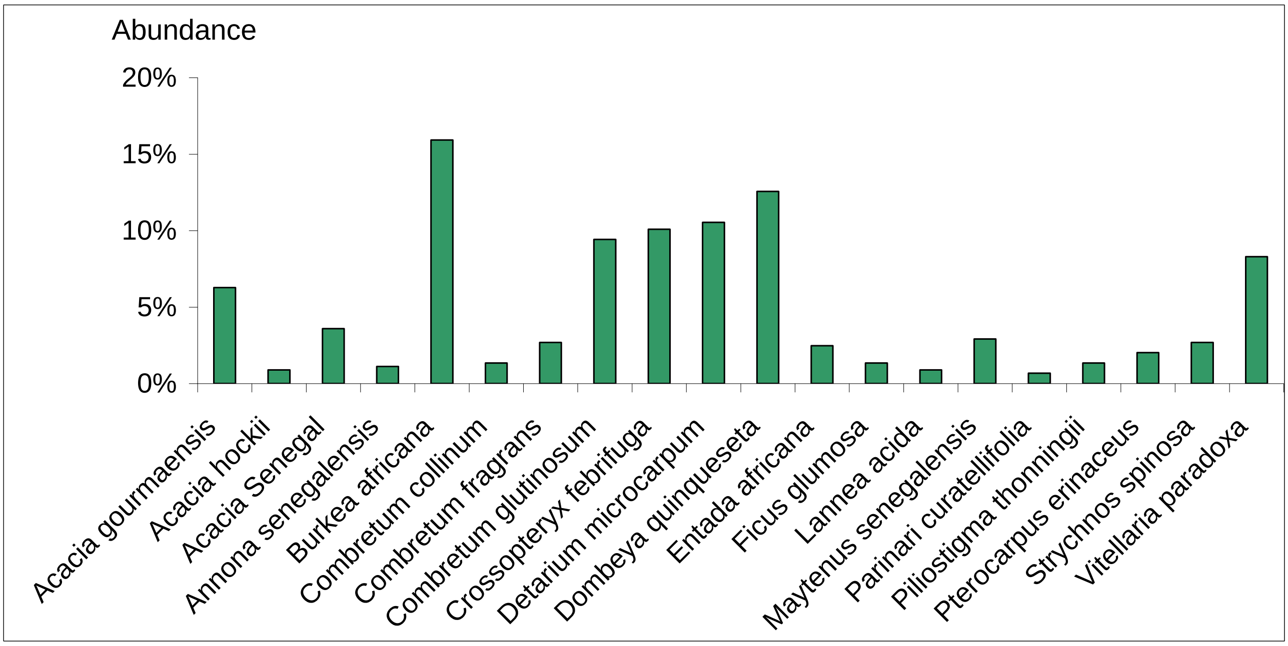


Figure 50: Relative abundance of woody plants in the hunting zone of the PNP

Relevés /soil profiles	Relevés properties			Woody cover					Topsoil parameters					
	Plots (m^2)	vegetation type	anthropogenic influence	tree cover (%)	grass cover (%)	shrub cover (%)	shrub mean height	tree mean height	texture	pH (KCL)	SOM (%)	Avail. P (ppm)	CEC	Clay (%)
1	1000 (hilltop)	tree savanna (*Burkea africana, Detarium microcarpum*)	fire	50	50	30	3 m	5 m	-	-	-	-	-	-
2 prof. 1	1000	shrub savanna (*Acacia gourmaensis, Detarium microcarpum*)	fire	-	20	60	3.5 m	-	sandy loam	6	1.5	5	8	11.5
3 prof. 2	1000	tree savanna (*Crossopteryx febrifuga*, *Detarium microcarpum*)	fire	30	40	60	4.m	8 m	loam	5.5	3	4.5	18	22.5
4 prof. 5	1000	tree savanna (*Burkea africana, Vitellaria paradoxa*)	fire	50	50	50	3 m	5 m	sandy loam	5.5	2.5	5.5	2	12.5
5 prof. 6	1000	tree savanna (*Dombeya quinqueseta, Acacia gourmaensis*)	fire	30	70	20	3 m	6 m	sandy loam	5	2.5	4.5	2	14
6* prof. 8	1000	shrub savanna (*Annona senegalensis*, *Combretum glutinosum*)	Fire and pasture	-	-	-	-	-	loam	5	5	5	2	23
7	1000 (hilltop)	shrub savanna (*Combretum glutinosum, Burkea africana*)	fire	20	50	-	4 m	8 m	-	-	-	-	-	-

Table 40: Description of surveyed relevés, vegetation structure and types in the hunting zone of the Pendjari National Park related to some g topsoil parameters. * At relevé 6 within plain adjoining hill, diameter at breast height (dbh) of plants were lower than 15 cm, thus only species with a minimum height of 1 meter are surveyed

Photo 21: Tree savanna in the hunting zone of Pendjari with mainly *Burkea africana* woody species characteristic for the savanna in the region, the soil surface is marked by its gravelous structure. Anne, Cheikh A. T. (29.05.05)

Photo 22: Tree savanna with *Terminalia avicenioides* and *Combretum collinum.* This site is characterised by the very dense grass cover at the end of the dry season and is partly seasonally flooded (14.05.05, Anne, Cheikh A. T.).

5.4.2.2. Structural analysis of vegetation types

The structural analysis and estimation of the diversity of woody plants imply in this study the identification and calculation of parameters such as species richness, basal surface and Shannon Index. While the vegetation structure and composition is approached through the classification of the relevés and the dendrometric characteristics of individual plants in diametric and height structure. The diametric structure is an important parameter characterising the population of vegetation groups. It provides information about the distribution of all species and respectively dominant species in relation to the diameter classes, which are identified following the tree-diameter ranges in the different sites. Height structures involve the classification of all surveyed individual trees with DBH ≥ 5 cm and their association with the total number of species and subsequently with the dominant individual species which are identified by the relative abundance (see above). The analysis of diversity and structural parameters occurs in a direct comparison of the different status of the sites. This will allow to assess the woody plant diversity state in protected and land-used areas in savanna landscapes and to highlight the key soil and environmental factors intervening in the differentiation and dynamic of woody plants. Nevertheless, a direct comparison of sites can optimally occur in the case of the plots located in south east BF and characterised by the similar climatic conditions, however, with different land use conditions. The vegetation analysis of the HZ provides further indication of vegetation structure and dynamic in a protected zone with national economical value because being part of the PNP.

Species richness is recognised as on of the important and the most intuitive criterion for the characterisation of community diversity (SHACKELTON 2000, ADAMS 2009). It refers to the total number of different species in sample population and incorporates evenness, that is, the relative abundance of species (MCGINLEY et al. 2010). In this study, the same number of relevés in the different sites is chosen. Thereby, the representative vegetation types associated with the environmental conditions and relief units are considered with the aim of reflecting the dynamic of the woody plants in each site. For example, within the land-used site shrub savanna in strong degraded slopes or not and in valleys are chosen. Within the partly protected site all *relevés* are considered because reflecting the different vegetation types, different degraded and /or stable conditions. In the total protected site of the HZ of PNP, top of the hills as well as plateau within gentle slopes and valleys are selected. It is evident that the ecological conditions of the different sites as well as vegetation composition in the study areas might be quite different and thus difficult to compare. Nevertheless, an analysis of the diversity and structure of the sites may provide information about woody plant composition and diversity in sites with different status. This occurs in the framework of scarcity of arable farm land in regions with high presence of protected areas.

From the results (tab. 36), it emerges that species richness increases continually from the land-used site to the partly protected site and total protected site. Indeed, from 6.5 species pro 1000 m^2 in Kikideni it changes to 9 species pro 1000 m^2in Natiabouani. Both sites are located in the same climatic north Sudan zone. The protected status of Natiabouani plot may play an important in the enhancement of species richness value. However, the species richness increase from the pasture and land-used site to the partly protected zone is quite unlikely to the results of similar studies, which were undertaken in the northern Province of South Africa (SHAKELTON 2000) and in the same study areas in South East BF (HAHN HADJALI et al.

2006). Following these latter authors, species richness of all species (woody and herb layer) is significantly higher in the pasture and land-used site of Kikideni than in the partly protected zone of Natiabouani. In addition, from the results of the woody cover analysis it is established that species richness was at the current state of investigation (2006) quite equal in both sites and subsequently species richness is not affected by pasture and land use. Furthermore, similar studies about phytodiversity and/or species regeneration in sites with different land-use conditions (HIGGINS et al. 1999, TRAORE et al. 2008) show like in the present study that species richness decreases in zones with strong human and cattle pressure. The varying results of the species richness comparison between land-used and protected areas accentuate the need for reconsidering the methodological survey of vegetation structure and diversity. Indeed, we advance the view that botanical investigations have to consider the variations of relief, soil types and subsequently the differentiation of vegetation communities of the study area. Botanical studies should take into consideration not only the homogeneity and affiliation of vegetation units (OUEDRAOGO 2006), but also all environmental features including relief and land use conditions (WALA 2004). In this study, the plots in the land-used area, which are characterised by their strong degradation and thus low vegetation cover, are chosen as well as those where traces of degradation are less visible and in seasonally waterlogged sites. This method reflects at best the dynamic and general diversity conditions and changes in an ecosystem compartment.
The tendency of the increase of species richness from the land-used to the protected areas is reinforced by the measured value in the HZ of Pendjari Park (13 species pro1000 m^2). However, this latter zone is part of the South Sudan climatic zone and geomorphological or rather geological features as well as occurring erosion processes and topsoil structure are different from those observed in the partly protected zone of Natiabouani (see 5.3). These factors may explain the differences of species richness between these two protected areas.
The analysis of the dominant species reveals the presence of *Combretaceae* family essentially in the land-used site while *Rubiaceae, Mimosaceae* and the couple *Caesalpiniaceae-Sterculiaceae* are present mostly in the protected zones of Natiabouani and in the HZ of Pendjari.

The basal surface, which refers to the total area of stump surface of trees at breast height, is a relative reliable parameter because of the fact that basal area of plants remain s constant during a year and may increase or decrease over a period of years. It is a useful measurement to characterise the density of a site and is, a further tool for phytodiversity assessment. Basal area (**G**) is calculated following the formula:

$$\mathbf{G} = \sum \prod D^2/4$$

D: diameter at breast height; ∏= 3.14

From the results of basal surfaces ranges, it is ascertainable that highest basal surfaces pro hectare plot are measured in the land-used site of Kikideni. They vary from 52 m^2 pro hectare (tab. 36) to 261.5 m^2 pro hectare at a seasonally flooded valley characterised by high woody cover (65 %) and soil organic matter. The basal surfaces ranges decrease generally in Natiabouani (47-190 m^2/ha). Like in the land-used site, plot with the highest basal surface in the latter zone is marked by the seasonally waterlogged conditions and high soil organic matter content (see tab. 34). Basal surface ranges within the HZ of Pendjari are the lowest measured ones (between 2 to 92 m^2 /ha). This constant decrease of basal surface from the land-used site to the partly and total protected zone may be related to the fire management, which occasions a loss of some woody cover and/or impede their growth. In addition, the fire management promotes the regeneration of the vegetation and it is hypothesised that the majority of the woody plants are relative young in the protected areas. The analysis of height and diameter class (see below) may give more information about this aspect of vegetation structure. Furthermore, the presence of Elephants in Natiabouani and in the HZ of Pendjari may play a role in the low presence of individual trees with high diameter at breast and thus high basal surfaces. It is known that elephants affect the vegetation structure and vegetation composition. Indeed, elephants in high densities may strongly modify woodland to shrub lands (BEN-SHAHAR 1993) and/or to grass lands. Elephant impacts on woody cover, which are likely to kill woody species, include uprooting, tree felling and bark stripping (CHAFOTA et al. 1996). The density of elephant population in the study areas is estimated to 0.13 pro km^2 (BLANC et al. 2003), also relative low in comparison with the densities in Botswana (3 to 12 individuals pro km^2; CRAIG 1990).The fire management based tools are usually confined to herbaceous layer but can cause at long term damage to mature trees. In the protected sites of our study areas, the combinations of fire and elephants presence seem to be decisive factors of changes in the vegetation composition and structure as observed through basal surface values and probably loss of adult woody plants.

The Shannon Index which represents the logarithm of the number of species in equal abundance is an indication that the woody population has a maximum index only when each species in the population is evenly represented (MC CUNE et al. 2002). This diversity index takes into account species richness and proportion of each species within a plot. From this definition, it emerges following the results of measurements of Shannon Index in the different sites that the partly protected site with 2.70 reveals a better distribution of individual among the species and the species in this site are more even than for example in the pasture and farming site of Kikideni characterised as observed below by the predominance of species like *Combretum molle.*

Land use conditions	Dominant species	Family	Shannon Index +	Species Richness +	Basal Surface*
Pasture and farming site (Kikideni)	*Combretum molle* *Combretum nigricans*	*Combretaceae*	2,28	6.5 species /1000 m^2	52-261.5 m^2 /ha
Partly protected site (Natiabouani)	*Crossopteryx febrifuga* *Acacia gourmaensis*	*Rubiaceae* *Mimosaceae*	2,70	9 species /1000 m^2	47-224 m^2 /ha
HZ (Pendjari Park)	*Burkea africana* *Dombeya quinqueseta*	*Caesalpiniaceae* *Sterculiaceae*	2,52	13 species /1000 m^2	2-92 m^2 /ha

Table 36: Species richness and dominant tree species in the different study areas; for more uniformity, the same number of relevés (5) is chosen for the calculation of species richness and basal surface. * The basal surface values represent the value ranges in the different relevés within a site. + The Shannon Index bears on the equal number of plots which are basis of the species richness calculation.

Diameter classes

The diameter values are derived from the measured circumferences of the woody plants at breast height (1.3 m above the ground) and with a minimum diameter higher or equal to 5 cm. They are arranged in 9 classes. The analysis relating to the entire species of 5 relevés in site of different land use status provides indications about the age and size structure of the woody plants and thus vegetation units (BATCHELIER 1985).
From the comparison of diameter classes in the study areas (fig. 48), it emerges generally that the majority of tree species in protected and none protected areas have a size ranged from 6 and 10 cm. Around 60 % of the surveyed individual trees are located in this size class for a total number of species **N** = 362 species in Kikideni, 452 in Natiabouani and 331 species in the HZ. In this diameter class a clear increase of the species number from the land-used site to the protected ones can be observed.

The size class [0-5[is characterised essentially by individual trees with a diameter of 5 cm in all sites and shows that the proportion of juvenile woody plants are higher in the partly and protected sites than in the land-used one. This observation may be an indication of different regeneration potential. The diameter class ranged from 11 and 15 cm where the adult individual species are supposed reveals generally low number of individual woody plants. Thereby, the partly protected site of Natiabouani is characterised by less presence of trees compared to the other sites. The number of woody plants in the high size classes (20 to 45 cm) is almost insignificant in all sites.

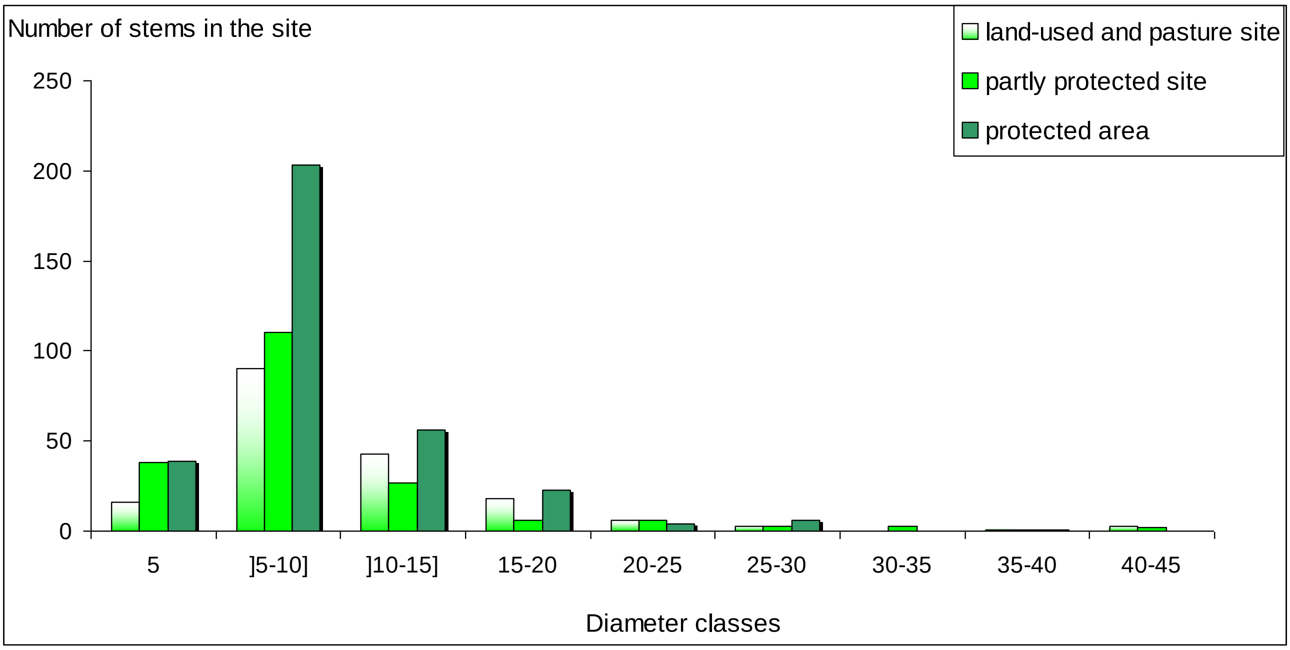


Figure 48: Comparison of diameter classes following the protected and non protected status of the study areas: the same number of relevés (5) is considered in each site taking into consideration the variation of the environmental conditions and thus vegetation cover.

The repartition of woody plants in diameter classes following the most dominant species in the different sites confirms the tendency described above. Indeed, within the land-used site (fig 49), *Combretum molle (C.m.)*, *Combretum nigricans (C.n.), Combretum glutinosum (C.g.)* and *Vitellaria paradoxa (V.p.),* which are the most abundant species show individual trees with a diameter comprised mostly between 6 and 10 cm. 50 % of the *C.m*, 80 % of *C.n.,* 90 % *C.g.*, and 50 % of the *V.p.* are present in this size class. It is important to mention that the proportion of adult individual trees of *C.m.* in the diameter class 11 and 15 is relative high compared with the other species in the same size. They are found principally in R2 (seasonally waterlogged valley) and R6 (gentle slope where the highest available P in the topsoil (8 ppm) is measured (photo 23). In addition, by *Vitellaria paradoxa*, 15 % of the individual trees have a diameter size between 25 and 30 cm. They are found, like part of *C.m*. in the class 11 and 15, principally in the tree savanna plot of R2.

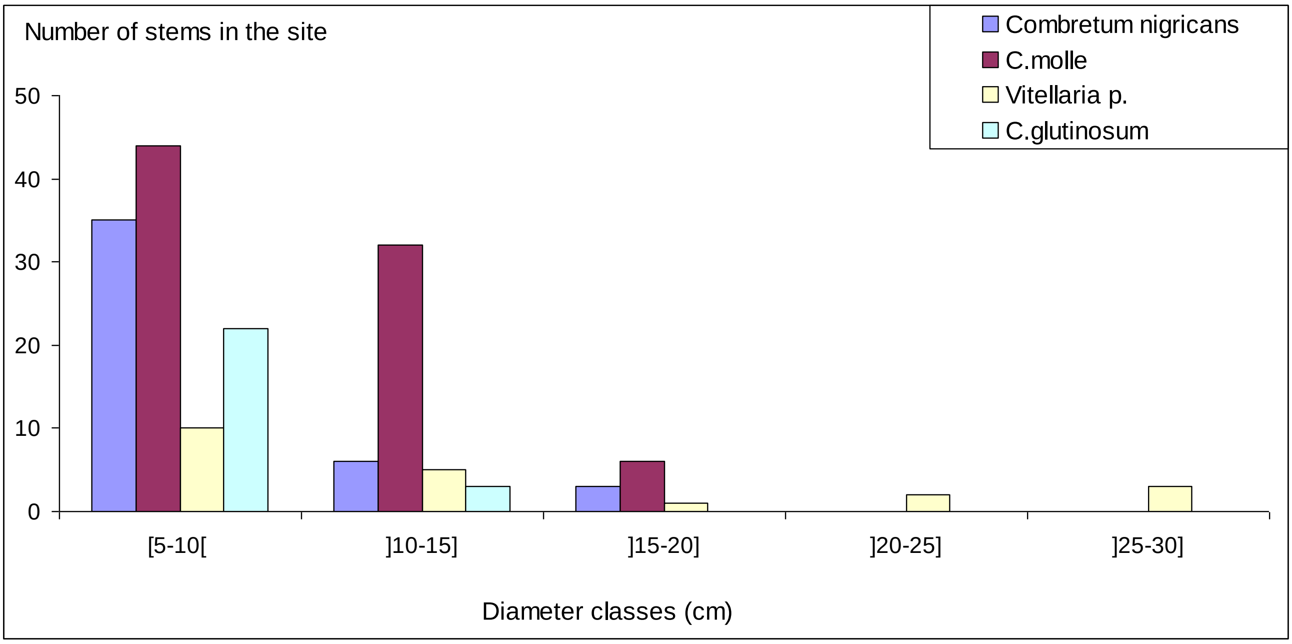
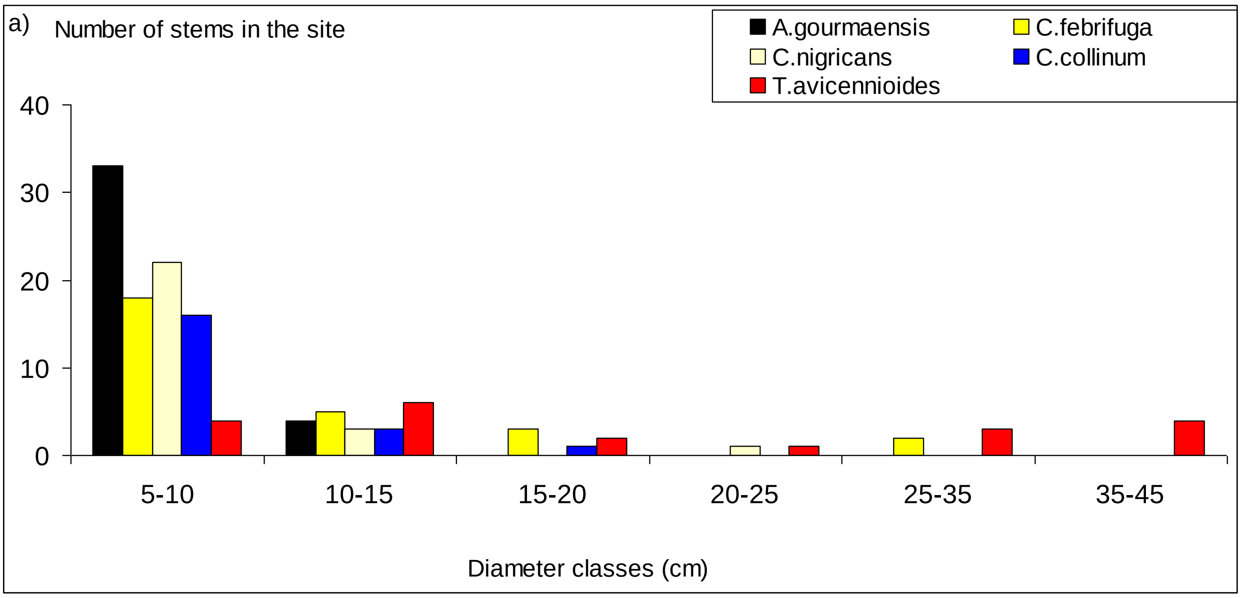


Figure 49: Distribution of diameter classes following the dominant species in the land-used site of Kikideni. The four dominant species are considered.

Photo 23: Shrub savanna within the land-used site of Kikideni. In the foreground *Combretum nigricans* and *Combretum molle* individual trees and numerous residues of dead individual trees (Anne, C. A. T., 08.06.07).

The diameter classes following the dominant species in the partly protected site and in the HZ follow nearly the same structure as described in the land-used site. From the dominant species, *Burkea africana*, *Dombeya quinqueseta*, *Detarium microcarpum*, *Combretum glutinosum and Vitellaria paradoxa* in the HZ and *Acacia gourmaensis*, *Crossopteryx febrifuga*, *Combretum nigricans*, *Combretum collinum* in the partly protected plot, the majority of individual trees have a diameter class comprised between 6 and 10 cm (fig. 50). Nevertheless *Terminalia avicennioides* individuals within the partly protected site are in the majority located in the size class 11 and 15 cm. These individual trees grow essentially in a site (R1, phot. 22) characterised by a relative deep soil profile (see 5.2.1.) where the laterite crust appear around 2 meters far below. In addition, some individual *Terminalia avicennioides* are found in the high diameter class 35 to 45 cm and give indication to the presence of adult species of this woody plant essentially located in the plot 1.

The distribution of diameter classes in the HZ shows that nearly 60 % of *Burkea africana* individuals are in the size class comprised between 6 and 10 cm and they are found principally on the top of hill unit with relative steep slope (R1 and R7). The distribution of *Dombeya quinqueseta, Detarium microcarpum and Combretum glutinosum* individual trees shows that around 90 % of the species are found in the size class [5-10 cm [. By *Vitellaria paradoxa,* 50 % are classified in the latter size class, 25 % in the diameter class 16 and 20 cm and around 20 % for the diameter class 11 and 15 cm.



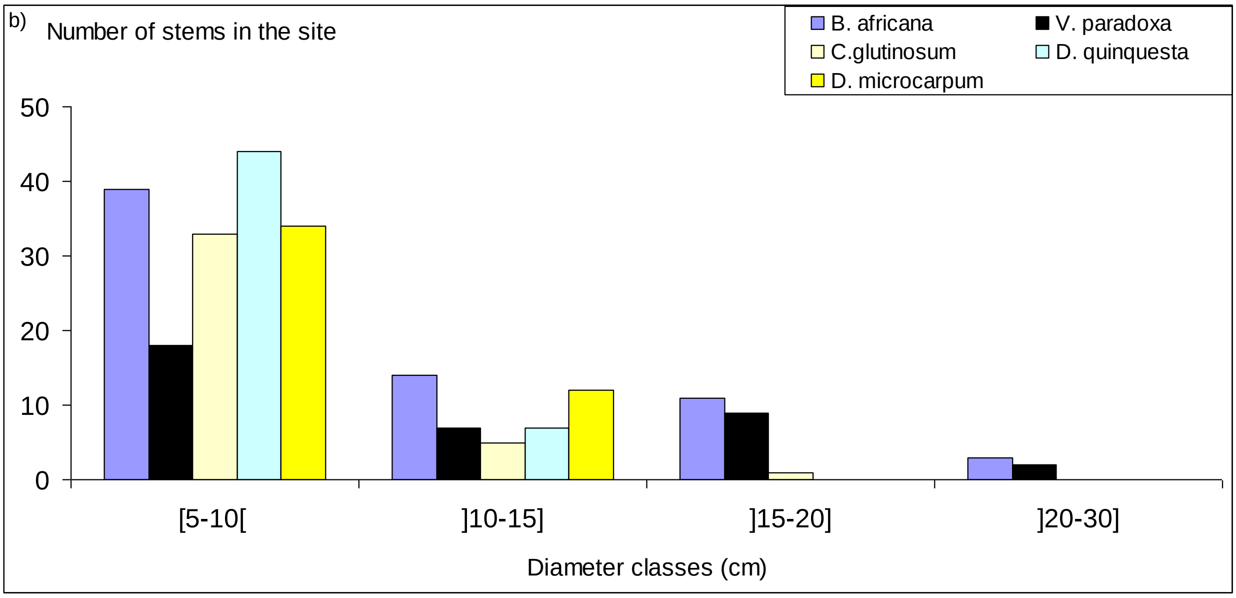


Figure 50: Diameter classes following the dominant species in the partly protected site of Natiabouani (a) and in the HZ of Pendjari (b). The 5 dominant species are considered.

Height class distribution

Following the same principle of the diameter class analysis, the measured heights of the entire woody species are classified in 6 size classes based on the same number of species like in the diameter analysis as observed in the following illustration (fig. 51).

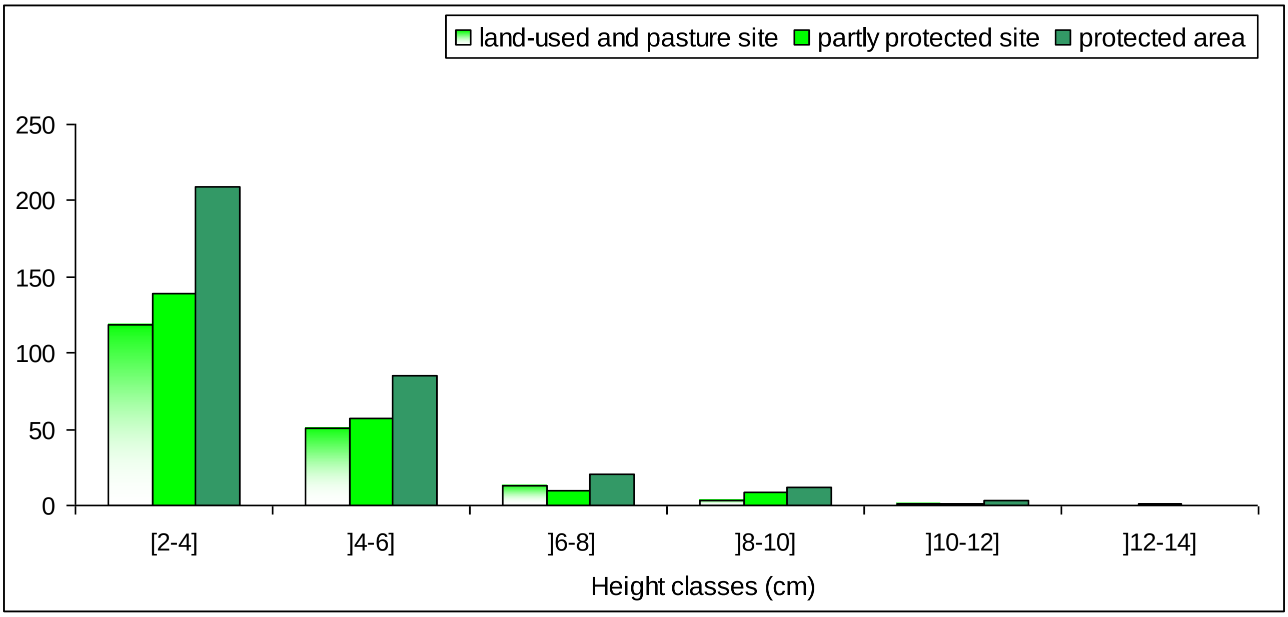


Figure 51: Comparison of the height class distributions in the land-used and protected zones.

From the results of height class distribution, it is ascertainable that the majority of woody plants in the surveying areas have a height which ranges from 2 to 4 meters. However, a clear increase of the number of stems from the land-used site to the protected areas can be observed in this size class and in the following height classes. The general distribution of height classes reflects the presence of more young plants independent of the status of the site. Nevertheless, the lower proportion of young trees in the land-used site may be an indication of the important presence of adult trees. This tendency is corroborated by the analysis of height distribution of the most dominant specie: *Combretum molle* (fig. 52-a) in the land-used area. Indeed, even if the total of stems of *C.m.* is higher in the class [2-4] with 50 % of the total individual trees (N = 82 species), around 45 % are located in the height class comprised between 5 and 6 meters. The height classification following the dominant species in the partly protected site (55-b) and in the HZ (55-c) show the clear predominance of species located in the first height class comprised between 2 and 4 meters in all woody plant species.

In addition to the diameter and height class analysis of the woody plants in the different study areas, the regeneration potential in the plots following the different relevés around soil profiles are focused. Subsequently, the general structure of plots are compared taking into consideration the status of the different sites, the prevailing pedological processes, the soil properties in the topsoil as well as the soil surface structure and environmental conditions.

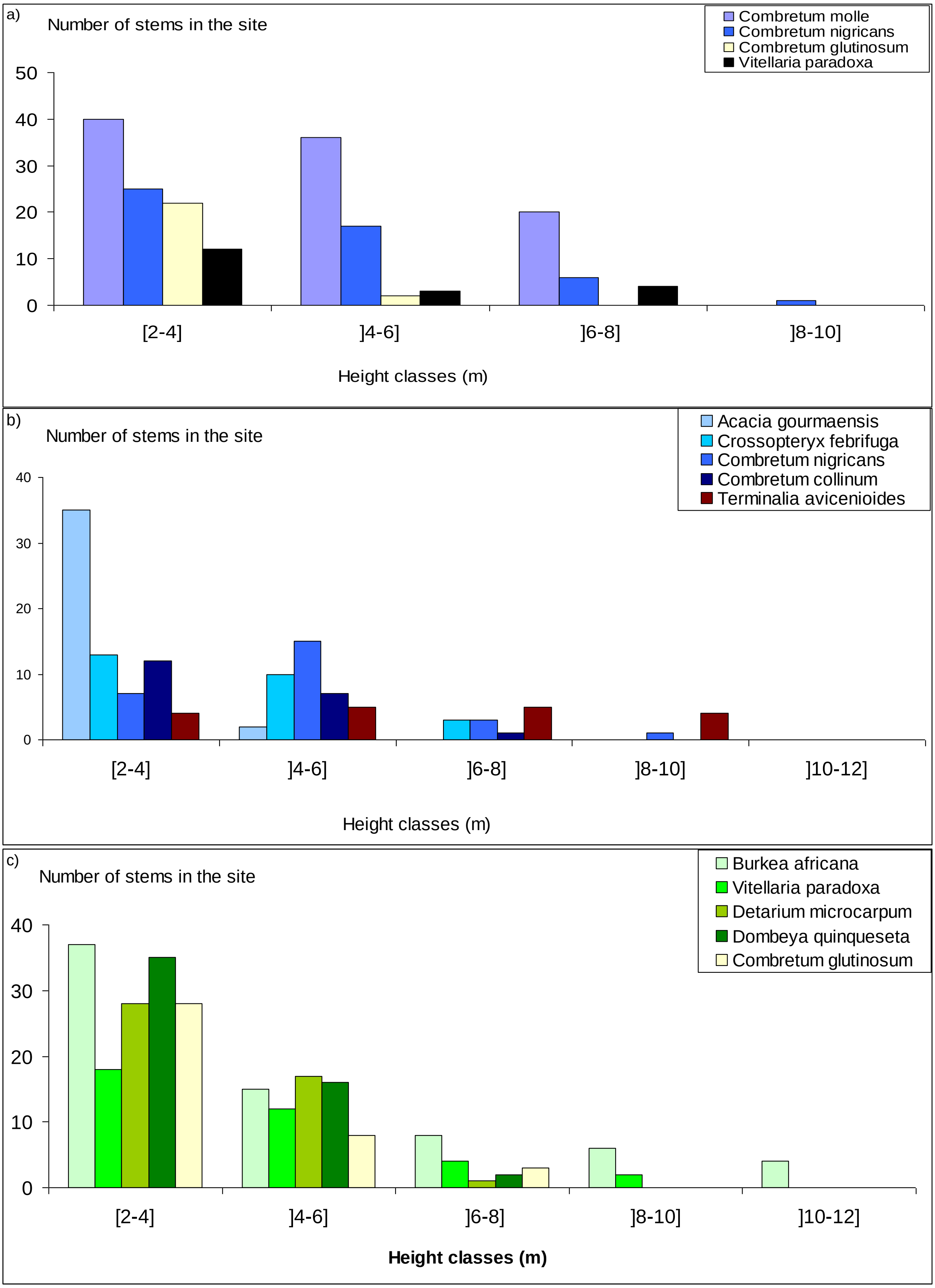


Figure 52: Distribution of height classes following the dominant species in the study areas (a: in the land-used site, b: in the partly protected site, and c; in the protected area).

Regeneration potential in the study areas

The regeneration potential in savanna woodland can be studied through the presence of juvenile plants as ascertained in many studies in the savanna landscapes (THIOMBIANO 2005, MWAWU et al. 2009). The woody plant regeneration depends on the nature of individual species, the type and intensity of degradation processes and/or disturbance in the plot (KY-DEMBELE et al. 2007, BATIONO 2002). To survey the regeneration plant of species in the different study areas, inventories of all juvenile plants in each relevé plot with a general standardised outer size of 50 m x 20 m, are undertaken. Thereby, all juvenile individuals with diameters less than 5 cm are considered. They are counted in the different sides of the standardised plots and in the middle (see 4.3). The analysis of the regeneration of woody plants is limited to a quantitative approach with the identification of woody species and their abundance, families as well as environmental conditions in the relevés.

In the land-used site of Kikideni the inventories of juvenile woody plants show the presence of 8 families (*Combretaceae, Mimosaceae, Balanitaceae, Rubiaceae, Rhamnaceae, Ebenaceae, Sapotaceae* and *Loganiaceae)* for 32 species (tab. 37). The *Combretaceae* family is omnipresent in all relevés. Thereby, unlike the adult woody plants abundance dominated by *Combretum molle* as observed above (see 5.4.2.1), *Combretum nigricans* is the most present plantlet with abundance ranged from 30 to 94 %. The total of juvenile plantlets in the land-used site averages 230 units.
However, the total plantlets are differently distributed according to the environmental and properties conditions of each plot. The site with the highest number of plantlets is identified in R2 with 57 individual plantlets for 6 families. This site is characterised by the seasonally flooded property as well as high organic matter and clay contents. These factors may support the regeneration of juvenile plants. The dominant specie *Feretia apodanthera Del.* member of the *Rubiaceae* family is, in addition, recognised as a typical woody plant growing in the temporary inundated zones of the Sudan zone ecosystems (ARBONNIER 2000). The regeneration potential in R4, R5 and R6 are rather limited in consideration of the amount of species (3 and respectively 2 juvenile plantlets are counted in each hectare plot). These sites are marked by the strong degradation of the surface and/or massive sheet wash erosion, pasture farmland through the *Fulani* local population (ethnic group which rear principally cattle) and thus scarcity of the woody plants as well as plantlets. The regeneration in these sites doesn't seem to be secured anymore. It is important to mention that species with a particular socio-economic importance for the population as *Vitellaria paradoxa,* characterised in the land-used site by a presence of relative high portion of adult individuals as observed in the diameter class analysis, are quite missing in the juvenile population of woody plants in the different plots. This observation is confirmed in previous studies about *Vitellaria paradoxa* regeneration potential which were hundertaken in the same zone (THIOMBIANO et al. 2000).
To summarize, it is ascertainable that regeneration potential in consideration to the number of plantlets in the land-used site changes in relationship to the degradation intensity and use conditions as well as drainage conditions.

Relevés	Species	Family	Dominant species	Abundance (%)	Total juvenile plants	Environmental conditions/ relief unit
1	5	*Combretaceae Mimosaceae Balanitaceae*	*Combretum nigricans Combretum glutinosum*	40 18	22	plot adjoining a valley, grazing
2	8	*Rubiaceae Rhamnaceae Combretaceae Mimosaceae Ebenaceae Sapotaceae*	*Feretia apodanthera Ziziphus mucronata*	75 7	57	seasonally flooded valley plot
3	5	*Combretaceae Mimosaceae*	*Combretum glutinosum Combretum nigricans*	37 30	46	slope related to the previous (valley)
4	3	*Combretaceae Rubiaceae*	*Combretum glutinosum Combretum nigricans*	65 29	17	plateau unit
5	2	*Combretaceae*	*Combretum nigricans*	83	6	slope following degraded zone, strong, sheet wash erosion
6	3	*Combretaceae Rubiaceae*	*Combretum nigricans Feretia apodanthera*	94 4	51	gully, grazing
7	7	*Combretaceae Mimosaceae Rubiaceae Loganiaceae*	*Combretum nigricans Combretum glutinosum*	56 16	32	profile located near termite mound, gentle slope, grazing
Total	**32**	**8**			**231**	

Table 37: Inventory of juvenile woody plants in the different plots around soil profiles in relation to environmental conditions in the land-used site of Kikideni.

In the partly protected site of Natiabouani the inventory reveals a total of 600 juvenile woody plants as observed in the following table (tab. 38). These individual plants are distributed in 13 families (*Anacardiaceae, Annonaceae, Bignoniaceae, Bombacaceae, Caesalpiniaceae, Celastraceae, Combretaceae, Fabaceae, Loganiaceae, Mimosaceae, Rubiaceae, Sapotaceae,* and *Tiliaceae).* The dominated families are *Rubiaceae* with species like *Crossopteryx febrifuga* and *Feretia apodanthera* and *Combretaceae with Combretum collinum* and *Combretum nigricans* and reflect partly the composition of the adult woody plants in the zone. A total of 44 plantlets species are identified. Nevertheless, they are unequally distributed in the different plots like in the land-used site. Indeed, R1, R3 and R4 are the plot with the highest total individual plantlets. R1 is located in a relative gentle slope adjoining the river (see 5. 1.2., phot.13) with dense woody and grass cover impeding *de facto* the development of sheet wash erosion and thus provides relative stabile conditions for plantlet regeneration. R4 where the highest number of woody families is identified (9) is marked by the seasonally waterlogged conditions and a dense grass cover even during the end of the dry season (phot.22). R3, which is characterised by the high presence of individual juvenile plants, reveals the presence of numerous termite mounds at the surface. But a direct link of regeneration potential and termite mound could not be established. The lowest species and juvenile plant numbers are counted in R2 and R5. Both plots are characterised by the presence of intense sheet wash erosion and thus instable conditions for the woody plant regeneration as observed in some plots within the land-used site of Kikideni.

Relevés	Species	Family	Dominant species	Abundance (%)	Total juvenile plants	Environmental conditions/ relief unit
1	11	*Combretaceae* *Rubiaceae* *Mimosaceae* *Sapotaceae* *Fabaceae* *Annonaceae* *Celastraceae* *Bignoniaceae*	*Combretum collinum* *Combretum nigricans*	28 16	89	plot adjoining river, thick fine material in soil profile
2	4	*Mimosaceae* *Combretaceae* *Rubiaceae*	*Acacia gourmaensis* *Feretia apodanthera*	43 30	23	plateau within a degraded site near the BIOTA hectare plot
3	11	*Combretaceae* *Mimosaceae* *Rubiaceae* *Anacardiaceae* *Bignoniaceae*	*Crossopteryx febrifuga* *Dichrostachys cinerea*	34 24	287	plot in site with termite mounds
4	16	*Combretaceae* *Mimosaceae* *Rubiaceae* *Fabaceae* *Loganiaceae* *Tiliaceae* *Caesalpiniaceae* *Bombacaceae* *Celastraceae*	*Combretum molle* *Feretia apodanthera*	17 15	151	temporary inundated site
5	2	*Combretaceae*	*Combretum nigricans*	97	49	plot within a eroded plateau
Total	**44**	**13**			**599**	

Table 38: Inventory of juvenile woody plants in the different plots around soil profiles in relation to environmental conditions in the partly protected site of Natiabouani.

The HZ of the Pendjari Park identified as part of the South Sudan savanna ecosystem with predominance of tree and savanna woodland reveals a total number of juvenile plants of 470 units. They are distributed in 13 families and 62 species (tab. 39). Nearly, the same plantlet families as those identified in the partly protected site of Natiabouani are surveyed in the HZ and that for 7 hectare plots. Because of the different properties of soil structure on the surface as well as prevailing erosion processes, a comparison between these two protected areas is sustainable only to a limited extent. Nevertheless, the components of the woody plantlets family reveal a certain affinity. Almost all hectare plots show the presence of juvenile species varying between 8 and 12 species. The most dominant species are *Pteolepsis suberosa, Combretum glutinosum* as member of the *Combretaceae* family and *Strychnos spinosa* (*Loganiaceae*). In conformity with abundance of species in the HZ, *Caesalpiniaceae* with species like *Burkea africana and Detarium microcarpum* are omnipresent particularly on the top of hill and/or in hectare plots by the stony structure of the soil surface and relative steep slopes (R1).

Relevés	Species	Family	Dominant species	Abundance (%)	Total juvenile plants	Environmental conditions/ relief unit
1	8	*Combretaceae, Mimosaceae, Rubiaceae, Fabaceae, Loganiaceae, Caesalpiniaceae*	*Pteolepsis suberosa* *Burkea africana*	58 12	161	Hill top, stony structure
2	12	*Loganiaceae Combretaceae Mimosaceae Rubiaceae Caesalpiniaceae Sapotaceae Meliaceae Bignoniaceae*	*Pteolepsis suberosa* *Detarium microcarpum*	33 18	51	plot in valley adjoining hill unit
3	8	*Mimosaceae Bignoniaceae Fabaceae Celastraceae Sapotaceae Annonaceae Combretaceae Caesalpiniaceae*	*Pterocarpus erinaceus* *Acacia gourmaensis/* *Vitellaria paradoxa*	35 19 -	37	Plain unit
4	12	*Combretaceae Caesalpiniaceae Mimosaceae Meliaceae Celastraceae Sapotaceae Loganiaceae Sterculiaceae Bombacaceae*	*Strychnos spinosa* *Burkea africana*	29 18	93	plateau unit with stony structure
		Sterculiaceae Mimosaceae				

5	11	*Loganiaceae* *Fabaceae* *Caesalpiniaceae* *Combretaceae* *Celastraceae* *Bombacaceae*	*Pterocarpus erinaceus* *Dombeya quinqueseta*	26 20	35	small valley, gravelous structure
6	2	*Combretaceae*	*Pteolepsis suberosa*	94	19	plain near hill
7	9	*Combretaceae* *Caesalpiniaceae* *Sapotaceae* *Mimosaceae* *Rubiaceae* *Sterculiaceae* *Celastraceae*	*Combretum glutinosum* *Dombeya quinqueseta*	24 20	74	hill top, stony structure
Total	**62**	**13**			**470**	

Table 39: Inventory of juvenile woody plants in the different plots around soil profiles in relation to environmental conditions in the HZ of Pendjari.

Conclusion

The analysis of the vegetation structure in the land-used and protected sites reveals some distinctive aspects in the diversity and/or dynamic of the woody plants. The comparison of the vegetation type reveals a change from shrub savanna with the predominance of *Combretaceae* in the land-used and pasture site of Kikideni to the tree savannas in the partly protected and in the HZ. The partly protected site is dominated, by *Combretaceae, Rubiaceae* (*Crossopteryx febrifuga)* and *Mimosaceae* (*Acacia gourmaensis*) while in the HZ of Pendjari *Caesalpiniaceae* (*Detarium microcarpum* and *Burkea africana*) and *Sterculiaceae* (*Dombeya quinqueseta*) are the dominant woody plant families.
The analysis of diversity indices as species richness shows an increase while basal surface of the woody cover decreases from the land-used site to the protected zones. The latter parameter gives an indication of the structure of surveyed woody plants in the different plots. Indeed, the analysis of diameter and height classes of the vegetation shows the importance of diameter classes comprised between 6 and 10 cm and height classes comprised between 2 and 4 meters in all sites. This generally indicates the presence of relative young woody plants. However, a focus on the higher diameter and height ranking of dominant species shows that the number of adult species are more widespread in the land-used sites indicating thus the presence of more young trees in the vegetation composition of the partly and protected areas. This statement is corroborated by the analysis of regeneration potential following the different plots in the different land use conditions. In addition, it is important to mention that like in the variations of soil properties within a transect (see 5.3), the vegetation structure and composition vary following the environment pedological processes as degradation, erosion and drainage conditions. The influence of individual soil parameters, except clay contents in the vegetation structure could not be identified. The following multivariate analysis may provide specific information about relationship soil parameters and woody plant dynamic and structure.

5.4.2.3. Multivariate analysis of woody plant communities

The ultimate aim of this part of the analysis of woody plant communities, its distribution and relationship to the environmental parameters or rather soil parameters involves finding ways to combine the vegetation composition of the different *relevés* with some soil properties. This can be achieved through complementary statistical and/or multivariate data analysis which is based on a graphical representation of samples plots and species. Thereby, two ordination types are chosen: the detrending correspondence analysis (DCA) and the canonical correspondence analysis (CCA see 4.4.2.).
The species and sites of the different study areas (land-used, partly protected and hunting zone) are classified in a main matrix including 42 species and 17 sites. In second matrix soil parameters as pH (KCL), thickness of topsoil, clay, sand and silt as well as CEC and total P representing important parameters that might influence on the vegetation distribution and composition are selected following the same sites chosen for the main matrix. The 2 matrix are reformatted into Lotus 1-2-3 files for PC-ORD and transposed so that the rows are now plots and the columns are species. The statistical summary of rows and columns computes different diversity parameters as species richness (see above), evenness index Shannon index and Simpson's diversity index according to the different sites (tab. 40). In the previous species richness and Shannon index were determined globally for each site. However, the variation of these diversity indices confirms the increase of species richness from the land-used site to the protected ones. Evenness index shows the species are better distributed in the partly protected site of Natiabouani. The Shannon index and Simpson's diversity are lower in the land-used site than in the protected areas.

Table 40: Summary of the diversity parameters computed in the different plots. **S**: species richness of each site, E: evenness index, E= H / ln (Richness), **H´**: Shannon index, **D´**: Simpson's diversity index for infinite population = 1 - sum (Pi*Pi) where Pi = importance probability in element i (element i relativised by row total). **Pl:** corresponds to relevé plot and the number to the soil profile.

Number.	Plot	**S**	**E**	**H`**	**D`**
Land-used site Kikideni (Kik)					
1	Pl. Kik*1	5	0.802	1.291	0.6716
2	Pl. Kik2	16	0.827	2.293	0.8587
3	Pl. Kik3	4	0.726	1.006	0.5747
4	Pl. Kik5	3	0.708	0.778	0.4383
5	Pl. Kik8	4	0.876	1.215	0.6667
6	Pl. Kik9	6	0.679	1.217	0.6084
7	Pl. Kik11	10	0.900	2.072	0.8535
	Averages	6.8	0.77	1.41	0.66
Partly protected site Natiabouani (Nat)					
8	Pl. Nat*2	10	0.870	2.003	0.8368
9	Pl. Nat4	5	0.816	1.313	0.6593
10	Pl. Nat7	11	0.910	2.182	0.8686
11	Pl. Nat9	9	0.902	1.981	0.8333
12	Pl. Nat11	9	0.784	1.723	0.7738
	Averages	8.8	0,86	1.84	0.8

Table 40, continued

Hunting zone of Pendjari (Cy)					
13	Pl. Cy*1	15	0.783	2.119	0.8204
14	Pl. Cy2	11	0.863	2.069	0.8438
15	Pl. Cy5	11	0.794	1.905	0.7897
16	Pl. Cy6	17	0.803	2.274	0.8319
17	Pl.Cy8	7	0.943	1.834	0.8200
	Averages	12.2	0,8	2,03	0,82

The indirect gradient analysis (DCA) represents an interesting method of ordination and visualisation of the phytosociological *relevés*. Indeed, it ordinates samples and species simultaneously following the axis by “detrending” (see 4.4.2.) and “rescaling”. “Detrending” in PC-ORD is the process of removing the arch effect, which is a distortion or artefact in the ordination diagram in which the second axis is an arched function of the first axis, by dividing the first axis into segments, then setting the average score on the second axis within each segment to zero (HILL et al. 1980). With the “rescaling” the DCA ordination equalises as much as possible the sample variance of species scores along the sample ordination axis.
With the “detrended by segments” the length of gradients of the different axis are determined. The latter are good indicator for the diversity of the woody plants in all the plots and thus a supplementary medium for assessing the diversity in the study areas. The rare species with 1 or 2 occurrence in a specific site are not considered in the DCA analysis in order to give rare species less weight and thus more equilibrium to the results. The results of the ordination reveal according to the amounts of eigenvalue for each dimension that axis 1 with 0.6 plays a more significant role in the partition of species followed by axis 2 with 0.4. This means that the first axis indicates a good dispersion of the species along this axis (fig. 53) and the latter are more different each other. Indeed, the eigenvalues decrease from axis 1 to axis 3. The total variance (TER BRAAK et al. 2002) which is the sum of eigenvalues reflects the spread of points around the centroid and represents the total variance in the context of correspondence analysis and amounts 3.9 in this analysis (tab. 41)
An important parameter in the DCA analysis is the length of gradient or “beta diversity” because measuring the amount of change in species composition along a directly measured gradient in environment (MC CUNE et al. 2002).The length of gradients along the different axis range from 3.2 standard deviation (SD) to 1.92 SD on axis 3. A length of gradient of 4 SD implies species turn over and that means that a certain number of species appear and disappear over a span of about 4 SD. Also, a species turnover is not observed in the different sites with different land use conditions, geomorphological features as well as partially climatic conditions. The maximum sample score is 3.3 SD along the second axis and indicates that no species are shared at the opposite ends of the gradient. The beta diversity on this axis as well as on axis 1 might be high or heterogeneous.

Axes	1	2	3	Total variance (Inertia)
Eigenvalue	0.62	0.41	0.22	3.81
Length of gradients	3.24	3.30	1.92	

Table 41: Summary of detrended correspondence analyses (*DCA*) based on the woody plants species in the *relevé* plot.

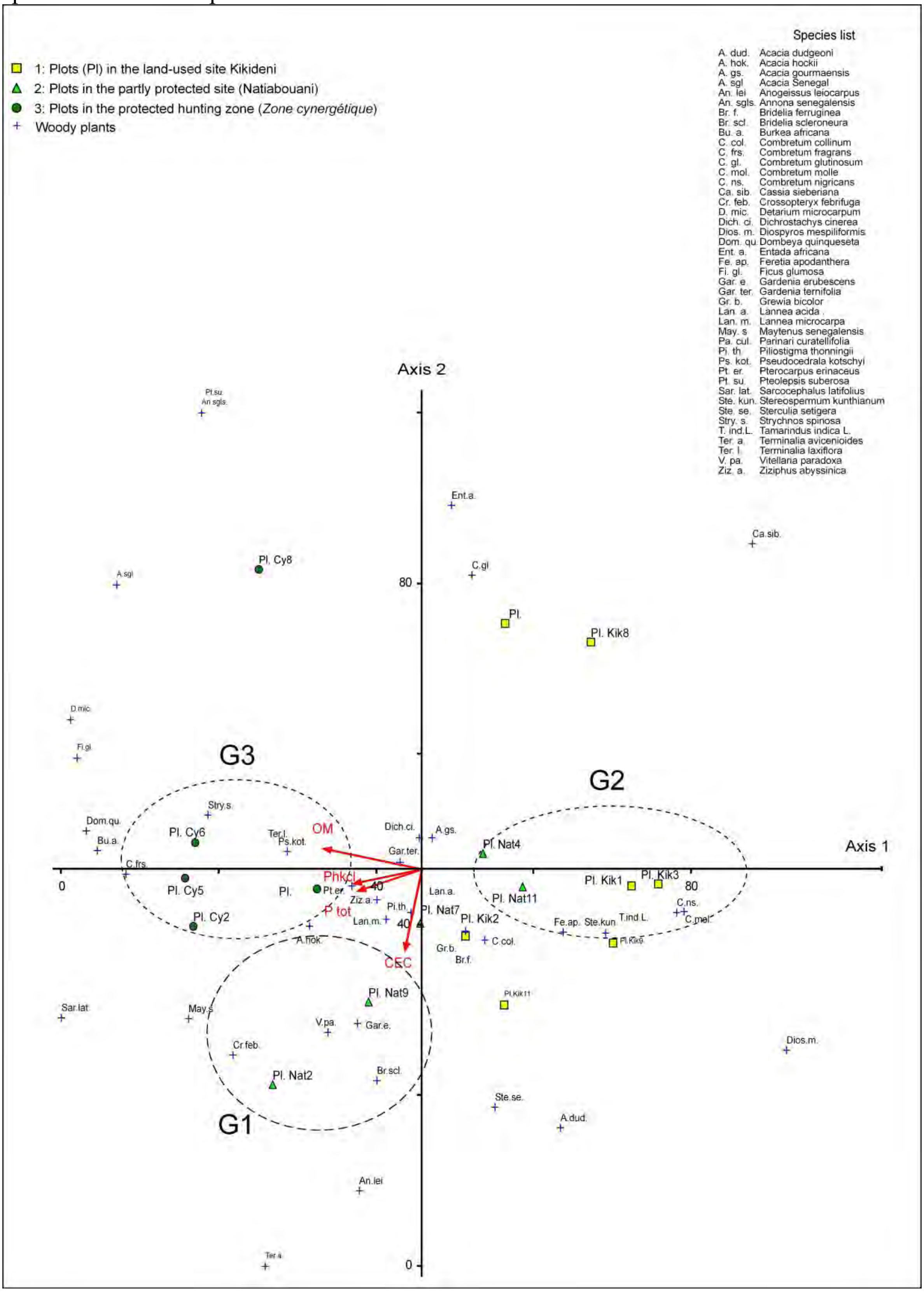


Figure 53: Ordination diagram of detrended correspondence analysis (DCA) in 17 sites and 44 woody species related to 8 soil parameters through join plot in the study areas.

The ordination diagram represented above tends to confirm the previous measures of length of gradients and eigenvalues of the different axis. Indeed, it is noticeable that the majority of samples and sites are correlated to the first axis. The DCA diagram dissociates from the left to the right 2 samples and sites scores groups which are quite dissimilar. G3 represents essentially the relevés plots from the hunting zone of Pendjari (plots 1, 2, 5 and 6) while the G2 is composed of sample and species scores from the land-used site of Kikideni, principally those sites which are identified as relative degraded (plots 1, 3 and 9) These plots show the lowest species richness in this zone (tab. 40). The first axis can be considered as climatic and anthropogenic gradient because separating clearly sites which have no similarities in the vegetation composition as well as in the prevailing environmental conditions (see 5.4.2.2.).

The axis 2 separates 2 groups. G4 which characterises the sites where a high pasture is noted (plots of the land-used areas and of the hunting zone). The plot Pl. Cy8 in the hunting zone located near hill units was recognised as trail for the illegal pasture activities in the hunting zone. This plot is characterised by the scarcity of the woody plants and the regeneration potential (tab. 44, R6). G1 assembles the plots characterised by relative stable conditions (deep soil, gentle slope like Pl. Nat 2 situated in the partly protected zone of Natiabouani and Pl. Kik 11 in the land-used site of Kikideni and presenting less degradation evidence) or seasonally waterlogged conditions (Pl. Nat 9 and Pl. Kik 2).

Furthermore, DCA provides a way of representing samples units and variables in a single diagram. These variables are mostly environmental ones (TER BRAAK 1986). In this analysis it is aimed to test the correlation of individual soil parameters to the relevés plots and species. Thereby, some soil parameters are chosen. Through the function biplot of PC-ORD, sample units are plotted as points, the variable in the species matrix as an additional set of points and the soil parameters as vector of various lengths radiating from the centroid of the diagram (fig 56). The DCA diagram shows 4 soil parameters which may play a role. The organic matter is more correlated to axis 1 and might explain the distribution of G3 better than G2 while the cation exchangeable capacity (CEC) is more correlated to the axis 2 and to the subgroup G1. These results tend to confirm the analysis of soil parameters in the different sites (see 5.3). Indeed, the relative amounts of soil organic matter in the different profiles in the hunting zone are higher than those measured in the land-used sites. Additionally, the mean amounts of CEC in the partly protected site of Natiabouani were on the highest measured values and may explain why the majority of the plot relevés of this site are correlated in the ordination diagram to the CEC vector.

This form of representation of samples and soil parameters based on the indirect gradient analysis corresponds to the main variation in the species data does not really inform about the correlation of soil parameters and species composition (LEYER et al. 2008). But the Canonical correspondence analysis is a complementary procedure to the DCA. CCA is designated as direct gradient analysis because incorporating the environmental data into the analysis. It is calculated using reciprocal averaging form of correspondence analysis. However, at each cycle of the averaging process, a multiple regression is performed of the sample scores on the environmental variables. New site scores are calculated based on this regression, and then the process is repeated, continuing until the scores stabilise. CCA is an iterative method. In the present analysis 100 numbers of runs or “rearrangements” are computed. The gradients of the ordination axes are supposed to have a linear relationship to the environmental parameters. This method provides a general framework for the estimation and the statistical testing of possible correlations. The estimation occurs principally through some statistical parameters as

inter set correlation of the 8 soil parameters species scores from the main matrix (TER BRAAK 1986), the Monte Carlo test as well as results of the species and environment correlations. The Monte Carlo test is a useful parameter for assessing the correlation between soil parameters and sample scores. The statistical analysis of the CCA is presented in the following tables (tab.42, 43).
From the results it is noticeable that inter set correlations following the different axes are generally low and it indicates that soil parameters explain marginally the sample and species scores. Soil organic matter is moderately negative correlated the axis 1 confirming, in fact, the results of the DCA diagram exposed above. Apart of this correlation coefficient, all other ones can e considered as very negligible. In addition, considering the Monte Carlo test with p = 0.14, a correlation between soil parameters and sample – species scores is not established because the test values has to be ≤ 0.05. If the criterion is not met like in this CCA analysis there is every indication of missing correlation.

Inter-set correlations for 8 soil parameters

	Correlations		
Variables	Axis 1	Axis 2	Axis 3
pH (KCL)	-0.269	**-0.460**	0.096
Thickness of topsoil	**0.414**	-0.248	-0.112
Clay	0.143	0.382	-0.365
SOM	**-0.682**	-0.122	-0.002
Total P	-0.321	-0.346	-0.291
CEC	-0.311	-0.263	-0.517
Total Sand	0.288	-0.205	0.240
Total silt	0.248	-0.118	**-0.411**

Monte Carlo Test results-species-environmental correlations

Real data		Randomised data Monte Carlo test, 99 runs			
Axis	Species env. corr. *	Mean	Minimum	Maximum	**p**
1	0.966	0.941	0.857	0.986	
2	0.927	0.932	0.849	0.984	**0.1400**
3	0969	0.923	0.810	0.991	

Table 42: Summary of the statistical analysis of the CCA analysis computed in PC-Ord.

These results are otherwise confirmed y the Pearson and Kendall correlations from the statistical analysis undertaken by the DCA ordination (tab. 48). The Kendall rank coefficient (tau) is often used as instrument in a statistical hypothesis test to set up whether two variables may be regarded as statistically dependent. The correlation coefficients indicate very low correlations like by the inter-set correlations and following the different axes. The Pearson

rank correlation of species and soil parameters shows the similar tendency of relationship between soil properties sample-site scores and distribution.
Furthermore they reflect the correlation of individual parameters like OM and CEC to the axis 1 and respectively axis 2.

Axis 1				Axis 2			Axis 3		
	r*	**r-sq***	**tau***	r	r-sq	tau	r	r-sq	tau
Phk cl	-0,4	0,2	-0,2	-0,2	0,0	-0,1	-0,1	0,0	0,1
Thic kn	0,1	0,0	0,1	-0,1	0,0	-0,1	-0,4	0,1	-0,2
clay	0,1	0,0	-0,1	-0,2	0,0	-0,1	0,0	0,0	-0,1
OM	**-0,5**	0,2	-0,5	0,2	0,0	0,0	0,1	0,0	0,1
Ptot	-0,4	0,2	-0,5	-0,2	0,1	-0,1	-0,2	0,0	-0,2
CEC	-0,3	0,1	0,0	**-0,6**	0,3	-0,5	-0,3	0,1	-0,1
San d	0,2	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,1
silt	-0,2	0,0	-0,2	0,2	0,0	0,1	-0,3	0,1	-0,1

Table 43: Results of the DCA correlation with the soil parameters (second and main matrix); **r**: Pearson correlation, **r-sq**: r^2, **tau**: Kendall rank correlation.

Conclusion

The multivariate analysis based on the DCA and CCA turns out to be an interesting tool for the study of relationship between vegetation communities and environmental parameters and particularly soil parameters. DCA procedure and the diagram representation provide information about the affinity of species and samples plots. They give indication about the interacting relation of sample plot and soil parameters through statistical and graph ordination. The combination of both methods is necessary for the full significance of correspondence analysis.
DCA specifies through the length of gradients a splitting of specie and sample scores and allow gathering different affinity groups. Nevertheless, in the framework of the present soil and vegetation communities study, the analysis of woody plant composition and structure undertaken elsewhere (5.4.) reflects better the dynamic and variation according to the sites and different environmental conditions.

6. DISCUSSION

6.1. Interaction between soil properties and woody plants diversity

The soil-vegetation relationship is an important issue in the framework of savanna landscapes of West Africa because involving two vital components of the ecosystems. Soil as resource, its properties, dynamics and the intensity of the pedological processes (sheet wash erosion, leaching) are influenced by the vegetation composition, structure and density. The typology of vegetation communities is conditioned by the climatic variations and anthropogenic activities. Furthermore, vegetation units and dynamic are related to the soil types and parameters at a broad scale as observed in different studies (LEVÊQUE 1979, WEZEL et al. 2004, PICARD et al. 2005). The relationship between soil and vegetation and the processes linked to them are overlapped. Consequently, it is difficult to make an exhaustive analysis. There is also the fact that in this study the analysis of the soil properties and vegetation diversity relationship was undertaken in sites with different land use conditions and climatic characteristics, at least, in comparison between the sites in the PNP and those located in the South East of BF. In addition, geological and geomorphological features are slightly different following the previous comparison pattern. Nevertheless, the sites in BF reveal similar climatic conditions like average annual rainfall, granitic parent material allowing a direct comparison of soil dynamic and vegetation communities.

It was supposed in the analysis of soil-woody plants relationship that individual soil physical and chemical parameters may influence the vegetation composition, structure and diversity. Furthermore, it was presumed that the land-used status of a site may influence the diversity of vegetation communities and thus their potential to regenerate. The validity of these hypotheses might be crucial for the suitability of the established and implemented strategies and politics in conservation and monitoring of savanna landscapes under high human pressure as well as the relevance of biodiversity management tools in West Africa.

The analysis of vegetation composition in the land-used site of Kikideni and in the partly protected one of Natiabouani reveals a differentiation in the vegetation type. While in the land-used site shrub savanna is prevailing, tree savanna is the widespread vegetation unit in Natiabouani. Both sites are characterised by the predominance of the *Combretaceae* family. However, this tendency bears some discrepancy. Indeed, the surveyed phytosociological *relevés* along transects indicate a certain heterogeneity. It is observable that tree and shrub savanna units are found in the two study areas. The presence of tree savanna within intensive farming and pasture site is related to the water availability and the drainage conditions because developed in seasonally waterlogged valleys. This vegetation type has an azonal occurrence as observed in inundated depressions *(bas-fonds)* of central BN (ORTHMANN 2005). The shrub savanna in the partly protected appears to be the results of the degradation of soil surface consecutive to the intensive superficial sheet wash erosion. The vegetation types in the HZ of the PNP are essentially tree savanna dominated by the *Caesalpiniaceae* and *Sterculiaceae* families. Furthermore, the HZ is characterised by the appearance of new vegetation families as *Caesalpiniaceae* with species like *Burkea africana, Detarium microcarpum* which are recognized as particularly abundant on the top of the hill units in the study areas and in the

Atakora chains (WALA 2005). The sites where shrub savanna prevails are valleys and/or depressions, characterised by intensive sheet wash erosion related probably to the steep hill units adjoining these sites.

The height and diameter structures represent a good indicator for the assessment of diversity and dynamics of woody plants. In this study, it appears from the results that there is no significant differentiation of the woody plant diameter and height structures from the land-used to the partly protected site and the HZ of the PNP. In fact, the majority of the woody plants have a diameter at breast height ≥ 5 cm comprised between 6 and 10 cm according to the total number of stems in the sample plots. This is observable also in the distribution of diameter classes following the dominant woody plants in the different sites. In addition, the height class distribution from the land-used site to the protected ones shows, for the most part, that the species are dominated by the presence of juvenile individual plants regardless of the land use status. Indeed, the height class comprised between 2 and 4 meters is the most widespread size for the woody plants. Nevertheless, an increase of the number of stems in the height and diameter class distributions from the land-used site of Kikideni to the partly protected one of Natiabouani is ascertainable as well as from the partly protected site to the HZ of the PNP indicating a differentiation in the composition , dynamics and diversity of woody plants in the sites.

The regeneration potential which is assessed by listing the juvenile plants with DBH ≤ 5 cm follows the same tendency of differentiation from the land-used to the protected sites as identified by the diameter and height class distributions. In the land-used site of Kikideni 230 juvenile plantlets are identified following seven sample plots. They aree distributed in 8 families for 32 species and the *Combretaceae* with *Combretum nigricans* and *Combretum glutinosum* is the dominant family confirming the conducted investigations about the regeneration of woody plants in the north Sudan zone and under similar land use conditions (OUEDRAOGO 2005) as well as the vegetation composition of the adult woody community from the *relevés*. In opposite, the regeneration potential in the partly protected site of Natiabouani seems generally to be higher with around 600 inventoried juvenile plants. These plantlets are divided in 13 families, which are mostly composed by *Combretaceae* (*Combretum collinum, Combretum nigricans* and *Combretum molle*), *Rubiaceae* (*Feretia apodanthera*) and *Mimosaceae* (*Acacia gourmaensis*) for 44 woody species. These results are obtained with a lower sample plot number than in the land-used site. It is important to mention that there is a significant variation of the regeneration potential according to the number of plantlets within a site. The number of juvenile plants is low in sites presenting apparent signs of degradation through anthropogenic factores like in Kikideni and/or sheet wash erosion in both sites. Furthermore, in the valleys which are seasonally waterlogged, the regeneration potential like the woody plant abundance is higher than in the other sites in Kikideni as well as in Natiabouani. In the HZ of the PNP, which is part of the south Sudan savanna ecosystem, 470 woody plantlets are counted distributed in 13 families and 62 species. The woody plant families are nearly the same as those identified in the partly protected site of Natiabouani although the climatic and geophysical features are varying. The apparently higher regeneration potential in the partly protected and in the total protected sites of the PNP are related, apart of the land use status, to the influence of fire management strategies, which aim to maintain the species and plant community diversity and thus to guaranty the preservation and the availability of wild animal feeds.

The analysis of the diversity of plant species in the different land use conditions which occurred through the calculation of parameters like species richness, Shannon index, evenness index as well as basal surface provide adequate quantitative tools for the differentiation of the sites in the study areas. Similarly to the regeneration potential, the species richness generally increases from the land-used site with an average of 5 species/ 100m^2 to the partly protected (9 species/ 1000 m^2) and the total protected one with 12 species/ 1000 m^2. It is important to note that the species richness vary following the local conditions of the sample sites like by the regeneration potential. The species richness values of the waterlogged sites are higher than those of the plots under strong anthropogenic activities and/ or sheet wash erosion in Natiabouani and Kikideni. The sites with the highest species richness in the HZ of the PNP are characterised by the gravelous structure of the topsoil with, in part, the presence of blocks from the bedrock that might impede the development of sheet erosion and thus provide to these sites stable conditions for the vegetation growth. The Shannon index follows the same variation as the species richness with an increase of its values from the land-used site to the protected ones. In addition, the highest mean index is measured in the partly protected zone and indicates a better distribution and more evenness of the species. From the analysis of the diversity parameters variations it is assessable that land use conditions, fire management, climatic conditions, drainage conditions as well as the relief (presence of hill units) are the most important factors influencing the diversity of woody plants in the different sites of the savanna landscapes in BF and BN.

A direct relationship between the vegetation diversity and soil types could not be established through the analysis of the vegetation composition and structure because of the fact that soil groups differ slightly in the sites of South East BF and those located in North West BN. In the both different regions soil are the results of the same parent material, granite in BF and quartzite and quartz sandstones in the PNP and of the similar pedological processes as erosion types and presence of laterite crust in the subsoil. Nevertheless, the soil profiles and their layers vary according to the drainage conditions as well as anthropogenic activities. The role of individual soil parameters in the distribution of woody plants are studied through the multivariate analysis. Thereby, the CCA ordination method as an analysis based on the direct gradient with a multiple regression of the sample scores involving the physical and chemical parameters of soil profiles is used. The CCA analysis shows that there is no relationship between the sample and species distribution and the individual soil parameters according to the Monte Carlo test.

Moreover, the DCA analysis based on the indirect gradient analysis permitted to individualise four species and samples affinity groups following the different axis. Along the first axis, the sites of the land-used site Kikideni, particularly those presenting apparent degradation signs and with diversity are opposed to the sites of the HZ of the PNP according to a climatic and anthropogenic gradient while the second axis differentiates sites with stable conditions and/or waterlogged conditions to sites under the influence of high pasture. The affinity groups reflect the similar environmental conditions of individual sample plots as well as the land use status confirming therefore the differentiation of the vegetation diversity from the land-used to the protected sites. In addition, the DCA ordination reveals a significant correlation of soil organic matter explain better the distribution sites located in the HZ of the PNP following the axis 1 and cation exchangeable capacity values are related to the sites and samples of the partly protected site of Natiabouani on the axis 2. This confirms the analysis of the chemical parameters within the transects in the different sites.

Despite the established correlation of single soil parameters to the axes and to the distribution and thus composition of several sample plots, it is apparent from the multivariate analysis that individual soil parameters seem to be irrelevant in the diversity of woody plants and their dynamics and structures in the land-used and protected site of the study areas. The prevailing physical features, the pedological processes as erosion types (with the presence of gully erosion and/or the intensity of sheet wash erosion) as well as the anthropogenic factors as fire management, land tenure and pasture affect the diversity of vegetation communities within a site and all the more in sites with different land use, climatic and geomorphological conditions.

6.2. Variation of soil profiles and stratigraphy within the transects

The study of soil properties and stratigraphy are closely related to the geological and geomorphological features in the study areas. At the small scale analysis within the pedomorphological transects it is an obvious purpose to focus on pedological processes which are determinant for the differentiation of soil properties. Soil types and groups differ only to a limited extent because being originated from the same parent material and/or under the influence of similar geomorphic processes. The differentiation follows principally the different soil sciences schools: German, American, French etc. Therefore, soil properties and profiles, were analysed in this study taking into consideration the geomorphic processes as formation and evolution of erosion surfaces.

The study areas in South East BF, which are characterised by the presence of wide and gently peneplains are marginally affected by tectonic activities. In these formations different pedological processes occur and control the stratigraphy, physical and chemical characters of the soils as well as the dynamics within these geomorphological units. From the study of the different sites in BF taking into consideration the superficial processes as sheet wash and gully erosion, it appears that the latter erosion forms play an important role in the differentiation of soils profiles. Furthermore, the differentiation of soil profiles is influenced by different environmental factors as mean annual rainfall as well as its intensity, anthropogenic activities and drainage conditions. Nevertheless, the lateral and vertical variation of soil profiles is relatively minimal in consideration to the total surveyed soil profiles. Indeed, some pattern of variations could be assessed in the land-used and in the partly protected site. Thereby, the drainage conditions with the presence of seasonally waterlogged site and small rivers affecting the soil stratigraphy of the surrounding zones as observed in Kikideni and Natiabouani sites are important differentiation factors. In addition, it is important to mention that soil profiles vary within the transects in consideration to the texture, colour, thickness and individual chemical parameters but preserve basically the general properties of soils in north Sudan savanna landscapes of West Africa characterised by the presence of an illuviated layer with a clay enrichment and the occurrence of laterite crust. The land-used or protected status of the sites seems to be irrelevant in the differentiation of the soil properties and stratigraphy, at least, considering the soil parameters. This observation shows the necessity of taking into consideration other components of the ecosystem for example the vegetation. Indeed, the variations in the vegetation composition and structure provide visible interpretation points of the variability of soil profiles.

From the analysis of the different soil properties and evolution processes at this small scale within pedomorphological transects, and taking into consideration the different theories about morphogenesis and planation surfaces in Africa (KING 1951, MICHEL 1967, FÖLSTER 1970, BÜDEL 1981, RUNGE 1989-1990 and 1993), it emerges in our opinion that the pedimentation processes play an important role in the study areas. Indeed, influencing directly soil evolution and landscapes forms, the concept of pedimentation can be applied in the South East BF in spite of the flatness of the relief. However, the pedimentation processes are more suitable to the dynamic and morphology of the landscapes in the North West region of BN which are affected by the Pan-African orogeny and the formation of hill units and mountains as well as large peneplains. It is noticeable in the sites of the Pendjari Park that sheet wash erosion is omnipresent and intensive because of the slope degree differences, particularly in the sites located in the central part of the PNP. Generally, the variation of soil profiles and stratigraphy is less accentuated than in the sites of BF. The gravelous structure of the soil surface as well as the very large peneplains may be the reason of the limited consequences of the erosion processes.

SUMMARY

The present thesis is part of interdisciplinary and widespread researches on the state of biodiversity in West Africa undertaken in the framework of the BIOTA-AFRICA project.
As an essential issue for each Ecosystem, the study of soil properties related to geomorphological features, environmental conditions and vegetation dynamic is of particular importance in West Africa because involving parameters which are key determinants for food security and the biodiversity conservation. Understanding the interdependency soil-vegetation diversity requires furthermore a clear recognition of the complexity and the role of different compartments as relief evolution, dynamic and form, climate as well as human activities.

This thesis aims to analyse in a first step the physical and chemical properties of soil profiles along pedomorphological transects in different land used conditions (protected, partly protected as well as cultivated and pastured areas) in North West Benin and in South East Burkina Faso. The information about soils, which are carried out in consideration of the pedogenesis processes like weathering types, saprolitisation, formation of laterite crusts and denudation within the planation surfaces are therefore correlated in a second step with the structure and dynamic of woody plant around individual soil profiles. The relationship soil properties and woody plant is investigated in order to assess the reciprocal influence between the diversity of woody plants and soil characteristics within a small scale study and under different land use conditions.

The identification and survey of pedomorphological transects follow the existing BO´s which are 1 km^2 common and standardised plots of investigations for all BIOTA-researches. These plots are previously chosen mainly in consideration to the vegetation unities and to the influence of human activities. The environmental conditions as anthropogenic influence and the particularities of soil surfaces (texture, presence or not of rock particles, occurrence and distribution of lateritic and ferruginous crusts and or pisolites) are described every 50 meters along the transects. These descriptions lead to the choice of given sites for soil profile surveying taking into consideration changes in the vegetation structure (clearing or density), evidences of human activities (pasture, fire management etc.) as well as changing relief units (valley, peneplains and hill units) and environmental observations indicating the degradation of soils for example bare soil surface with very sparse woody and grass cover. The soil profile are standardised to 80 cm depth because of the occurrence of laterite crusts and / or hardening layer at this depth in the soil units of the savanna landscapes in South East Burkina Faso and North West Benin. Altogether 69 soil profiles are dug up for 191 soil samples.

The preliminary analysis of soil profiles and samples occurs first during the field works with description, measurement as well as estimation of colour, thickness, particle size as well as rooting system of the different soil layers and soil samples. In addition, the general characteristics of the woody and grass cover around the profile are briefly described with the identification of dominant species and the estimation of their height. The anthropogenic influences as grazing or fire are noticed. Finally, working hypotheses are developed in order to give reason for particular occurrences as outcrop of bedrock in the site, very sparse vegetation cover or massive presence of coarse material on the soil surface.

Apart from the observations at the field soil samples are analysed in the soil science laboratory of the University of Cotonou in Benin. The physical and chemical parameters which are significant for the soil-vegetation relationship are measured and analysed (chapters 5.1-5.2-5.3). Thus, the particle size distribution in the different layers is measured using the Robinson method which separates the soil fraction through sieve proceeding in fine and coarse sand, fine and coarse silt as well as clay. pH (H_2O), pH (KCl) as well as organic matter are estimated in the soil samples. Among the primary macronutrients Phosphorous and available Phosphorous for plants, Total Nitrogen as well as Potassium which are key elements for the plant nutrients are measured. At least Cation Exchange Capacity an important parameter for the assessment of agricultural and environmental features of soils is calculated taking into account the ion exchange in soils.

Moreover an exhaustive analysis of soil properties and dynamic requires highlighting some important geomorphic processes as planation surfaces and the formation and evolution of geomorphological units under climatic fluctuation particularly in the savanna landscapes of West Africa (chapter 4.4). The dynamic within these planation surfaces identified as *surface d´aplanissement* (MICHEL, 1973) or *Rumpffläche* (wide gently peneplains studied by BÜDEL, 1957) is influenced in the study areas of Burkina Faso and Benin by the alternating dry and humid season with important weathering types and erosion forms on the soil surface. The soil profiles and their classification in soil types are consequently conditioned by these processes.

Around the soil profiles, vegetation inventory are carried out following the same particularities leading to the choice of soil profiles because related to them. The homogeneity of the woody plant cover and its density are considered for the identification of *relevés* sites. Furthermore, the changing in the relief with different topography units like seasonally waterlogged valleys, plains and hill units constitute important factors for the analysis of vegetation structure and dynamic. For the surveying of the woody plant diversity, standardised plots (1000 m^2) are surveyed. The woody cover consisting of tree and shrub layer with Diameter Breast Height (DBH around 1.30 m from the soil) greater or equal to 5 cm is measured. In addition, the regeneration potential of each plot is studied through the inventory of woody plant species whose DBH less or equal to 5 cm. In the different study areas 20 phyto-sociological relevés are conducted for a total of 44 vegetation species. The investigations of vegetation dynamic and structure are based on the measurements of diametric structure by analysing all species in diameter classes, specific structure consisting of the ranking of diameter classes following the individual species and on the vertical structure involving the height of species. The estimation of the woody plant diversity occurs taking into consideration some parameters as species richness, basal surface and Shannon index.
Consecutively to the analysis of soil profile properties in the different land use conditions as well as their vegetation composition, dynamic and diversity (Chapter 5.4), the relationship soil and vegetation diversity is focused (chapter 5.5). Hereby, the multivariate analysis method is applied using the ordination techniques involving the soil parameter in the upper layer of the profiles and the woody plant species in the inventory plots surrounding the soil profiles.

The study of soil profiles in South East Burkina Faso and North West Benin reveals a common vertical and lateral differentiation of physical and chemical properties regardless of the partly protected, protected and cultivated status of the sites. Indeed, soil properties as texture, thickness, colour, rooting density, soil organic matter, available phosphorous among other

parameters vary considerably from the topsoil with a thickness varying from 0 to 20 cm depending on the status of the study areas and on the relief unit of the profile to the underlying layers (subsoil 20-80 cm). But the lateral differentiation of soil surfaces within the slope is generally more accentuated. This differentiation is obviously related to the intensity of erosion processes as well as the drainage conditions of site profiles. Thus, in the cultivated site of Kikideni and in the partly protected zone of Natiabouani (South East Burkina Faso) sandy loam and sandy clay loam soil surfaces are widespread because of the occurrence of similar erosion processes like sheet wash, rill and gully erosion while in the central part of the Pendjari National Park loamy soil textures are prevailing. In fact, the steepness of the relief and the length of the slopes in the Pendjari Park seem to limit the development of some erosion forms as gully. Furthermore, the classification of soils reflects the variation of pedological processes along the transects and thus the occurrence of different soil types.
The status of the sites may play an insignificant role in the differentiation of soil properties within the scale of small pedomorphological transects. Nevertheless, it is important to mention that the ratios available Phosphorous as well as the rooting density in the different layers and along the slopes seems to be a differentiation factor between land used on the one hand and protected sites on the other hand.

Comparatively to the detailed analysis of soil properties, the study of the vegetation diversity and structure which is closely linked to the changing in soils shows marked differences between sites. A direct comparison of the vegetation type in the land use respectively partly protected and in the total protected sites (National Park of Pendjari) reveals a transition from the shrub savanna to the tree savanna. *Combretacea* composed mostly *by Combretum molle*, *C. glutinosum* and *C. nigricans* appears in the land use site while *Rubiaceae* (*Crossopteryx febrifuga*), *Mimosacea* (*Acacia gourmaensis), Cesalpinacea* (*Detarium microcarpum*) as well as *Sterculiaceae (Dombeya quinquesta)* mixed with *Combretacea* are the dominant woody plant families in the protected zones. The seasonally flooded valleys are characterised by the occurrence of tree savanna independent of the status of sites.
The analysis of diameter and height classes shows that the majority of the individual species are young woody plants in all sites with diameter comprised between 6 and 10 cm and height between 2 and 4 meters. Nevertheless, by focussing on the higher diameter and height ranking, it is noticeable that the number of adult species is more important in the land use site than in the protected ones. Hereby, the use of fire for ecological management in the protected areas as well as the presence of wild animals (elephants) may be limiting factors for the development of trees.
The calculation of diversity indices like species richness which is an important factor for the characterisation of community diversity shows an increase from the land used site of Kikideni with 6.5 species / 1000 m^2 to the partly protected site of Natiabouani (9 species / 1000 m^2) while 13 species pro 1000 m^2 are recorded in the hunting and central zones of the Pendjari National Park. In contrast, the basal surface measurements indicate that the highest values are stored in the land use site (261.5 m^2 pro Hectare at a seasonally flooded valley). They decrease generally in the partly protected site and the lowest values are registered in the total protected sites of the Pendjari National Park. Similarly to the results on diameter and height classes the fire management seems to play an important role in the development of basal surfaces of woody plants.

In conclusion it is important to insist on the fact that the variations of soil parameters within small slopes and the different sites are more conditioned by varying erosion processes and drainage conditions than the status protected or land use sites while the composition and diversity of plants is influenced by the status of the sites, the prevailing management tools, the pedogenetic conditions as well as the presence of wild animals like elephants

The focussing on individual soil parameters (pH (KCL), thickness of topsoil, clay, sand and silt, Cation Exchange Capacity and total P) and their relationship to plant communities and its distribution occurs by using the detrending correspondence analysis (DCA) or indirect gradient analysis. The ordination diagram through DCA in 17 sites with 44 species related to 8 soil parameters shows that the organic matter is better correlated to the subgroup representing principally the sites of the hunting zone of the Pendjari Park and might be an explaining factor to the distribution of these sample sites groups while CEC values are strong correlated on the axis 2 to the subgroup characterised by stable conditions (deep soil, gentle slope and or presenting less degradation evidences). CEC ratios in the partly protected site of Natiabouani represent the highest measured in all sites. Nevertheless, statistical analysis of the CCA (canonical correspondence analysis) based on inter set correlation of soil parameters to the different Axis (1, 2 and 3) indicates generally a low correlation. This tendency is consolidated by the Monte Carlo test ($p=0.14$) which is a good indicator of species and environmental conditions. In fact, the correlation between soil parameters and sample species scores is only establish if test value ≤ 0.05. Soil parameters explain insignificantly the sample and species scores in the study areas

The detailed analysis of soil properties and the vegetation dynamic as well as their relationship within small pedomorphological transects represent an important pedological and botanical data collection involving different compartments. This thesis contributes to the better understanding of the savanna landscapes of West Africa and may provide essential scientific background for each development project directed towards interdisciplinary and integrative researches.

ZUSAMMENFASSUNG

Die vorliegende Arbeit ist Teil der interdisziplinären Forschung über den Stand zur Biodiversität in Westafrika, welche im Rahmen des durch das Bundesministerium für Bildung und Forschung (BMBF) gefördeten BIOTA-AFRIKA-Projektes durchgeführt würden. Als wesentlicher Bestandteil des Ökosystems die Bodeneigenschaften, werden unter Berücksichtigung der geomorphologischen Merkmalen, der Umweltbedingungen und der Vegetationsdynamik untersucht. Die Untersuchung der Böden in Westafrika ist von großer Bedeutung, da diese einen entscheidenden Faktor zur Ernährungssicherung und zum Erhalt der Biodiversität darstellen.

Ziel dieser Arbeit ist zum einen das Verstehen der Wechselbeziehungen zwischen den Bodencharakteristika und der Diversität von Gehölzen im Untersuchungsgebiet und zum anderen die Einbindung des geomorphologischen Prozessgefüges in diese Wechselbeziehungen. Es erfordert eine klare Identifikation der Funktion verschiedener Prozesse wie die Reliefentwicklung, -dynamik und -form, das Klima sowie die anthropogenen Aktivitäten. In einem ersten Arbeitsschritt werden die physikalischen und chemischen Eigenschaften von Bodenprofilen entlang geomorphologischer Transekte in verschiedenen Stadien oder Nutzungsformen (geschützte, teilweise geschützte sowie angebaute und beweidete Gebiete) in Nordwest-Benin und Südost-Burkina Faso untersucht. Die Analyse der Böden und ihrer pedogenen Prozesse wie Verwitterung, Bildung von Lateritkrusten und Denudation innerhalb der Einebnungsflächen wird in einem zweiten Arbeitsschritt mit der Struktur und Dynamik der Gehölze an den einzelnen Bodenprofil-Standorten korreliert. Die Identifikation und Untersuchung pedomorphologischer Transekte erfolgen in Anlehnung an die bestehenden Biodiversitätsobservatorien (BO´s). Dabei handelt es sich um gemeinsame und standardisierte Langzeituntersuchungsflächen, auf denen alle BIOTA-Studien stattfinden. Sie würden in erster Linie ausgewählt, um die Vegetationseinheiten und die Auswirkung der Landnutzung auf sie hervorzuheben. Die Umweltbedingungen wie anthropogene Einflüsse und Besonderheiten der Geländeoberflächen (Textur, Präsenz von Gesteinspartikeln, Vorkommen und Verbreitung von eisenhaltigen und lateritischen Krusten sowie Pisolithe) wurden alle 50 m entlang der Transekte aufgenommen. Zusammenhang zwischen den Bodeneigenschaften und auftretenenden Gehölzarten wurde untersucht um die wechselseitige Beeinflussung zwischen der Diversität von Gehölzen und Bodencharakteristika festzustellen. Diese Beschreibungen führten zur Auswahl einiger Standorte für die detaillierte Bodenaufnahme unter Berücksichtigung von Veränderungen in der Vegetationsstruktur (zunehmende Dichte oder Auflichtung der Vegetation), von Anzeichnen anthropogener Aktivitäten (Beweidung, Feuer-Management etc.), von Änderungen der Reliefeinheiten (Täler, Peneplains und Hügel) und von Umweltbeobachtungen, die auf Bodendegradation hinweisen. Dazu zählen vegetationslose Böden mit spärlichen Gehölzen und Grasbedeckung. Die Bodenprofile sind aufgrund des Vorkommens von Lateritkrusten und / oder verhärteten Schichten in den Böden der Savannenlandschaften im Untersuchungsgebiet auf eine standardisierte Tiefe von 80 cm limitiert. Insgesamt wurden 69 Bodenprofile angelegt und 191 Bodenproben entnommen.

Während der Geländearbeit fand die Untersuchung der Bodenprofile und Bodenproben bereits vorläufig in Form einer descriptiven Aufnahme statt mit der Einmessung sowie der Klassifikation von Bodenfarben, Horizonr-Mächtigkeit, Korgröße und Durchwurzelungsintensität der verschiedenen Bodenschichten und Bodenproben. Zusätzlich wurden die allgemeinen Eigenschaften von Gehölz- und Grasbedeckung in der direkten Umgebung der Bodenprofile erfasst und beschrieben. Die Aufnahme umfasste auch die Identifikation der vorherrschenden Arten und der Einschätzung ihrer Höhe. Anthropogene Einflüsse wie Weidewirtschaft wurden ebenfalls festgestellt. Anhand von Aufschlüssen anstehenden Gesteins, spärliche Vegetationsbedeckung oder hohe Präsenz von Grobmaterial auf der Bodenoberfläche wurden bereits im Gelände erste Arbeitshypothesen entwickelt.

Abgesehen von diesen Feldbeobachtungen wurden die Bodenproben in dem bodenkundlichen Labor der Universität Cotonou in Benin analysiert. Die wichtigsten physikalischen und chemischen Bodenparameter für die Analyse der Wechselwirkungen zwischen Boden und Vegetation wurden gemessen (Kapiteln 5.1, 5.2, 5.3). Die Korngrößenverteilung (fünf Fraktionen: Feinsand, Grobsand, Fein- und Grobschluff sowie Ton) wurden durch Siebverfahren bestimmt. Der pH-Wert (H_2O und KCL) und organisches Material wurden ebenfalls analysiert. Die Hauptnähstoffe wie Phosphor, Pflanzenverfügbares Phosphor, Gesamtstickstoff sowie Kalium und Kationenaustauschkapazität wurden ermittelt. Letztere stellen entscheidende Parameter für die Nährstoffversorgung der Pflanzen dar.

Außerdem erforderte die umfassende Analyse der Bodeneigenschaften und -dynamik die Typisiereung wichtiger geomorphologischer Prozesse wie die Genese von Einebnungsflächen sowie die Bildung und Weiterentwicklung von geomorphologischen Einheiten unter dem Einfluss klimatischer Schwankungen in den Savannenlandschaften Westafrikas (Kapitel 4.4). Die Dynamik innerhalb der Einebnungsflächen (MICHEL, 1973: *surface d´aplanissement* ; BÜDEL, 1957: *Rumpffläche*) in den Arbeitsgebieten Burkina Fasos und Benins, ist beeinflusst von wechselnden Feucht- und Trockenzeiten mit charakteristischen Verwitterungstypen und Erosionsformen auf der Bodenoberfläche. Die Klassifikation der Böden und die Genese unterschiedlicher Bodenprofile sind folglich das Resultat dieser Prozesse.

Die Vegetationsaufnahmen wurden in direkter Umgebeung der Bodenprofile durchgeführt, angelehnt an dieselben Kriterien, die zur Auswahl der Standorte der Bodenprofile führten aufgrund des Zusammenhangs beider Faktoren. Die Homogenität und die Dichte der Pflanzenbedeckung sind entscheidend für die Identifikation von *relevés*-Standorten. Darüber hinaus stellen die Unterschiede im Relief mit verschiedenen geomorphologischen Einheiten (temporär wassergesättigte Täler, Ebenen und Hügel) wichtige Parameter für die Analyse der Vegetationsstruktur und -dynamik dar. Standardisierte Plots (1000 m^2) wurden für die Untersuchung der Pflanzendiversität ausgewählt. Die Pflanzenbedeckung, bestehend aus Baum- und Buschland mit einem Durchmesser in Brusthöhe (DBH 1,30 m vom Boden) größer oder gleich 5 cm, wurde gemessen und erfasst. Das Regenerationspotential der

Gehölze in jedem Plot wurde durch die Bestandsaufnahme von Gehölzpflanzen, deren DBH kleiner oder gleich 5 cm war, untersucht. Insgesamt sind 20 phytosoziologische Datenaufnahmen für 44 Pflanzenarten in den verschiedenen Untersuchungsgebieten erhoben worden. Die Erforschung der Vegetationsdynamik und Struktur erfolgte anhand der Klassifikation nach Durchmesser aller und einzelner Pflanzenarten. Zusätzlich wurden die Arten nach Höhe klassifiziert. Für die Einschätzung der Pflanzendiversität wurden Parameter wie Artenreichtum, Basalfläche und *Shannon Index* gemessen. Im Anschluss an die Analyse der Bodeneigenschaften und der Vegetationszusammensetzung-, dynamik und diversität (Kapitel 5.4) innerhalb der verschiedenen Landnutzungsformen, wurden die Wechselbeziehungen zwischen Boden und Vegetation erläutert (Kapitel 5.5). Dies entspricht einem multivariaten Analyseverfahren mit Ordinationstechniken unter Einbeziehung von Bodenparametern in der oberen Bodenschicht und der Vegetationsaufnahmen von Gehölzen an den Bodenprofil-Standorten.

Die physikalischen und chemischen Parameter der Bodenprofile in Südost-Burkina Faso und Nordwest-Benin zeigen eine breite vertikale und laterale Differenzierung ungeachtet des Status der Standorte. Die Bodenparameter wie Korngröße, Mächtigkeit, Farbe, Durchwurzelungstiefe, organisches Material sowie verfügbares Phosphor der oberen Bodenschicht (0 bis 20 cm Mächtigkeit) unterscheiden sich deutlich vom Unterboden (20 bis 80 cm). Allerdings dominiert die laterale Varianz innerhalb der Hänge deutlich. Die Differenzierung ist wesentlich von der Intensität der Erosionsprozesse sowie der Wasserleitfähigkeit der Bodenprofile abhängig. In der Anbaufläche von Kikideni und in dem teilweise geschützten Natiabouani Gebiet (Südost-Burkina Faso) sind sandiger Lehm, sandiger Ton und Lehm an der Bodenoberfläche verbreitet mit vergleichbaren Erosionsprozessen wie etwa *sheet wash*, Rillen- und Gully-Erosion vorherrschen. Die hohe Hangneigung und die -länge wie im Pendjari Nationalpark mit Lehmböden schränken offensichtlich allem die Verbreitung der Gullyerosion ein. Außerdem reflektiert die Bodenklassifikation die unterschiedlichen pedogenen Prozesse entlang der Transekte und damit die Bodenarten. Der Status der Standorte dürfte eine unbedeutende Rolle in der Differenzierung der Bodeneigenschaften innerhalb der kleinen pedomorphologischen Transekte spielen. In diesem Zusammenhang ist es wichtig zu erwähnen, dass die Ratio verfügbaren Phosphors und die Durchwurzelung gute Faktoren zur Differenzierung von geschützten und genutzten Flächen darstellen.

Die Studie der Pflanzendiversität und -struktur verbunden mit den Änderungen der Bodentypen weist deutlichere Unterschiede zwischen den verschiedenen Standorten auf. Der direkte Vergleich von Vegetationstyp in genutzter Fläche, teilweise geschütztem und total geschütztem Gebiet zeigt einen Übergang von Strauch- zu Baumsavanne. *Combretacea* mit Arten wie *Combretum molle*, *C. glutinosum* und *C. nigricans* stellen die Mehrheit der Population in dem genutzten Gebiet dar, während *Rubiaceae* (*Crossopteryx febrifuga*), *Mimosacea* (*Acacia gourmaensis),* *Cesalpinacea* (*Detarium microcarpum*) sowie *Sterculiaceae (Dombeya quinquesta)* durchmischt mit *Combretacea* die vorherrschenden Pflanzenfamilien in den geschützten Gebieten sind. Die temporär wassergesättigten Täler sind durch die Präsenz von Baumsavanne gekennzeichnet, unabhängig vom Protektionsstatus der Standorte.

Die Analyse von Durchmesser- und Höhenklassen zeigt hauptsächlich junge Populationen mit Durchmessern zwischen 6 und 10 cm und Höhen zwischen 2 und 4 m. Betrachtet man die höheren Durchmesser- und Höhenklassen ist es auffällig, dass die Anzahl ausgewachsener Pflanzen in dem genutzten Gebiet höher ist, als in den ungenutzten Gebieten. Das Feuer-Management in den geschützten Gebieten und die Präsenz von Wildtieren sind wahrscheinlich ein limitierender Faktor für das Höhenwachstum der Bäume. Die Berechnung von der Diversität mit Indizes wie Artenreichtum zeigt einen Anstieg vom genutzten Standort Kikideni mit 6.5 Arten/1000 m^2 zum teilweise geschützten Standort Natiabouani (9 Arten/1000 m^2) während 13 Arten/1000 m^2 in der Jagdzone und im zentralen Teil des Pendjari-Nationalparks erfasst wurden. Die Basalfläche hingegen nimmt vom genutzten (261,5 m2/ha) zu den geschützten Gebieten hin ab. Ähnlich wie Durchmesser und Höhenklassen, spielt das Feuer-Management eine entscheidende Rolle in dieser Tendenz.

Generell ist festzustellen, dass die Unterschiede der Bodeneigenschaften in den Hanglagen und an den verschiedenen Standorten mehr von den Erosionsprozessen und Drainagekonditionen als vom Protektionsstatus der Untersuchungsgebiete geprägt sind. Die Pflanzenzusammensetzung und Pflanzendiversität korrelieren hingegen mit dem Status der Standorte, dem Management und der Präsenz von Wildtieren wie Elefanten. Der Zusammenhang einzelner Bodenparameter (pH KCL, Mächtigkeit, Korngröße, Kationenaustauschkapazität) mit der Pflanzengesellschaft und deren Verteilung erfolgt durch *detrending correspondence analysis* (DCA), welche die 17 Standorte mit 44 Pflanzenarten in Affinitätsgruppen aufteilt. Das Ordinationsdiagramm zeigt, dass organisches Material mit der Gruppe von Plots korreliert, die in der Jagdzone oder an Viehweide-Standorten lokalisiert sind. Im gegensatz dazu korreliert die Kationenaustauschkapazität stark mit den Plots, die sich durch stabile Konditionen (mächtige Böden, flache Hanglagen) und/oder Degradationserscheinungen auszeichnen. Diese Standorte liegen meistens in dem teilweise geschützten Gebiet von Natiabouani. Dennoch deutet die statistische Analyse der *canonical correspondence analysis* (CCA) mit der *Inter set correlation* von Bodenparametern und den verschiedenen Achsen (1, 2 und 3) auf eine allgemein geringe Korrelation hin. Das Monte Carlo Test-Ergebnis ($p=0.014$), das einen guten Indikator für das Verhältnis von Arten und Umweltbedingungen darstellt, weist auch eine geringe Korrelation auf. Dies ist gegeben, wenn das Testergebnis $p \leq 0.05$ beträgt. Die Bodenparameter erklären in einem nur geringen Umfang die Präsenz von Pflanzenarten sowie deren Verteilung und Dynamik.

Die umfangreiche Analyse von Bodeneigenschaften und Vegetationsdynamik sowie deren Zusammenhang innerhalb kleiner Transekte stellt einen wichtigen Datenbestand dar, da verschiedene Elemente des Ökosystems involviert sind. Diese Arbeit leistet einen wichtigen Beitrag zu einem besseren Verständnis der Savannenlandschaft für zukünftige interdisziplinäre Forschungen sowie Entwicklungsprojekte in Westafrika.

RESUME

Cette présente thèse est partie intégrante d'un programme détaillé de recherche sur l'état de la biodiversité en Afrique de l'Ouest et a été conduit dans le cadre du projet BIOTA-AFRIKA.

Comme composante essentielle de tout écosystème l'étude des sols et de leurs propriétés qui sont liés à certaines spécificités géomorphologiques, aux conditions environnementales et à la dynamique du couvert végétal revêt une importance de taille parce qu'impliquant des éléments clé à la sécurité alimentaire et à la conservation de la biodiversité. Par ailleurs, comprendre l'interdépendance sol et diversité de la végétation requiert une prise en compte assez pointue de la complexité et du rôle des différents paramètres comme l'évolution du relief, sa dynamique et ses formes, le climat ainsi que les influences anthropiques.

Ce travail a pour but d'analyser dans une première étape les propriétés physiques et chimiques des sols le long des transects pédomorphologiques et ceci dans différentes conditions d'exploitation (zone protégées, partiellement protégées ainsi que les zones sous l'emprise des activités agricoles) au Nord-Ouest du Bénin et au Sud-Est du Burkina Faso. Les données ainsi recueillies sur les sols, tenant compte des processus pédogénétiques comme les formes d'altération, la saprolitisation, la formation des croûtes latéritiques et la dénudation sur les surfaces d'aplanissement, sont corrélées dans une deuxième étape à la structure et à la dynamique des espèces ligneuses autour de chaque profil pédologique. Le rapport entre les propriétés des sols et la dynamique des espèces ligneuses est étudiée en vue d´établir les influences supposées entre la diversité des espèces et les caractéristiques du sol à l´échelle de transects et dans différentes conditions de mise en valeur.

L´identification et l´étude topographique des transects pédomorphologiques sont calquées sur les observatoires de biodiversité déjà existants. Ces dernières sont des parcelles communes de 1 Km^2 où toutes les recherches dans le cadre du projet ont été menées. Le choix du site de ces parcelles était par ailleurs lié à la dynamique du couvert végétal et aux influences anthropiques. Les conditions environnementales comme l´influence anthropogénique et les particularités relevées à la surface du sol (texture, présence ou non de particules de roches, l´apparition et la distribution de croutes ferrugineuses et latéritiques et ou pisolithes) sont décrites chaque 50 mètres le long des transects. Ces descriptions ont conduit au choix des sites de prélèvement du sol en prenant en compte les changements dans la structure végétale (densité ou éclaircie), les témoins des activités agricoles et pastorales (pâturage, gestion écologique par les feux etc.) ainsi que les changements dans les unités de relief (vallées, pénéplaines et collines) et les observations d´ordre environnemental indiquant la dégradation des sols comme le caractère dénudé de la surface des sols avec une faible couverture ligneuse et herbacée. Les profils de sols ont été prélevés à une profondeur standard de 80 cm à cause de l´apparition de la croute latéritique et ou d´une couche indurée dans les sols du Sud-Est au Burkina Faso et du Nord-Ouest du Bénin. En tout 69 profils ont été prélevés pour 191 échantillons.

Les échantillons et les caractéristiques des profils pédologiques ont été dans un premier temps analysés lors des travaux de terrain avec la description, la mesure et ou l´estimation de la couleur, la granulométrie ainsi que le système racinaire dans différentes couches de sols. En outre, les caractères généraux de la couverture herbacée et ligneuse autour des profils sont brièvement décrits en identifiant les espèces dominantes et en estimant leurs hauteurs respectives. Les influences anthropogéniques sont notées. Enfin, des hypothèses de travail sont développées à chaque occasion pour expliquer l´apparition de certains phénomènes particuliers comme l´affleurement de la roche mère, couverture végétale et herbacée très clairsemée ou présence massive de matériel graveleux en surface.

En dehors de ces observations sur le terrain, les échantillons des sols sont analysés dans le laboratoire de pédologie de l´université de Cotonou au Bénin. Les paramètres physiques et chimiques qui sont déterminants pour l´analyse du rapport sol-végétation sont mesurés comme la granulométrie par la méthode Robinson de séparation des fractions de sols en sables fins et grossiers, les limons fins et grossiers et l´argile. PH (H_2O), pH (KCL) ainsi que la matière organique sont estimés. Parmi les macronutriments primaires le phosphore total et le phosphore disponible pour les plantes, l´azote total ainsi que le potassium qui sont des éléments essentiels pour la nutrition des plantes sont mesurés. La capacité d´échange cationique qui est un paramètre important pour l´évaluation de caractéristiques agricoles et environnementales des sols est calculé.

Par ailleurs, pour une analyse exhaustive des propriétés et de la dynamique des sols nous avons choisi de mettre l´accent sur certains processus géomorphiques comme les surfaces d´aplanissement et la formation et l´évolution des unités géomorphologiques sous l´influence des fluctuations climatiques dans les paysages de savane en Afrique de l´Ouest (chapitre 4.4). La dynamique au sein des surfaces d´aplanissement (MICHEL, 1973) ou *Rumpffläche* (vaste pénéplaine à flanc modéré étudié et caractérisé par BÜDEL, 1957) est influencée dans les zones d´étude du Burkina Faso et du Bénin par la succession de saisons humide et sèche avec d´importants types d´altération et des formes d´érosion en surface. Les profils des sols et leurs classements en types de sols sont en effet conditionnés par ces derniers processus.

L´inventaire de la végétation ligneuse autour des profils de sols a été réalisé en suivant les mêmes particularités qui ont présidé au choix des profils puisque étant sous les même influences environnementales. L´homogénéité de la couverture ligneuse et sa densité sont considérées pour l´identification des relevés phytosociologiques. En plus les changements dans le relief et la topographie comme les vallées inondables, les plaines et les collines constituent d´importants facteurs pour l´analyse de la dynamique et la structure de la végétation. Pour étudier la diversité des ligneux, des parcelles de 1000 m^2 sont retenues. La couverture ligneuse concernant des espèces de la couche arborée et arbustive avec des diamètres à hauteur de poitrine (1,30 m du sol) supérieurs ou égal à 5cm est comptabilisée. Il s´y ajoute que le potentiel de régénération des espèces ligneuses sur chaque relevé est étudiée grâce á l´inventaires des individus dont les diamètres à hauteur de poitrine sont inférieurs ou égal à 5 cm. En tout 20 relevés phytosociologiques ont été effectués et 44 espèces identifiées. L´étude de la dynamique de la végétation est basée sur les mesures de la structure décamétrique analysant toutes les espèces par classe de diamètre, de la structure spécifique qui consiste au rangement des classes de diamètre selon les individus relevés et enfin la structure verticale impliquant les hauteurs des espèces. L´estimation la diversité des plantes, quant à elle prend en compte des paramètres comme la richesse des espèces, la surface terrière ainsi que l´indice de diversité de Shannon.

Consécutivement à l´analyse des propriétés des sols dans les différentes conditions d´utilisation de la zone concernée ainsi que l´étude de la composition, du dynamisme ainsi que de la diversité de la végétation (chapitre 5,4), l’interdépendance sol et diversité de la végétation est mise en relief (chapitre 5,5). A ce propos, la méthode de l´analyse multi variée est utilisée usant de techniques d´ordination impliquant les paramètres des sols dans les premiers horizons et les espèces ligneuses relevés autour des profils de sols.

L´étude des profils dans les différentes zones d´étude révèle une différenciation latérale et verticale des paramètres physiques et chimiques des sols en dépit du fait que le site est protégé, partiellement protégé ou cultivé. En effet, les propriétés du sol, comme la texture, l´épaisseur de l´horizon, la couleur, la densité de l´enracinement, la matière organique, le phosphore assimilable entre autres varient significativement des horizons superficiels avec une épaisseur moyenne de 20 cm aux horions sous-jacents (20 à 80 cm). Cependant la différenciation latérale le long des pentes est davantage plus accentuée. Cette différenciation est essentiellement liée à l´intensité des processus d´érosion ainsi qu´aux conditions de drainage autour des profils de sols. A cet effet, dans la zone sous forte pression des activités agricoles de Kikideni et dans la zone partiellement protégée de Natiabouani (Sud-Est Burkina Faso) les horizons superficiels sont dominés par les textures sablo-limoneuses et sablo-argilo-limoneuses puisque marqués, ces sites, par la prédominance de processus d´érosion similaires comme l´érosion en nappe, en rigole ainsi qu´en gully. Par contre, dans les zones situées dans le Parc de la Pendjari la texture limoneuse prédomine. La raideur et la longueur des pentes y sont plus accentuées et limiteraient le développement de certaines formes d´érosion comme en gully. En plus, le résultat de la classification des sols le long des transects reflète une variation des processus pédologiques et donc l´apparition de différents types de sols.

Le statut des sites semble jouer un rôle insignifiant dans la différenciation des propriétés des sols á l´échelle des petits transects pédomorphologiques. Cependant, il urge de signaler que les taux de phosphore assimilable par les plantes ainsi que la densité de l´enracinement dans les différents couches du sol le long des transects semblent être un facteur de différenciation entre la zone cultivée, d´une part, et les zones protégées d´autre part.

Comparativement à l´analyse détaillée des propriétés des sols, l´étude de la diversité et de la structure de la végétation qui est en étroite relation avec les changements dans les sols montrent des différences notables entre les différents sites. Une comparaison directe des types de végétation dans la zone cultivée respectivement partiellement protégée et dans les sites complétement protégés du Parc Pendjari montre le passage d´une savane arbustive à une savane arborée. La famille des *Combretacea* composée essentiellement *par Combretum molle*, *C. glutinosum* and *C. nigricans* peuple le site cultivé de Kikideni tandis *Rubiaceae* (*Crossopteryx febrifuga*), *Mimosacea* (*Acacia gourmaensis), Cesalpinacea* (*Detarium microcarpum*) ainsi que celle des *Sterculiaceae (Dombeya quinquesta)* qui sont combinées aux *Combretacea* représentent les familles dominantes dans les zones protégées. Les vallées qui sont temporairement inondables sont tous caractérisés par la présence de savane arborée indépendamment du statut des sites.

L´analyse des classes de diamètre et de hauteur montre que la majorité des espèces sont jeunes parce qu´ayant des diamètres compris entre 6 et 10 m et des hauteurs comprises entre 2 et 4 m. Toutefois, le nombre des populations adultes qui se singularisent par des rangs de diamètre et de hauteur très élevés se retrouvent essentiellement dans la zone cultivée. L´usage de feux de brousse comme stratégie de gestion des sites protégés ainsi que la présence d´animaux sauvages comme l´éléphant semblent être un facteur limitant pour le développement des arbres.

Le calcul des indices de diversité comme la richesse en espèces montre une augmentation du site cultivé de Kikideni avec 6,5 espèces/1000m^2 à la zone partiellement protégée de Natiabouani (9 espèces/1000 m^2) pendant que 13 espèces/1000 m^2 ont été recensées dans la zone cynergétique et les parties centrales du Parc Pendjari. A l´opposé les mesures de surface terrière montrent que les valeurs les plus élevées sont enregistrées dans la zone cultivée (261,5 m^2 pro hectare dans une vallée inondable). Elles diminuent généralement dans la zone partiellement protégée et les valeurs les basses ont été mesurées dans les zones complètement protégées. Ici aussi l´usage des feux de brousse semble aussi déterminante dans le développement des surfaces basales des ligneux.

En conclusion il est important d´insister sur le fait que les variations des paramètres de sol le long des transects sont plus conditionnées par les processus d´érosion et les conditions de drainage que par les statuts protégés ou non tandis que la composition et la diversité des

plantes est strictement liés aux statuts des sites, aux méthodes d´aménagement et de gestion, aux conditions pédogénétiques ainsi qu´à la présence ou non d´animaux sauvages comme l´éléphant.

La relation de certains paramètres du sol (pH (KCL), épaisseur des horizons de surface, argile, sable et limon, capacité d´échange cationiques (CEC) et Phosphore total) avec les communautés végétales et leur distribution est établie en usant de l´analyse du gradient indirect (detrending correspondence analysis DCA) et divise les 17 sites et 44espèces en groupe d´affinités. Le diagramme d´ordination monte que la matière organique est plus corrélée au groupe incluant des sites situés presque exclusivement dans la zone cynergétique du Pendjari. Par contre les valeurs de CEC sont fortement corrélées aux sites qui se caractérisent par des conditions plutôt stables (sols profonds, pentes relativement plats) et présentant peu d´indices de dégradation. Ces sites sont généralement ceux de la zone partiellement protégée de Natiabouani. Néanmoins, l´analyse statistique de la CCA (canonical correspondence analysis CCA) ave la corrélation *Inter set* des paramètres des sols et des différents axes (1, 2 et 3) montre une corrélation assez faible. Le test de *Monte Carlo* (p=0,014), qui constitue un bon indicateur d´évaluation de la liaison des espèces aux facteurs environnementaux en particulier du sol, montre aussi une corrélation très faible. En effet, une bonne corrélation est garantie si le résultat du test p est inférieur ou égal à 0,05. Les paramètres des sols semblent peu influer sur la présence ainsi que la répartition des espèces dans les zones d´étude.

L´analyse détaillée des paramètres des sols et de la dynamique de la végétation ainsi que leur interdépendance au sein des transects pédomorphologiques représente un réservoir important de données pédologiques et botaniques impliquant des compartiments essentiels de l´écosystème. Cette thèse contribue à une meilleure compréhension de la dynamique au sein des écosystèmes de savane en Afrique de l´Ouest et devrait pourvoir assez d´informations de base pour tout projet de développement et toute recherche pluridisciplinaire et intégrée.

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WPT	Distanz	Northing	Easting	Grad	Textur	Bioindikatoren			Bemerkungen*
						Th	W	A	
Wpt 050		0347457	1250154						BEGINNING OF TRANSECT TOWARDS SSE !KM%==
WPT 151	0-28,5 M	0347447	1250197	-30°	gravellous mit feinsand				• *Burkea africana (mehrheit) • Termite mound red braun (Photo) • Fire influence
WPt 152	28,5-52	0347423	1250227	-25°	Gravelous material				*Burkea africana+detarium microcarpum
Wpt 153	52-152	0347382	1250306	-20°	Same unity strucuture with Block of bedrock				* Burkea+Dezarium+Combretum
Wpt 154	152-252	0347339	1250398	-10°	Gravelous structure and block from the lateritcrust				Combretuj, Acacia Seyal and guirmaensis
Wpt 155	252-352	0347297	1250470	-1°	Gravelous bit with marginal blocks only small block transported from the plateau Fine-grained hardened Influence of fire perceptible				* Vegetation: Combretum, Gardenias p., Terminalia avicennoides
Wpt156	352-402	0347256	1250557	-1	Termite mound small. Sandy silty. No block on the surface. Intensive activity of termite. Traces of fire . Block of laterit crust everywhere. No or sparse vegetation cover Combretum, terminalia*				
Wpt157	402-502	0347207	1250643	-1	Identic unite, block of laterit block Combretum, maytenus Senegal, Terminalia av.				

Wpt158	502-602	0347153	1250732	-1		Termite mound small. Bigger block of laterit on the point 158 big termite mound washed up but with a high of 1,5m Traces of elefant on the surfacr Vegetation: Detarium, combretum, Terminalia av. Lannea acida
159	602-702	0347096	1250811	0		Terminalia av., Combretum, Gardenia, traces of elefant o the soil surface and produce a arched structure
160	702-822	0347030	11250915	0	Sandy silty	Termite mound 1,5 Bigger trees: Combretum, Terminalia av., gardenia Rough surface
161	822-922	0346995	1251008	0		Sandy silty Termite mound small. No cover of vegetation on the surface But many small regenerated plants of Combretum and Terminalia
162	922-1022	0346954	1251101	-0,5		Termite mound small Same unite as 161 Rough surface Influence of fire Big termite mound after 60m on the distance but a little washed up
163	1022-1122	0346917	1251196	-0,5		Same unite Terminalia av.healthy More herbaceous

164	1122-1222	0346873	1251282	0	*sandig-schluffig	Same unite only more vegetation cover Pterocarpus…
165	1222-1322	0346825	1251373	0		Small termite mound Terminalia Lannea acida Combretum Sarcocephalus latifolius (typic for inondable zone)
166	1322-1422	0346771	1251454	0		2 big small termite mound
167	1422-1522	0346744	1251553	0		Terminalia Combretum
168	1522-1622	0346706	1251643	0		Terminalia Combretum Pteliopsis suberosa
169	1622-1672	0346686	1251692	0		
170	1672-1772	0346653	1251787	0		

Description of the soil surface along the pedomorphological transects during field work in the hunting zone of the Pendjari National Park

Methodology and principles of soil analysis (source: Guillaume Amadji, pedologist, Laboratory of soil science at the University Cotonou)

1) <u>Le potentiel Hydrogène : pH</u>

La mesure du pH se fait par la **méthode potentiométrique** ou **pH-métrique** qui est une méthode analytique basée sur des mesures de potentiel.

Le principe est de mesurer le potentiel d'une électrode indicatrice sensible à un composé ou ion (hydronium) de la solution du sol, par rapport à une électrode de référence. La solution du sol étant dans un rapport sol / eau distillée de 1 / 2,5.

2) <u>Le Carbone Organique</u>

Le carbone organique dans le sol est déterminé par la **méthode de Anne Modifiée**. Cette méthode consiste à oxyder le carbone organique par du bichromate de potassium en milieu acide (acide sulfurique). Le bichromate étant en excès, la quantité réduite est proportionnelle à la teneur en carbone organique. L'excès de bichromate de potassium est dosé par colorimétrie.

NB : Le taux de matière organique est déduit du taux de carbone organique par la formule suivante : %MO = %Corg x 1,724

où Corg = carbone organique et MO = matière organique.

3) <u>L'Azote Total</u>

L'azote total est déterminé par la **méthode de KJELDAHL**.

Le principe de la méthode consiste à l'attaque du sol par l'acide sulfurique (H_2SO_4) concentré en présence d'un catalyseur, puis après neutralisation par la soude (NaOH) et passage en milieu alcalin, distillation de NH_3 et dosage par titrimétrie.

$$2\,NH_3 + H_2SO_4 \longrightarrow (NH_4)_2SO_4$$

$$(NH_4)_2SO_4 + 2NaOH \longrightarrow Na_2SO_4 + 2NH_4OH$$

$$H_2SO_4 + NaOH \longrightarrow Na_2SO_4 + 2H_2O$$

4) <u>Le Phosphore Assimilable</u>

Le phosphore assimilable est déterminé par la méthode BRAY-1.

Principe :

Le phosphore assimilable est extrait par la solution de Bray I (solution de fluorure d'ammonium et d'acide chlorhydrique à faible concentration). L'extrait est ensuite utilisé pour le dosage du phosphore assimilable.

En milieu acide et en présence de molybdate d'ammonium, l'acide phosphorique forme des complexes molybdiques. Ces complexes phospho-molybdiques subissent l'action d'un réducteur beaucoup plus facilement que les molybdates. Comme réducteur, on utilise une solution d'acide ascorbique ; les complexes se transforment en bleu de molybdène. On mesure l'intensité du bleu de molybdène, donc la concentration en acide phosphorique, par comparaison avec la coloration obtenue à l'aide de solutions témoins, au colorimètre à la longueur d'onde 660 nm.

5) <u>Le Phosphore Total</u>

Le phosphore total est déterminé par la méthode de DUVAL

Principe :

Le principe consiste à extraire dans un premier temps les phosphates par attaque du sol en milieu acide fort (HNO_3) ou par incinération (à 700°C), puis extraction proprement dite par l'acide sulfurique H_2SO_4 (1N). Il se forme ainsi de l'acide phosphorique.

En présence de molybdate d'ammonium, l'acide phosphorique forme des complexes molybdiques. Ces complexes phospho-molybdiques sont formés par la coordination des ions molybdiques et le phosphore ; ce dernier étant l'atome central, l'oxygène du radical molybdate étant substitué par celle du PO_4^{3-}. Il existe une possibilité de réduire le complexe phospho-molybdique ; cette réduction s'accompagne d'une coloration bleue dont l'intensité est proportionnelle à la quantité de phosphomolybdate réduit, et en conséquence de phosphates présents dans le milieu (sol). Dans la méthode de Duval, le réducteur utilisé est l'acide ascorbique. Ce réducteur est utilisé à chaud (80°C), et présente l'avantage de donner une coloration stable. Par ailleurs, un excès d'acide ascorbique n'a pas d'effet nuisible et il permet d'éliminer l'action de certains ions gênants comme le fer ferrique qui se trouve également réduit.

Enfin l'intensité de la coloration bleue du phosphomolybdate réduit est mesurée au colorimètre à la longueur d'onde 650 nm.

6) <u>Les Bases Echangeables et la Capacité d'Echange Cationique (CEC)</u>

Les bases échangeables sont déterminées après extraction à l'acétate d'ammonium (1N, pH=7), puis dosage des cations (Ca^{2+} et Mg^{2+}) au Spectromètre à Absorption Atomique et des cations (K^+ et Na^+) au Spectromètre par Emission.

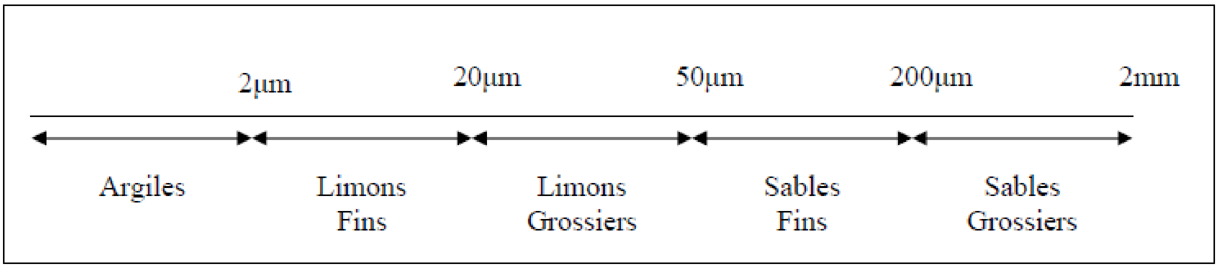
La capacité d'échange cationique (CEC) par la **méthode de METSON** qui consiste à saturer le complexe d'échange à l'acétate d'ammonium (1N, pH=7), puis à déplacer les ions NH_4^+ par une solution de Kcl (1N) et doser l'azote après distillation.

7) <u>La Granulométrie</u>

La granulométrie est déterminée par la **méthode Internationale avec l'utilisation de la pipette de ROBINSON.**

L'analyse granulométrique s'effectue sur la prise d'essai de terre fine (particules ≤ 2mm de diamètre). Elle a pour but de déterminer le pourcentage des différentes fractions de particules minérales constituant les agrégats.

Les particules minérales peuvent être classées de la façon suivante :



(Classification d'ATERBERG adoptée par l'Association Internationale de la Science du Sol)

La méthode consiste à :

- détruire la matière organique par une attaque à l'eau oxygénée (H_2O_2) ;
- ajouter un dispersant énergique tel que l'hexa-métaphosphate de sodium ;
- agiter mécaniquement pendant deux heures ;
- procéder au prélèvement des particules de différentes dimensions en suspension (argiles, limons et sables) à l'aide de la pipette de Robinson, dans des flacons à sédimentation, à des profondeurs et à des moments déterminés (application de la loi de STOKES, loi de sédimentation des particules dans un liquide).

Sample of soil parameter descriptions in the different layer within the protected sites

Titeldaten

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü.M.	Lage im Relief	Metrische Angaben zum Relief
1	11.05.05	09:09	150	1287462	31 229994	253m	Plateau (bas glacis) neben dem Gully	

Horizontbezogene Daten

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen
1	0-25	Hue 7,5 YR 2/2	sehr stark	*sandig-schluffig *mit Grobmaterial von Lateritkruste	- dunkler, mächtiger Humushorizont
2	25-80+	Hue 5 YR 4/8	schwach	Lateritkruste	- Lateritkruste schon ab 25 cm Tiefe

Bemerkungen

Vegetation	Anthropogene Einflüsse	Ansatz
→relativ dicht *Gehölze: -Höhe: - 5m, -Abstand ca. 5m. -Mehrheit „*osakuarbu*“ (hohe Individuen 2-5m) *Gräser: -gute Bedeckung, grün -„*eguanguamoné*“ -Höhe –0,5m		- Vergleich mit den Sedimentationsprozessen im Gully - Beschreibung des Bodentyps

Titeldaten

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü.M.	Lage im Relief	Metrische Angaben zum Relief
1	11.05.05	08:38	116	1287486	31 229964	251m	in Gully, Erosionsrichtung: SSO-NNW	

Horizontbezogene Daten

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen
1	0-28 0-18 cm	Hue 7,5 YR 2/3 Hue 7,5YR3/4	sehr stark sehr stark	*sandig-schluffig und *grobe Komponenten (Pisolith, 5-15+mm)	Sandig mit viel Körnchen Pisolit aber braun gefärbt
2	28-50 18-36 cm	Hue 10 YR 5/6 Hue 7,5YR4/3	Stark Sehr stark	*gravelous *grobkörnig *Ton	- mehr grobes Material in Horizont 2 als in Horizont 3 Grossere Anteil von Pisolite auch Körnchen Grosse (3cm)
3	50-80+ 36-53 cm	Hue 7,5 YR 5/8 Hue 10 YR 7/2 10YR5/6	sehr schwach schwach	*sehr tonig *kompakte Struktur mit groben Komponenten	- aufgrund der Feuchte sind die groben Komponenten sehr weich Fast selbe Struktur aber mehr Kompaktion Präsenz von Ton
	53-80+ cm	Hue 5YR 5/8-4/8	Sehr schwach		Verhärtete Horizont von Laterit
3 Horizon wahrscheinlicher					Zur Zeit sehr gut bedeckt von Gräser und teilweise Combretum

Bemerkungen

Vegetation	Anthropogene Einflüsse	Ansatz
*im Gully nur Gräser: grün, niedrig (-50cm)→ „*tomuatbandi*“ *in der Umgebung und an den Hängen des Gullys viel Vegetation, Abstand der Gehölze ca. 1m		- Bodensedimente (Struktur) im Gully - Vergleich mit der 1. Grabung

Titeldaten

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü.M.	Lage im Relief	Metrische Angaben zum Relief
2	11.05.05	07:50	121	1287686	31 229800	252m	Fläche vor dem Haupttal	

Horizontbezogene Daten

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen → viele Ameisen an der Oberfläche, auch in der Grabung
1	0-14 0-25 cm	Hue 10YR 2/2 Hue 10YR3/3	sehr stark sehr stark	*sandig-schluffig Sandig-humus	- Humusschicht → starke organische Zersetzung
2	14-44 25-55 cm	Hue 10 YR 4/4 Hue 5YR4/4	sehr stark stark	*Ton	Les herbacées sont très développés et dépassent parfois le métre- herbacées annuelles Andropogon gayanus
3	44-80+ 55-80 cm	Hue 10 YR 5/4 Hue 7,5YR4/4	Stark Schwach	*sandig *Ton Ton	

Bemerkungen

Vegetation	Anthropogene Einflüsse	Ansatz
→ dicht * Gräser: - starke Bedeckung - „*obuangarmu*" * Gehölze: -Höhe durchschnittlich 4-10m -Abstand ca. 2m -„*osambu", combretum glytinosum* -„*linadjali" (combretum nigricans)* -„*osiebu"* -„*okokwodongu"* -„*osarkuabu"* -„*lijangmari"*	Wege im Gras (Gräser umgeknickt)	- Vergleich der Sedimentationsprozesse mit denen von Grabung 1 und 2 und mit dem Aufschluss im Haupttal

Titeldaten

Relevé

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü.M.	Lage im Relief	Metrische Angaben zum Relief
3	09.05.05	10:30	124	1287785	31 229828	251m	Aufschluss am Ufer des Haupttales	

Horizontbezogene Daten

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen
1	0-45	Hue 10YR 5/4 Hue 10Yr4/6	Stark stark	*sandig-schluffig	
2	45-130 44-118	Hue 10 YR 5/6 Hue 7,5YR3/4	Stark Sehr stark	*Ton Sandig bis tonig	
3	130-155 118-155+	Hue 10 YR 5/6 Hue 7,5YR5/4	sehr schwach stark	*Grobmaterial *Feinmaterial: Ton	* nur im Horizont 3 grobe, verhärtete Komponenten --> mächtigster Horizont

Bemerkungen

Vegetation	Anthropogene Einflüsse	Ansatz
*große Bäume *Gräser: gute Bedeckung		- Ablagerung der Sedimente im Tal/ am Ufer des Tales

Sample of soil parameter descriptions in the different layers within the land used site of Kikideni

Titeldaten

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü:M.	Lage im Relief
1	28.04.05	08:39	069	1314509	31 215883	294m	Hang vor dem 1. Tal

Bemerkungen

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen
1	0-18 0-16 cm	Hue 5 YR 6/2 Hue 5YR4/4	Schwach Stark	sandig-schluffig	- feines Material - grau-dunkelgrau - gemischt mit gröberen Komponenten(2-3mm)
2	18-52 16-44 cm	Hue 10 YR 7/6 Hue 10YR8/5	Schwach Schwach	sandig-schluffig und grobkörnig	- feines Material - gemischt mit größeren Komponenten (verwittertes anstehendes Gestein und verwitterte Lateritkruste) Mit kleinen Pisoliten Anteiletwa 80% der gesamten
3	52-80+ 44-80+ cm	sandiger Teil: 10 YR 7/6 grobkörniger Teil: Hue 10 YR 6/6 Hue 10YR6/4	0 Sehr schwach	Grobkörnig Lateritkruste	- hartes Material, mit Feinmaterial gemischt - Struktur kompakt Präsenz von Quartz in der Struktur trotz Regen noch Trocknet

Vegetation	Anthropogene Einflüsse	Ansatz
- Gehölze, Gräser - viele kleine Individuen von der Stufe 0,5-1,5m - z.T. Laubbedeckung, sammelt sich besonders um Gräser und Sträucher (wie kleine Inseln)	- Spuren von Beweidung - Wege (Trampelpfade)	- Vergleich mit Talsedimente - Ablagerung der Sedimente hier im Tal? - Einfluss der Tiere auf Sedimentation? Relevé und Betrachten der Einheit vor dem ersten kleinen Tal

Titeldaten
Inventaire des espèces

Nr.	Datum	Uhrzeit	WPT	Northing	Easting	Höhe ü:M. in m	Lage im Relief	Metrische Angaben zum Relief
2	28.04.05	09:49	070	1314466	31 215862	266	im 1. Tal	ca. 0,5 m unterhalb dem Niveau der Umgebung

Horizontbezogene Daten

Horizont	Mächtigkeit cm	Farbe	Durch-wurzelung	Korngröße	Bemerkungen
1	0-15 0-20 cm	Hue 10 YR 5/2 Hue 10YR3/2	sehr stark sehr stark	sandig-schluffig	- dunkelgraues Material/ Sediment - mit Komponenten, die durch Trockenheit entstanden sind(Aggregate)
2	15-30 20-43 cm	Hue 2,5 Y 7/2 Hue 10R4/6?	Stark sehr stark	schluffig	- hellgraues Material mit harten Körnern (ca. – 1cm) - zementierte Struktur am Profil sichtbar
3	30-57 43-63 cm	Hue 2,5 Y 7/4 Hue 10R4/6	Stark schwach	tonig	- toniges Material, kompakt, mit gelb-roten Flecken - mächtiger als Horizont 1 und 2
4	57-66 63-80+ cm	Hue 7,5 Y 8/1 Hue 7,5 YR4/4	0 schwach	grobkörnig und schluffig	- sieht aus wie eine stone-line Lage - mit kleiner Komponenten/Material Präsenz von Eisen sichtbar an den roten Flecken Farbe braun bis rotlich 3° Horizon deutlich sandiger als die 2° Hordie mehr oder wenoger tonig ist. Durchwürzelung schwach in den unteren Hor. Die Bäume gerade nicht present an der unmittelbaran Nähe der Grabung
5	66-80+	Hue 2,5 Y 7/4	schwach	sandig-schluffig	- weiche konkretierte Elemente

Bemerkungen

Vegetation	Anthropogene Einflüsse	Ansatz
- große Gehölze (z.T. – 10 cm), z.T. mit grünen Blättern - hohe Gräser (-3 cm), auch in Trockenzeit	- Spuren von Beweidung - Wege (Trampelpfade)	- Transport und Depot/ Lagerung der abgetragenen Sedimente zu überprüfen - Ist der 4. Horizont eine Übergangsschicht für die Ablagerung der Sedimente?