Microbiological indicators for quality of soils at various stages of degradation in the forest-savanna-transition zone, south-western Nigeria

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List of Abbreviations

Bray-I P	available inorganic phosphorus
CEC	cation exchange capacity
C_{mic}	microbial biomass
C_{mic}/C_{org} (%)	ratio of microbial biomass to total organic carbon
$cmol^{+}\ kg^{-1}$	centimole charge per kilogram
C_{org}	total organic carbon
ctrl	control
DM	dry matter
ECEC	effective cation exchange capacity
ha	hectar
IITA	International Institute of Tropical Agriculture, Ibadan, Nigeria
leuc	leucaena
m.a.s.l.	meters above sea level
$Mg\ m^{-3}$	tonne per cubic meter
n.a.	not available
n.d.	not determined
$NaHCO_3$-P_i	labile inorganic phosphorus, including resin membrane extractable P
$NaHCO_3$-P_{org}	labile organic phosphorus, bicarbonate extractable
NaOH-P_i	non-occluded inorganic phosphorus associated with Fe/Al-phosphates
NaOH-P_{org}	organic phosphorus of the fulvic acid fraction
nat.regrowth	natural regrowth
ns	not significant
N_{tot}	total nitrogen
PCA	Principal component analysis
PC	principal components
puer	pueraria
r	Pearson`s correlation coefficient
RCMD	Resource and Crop Management Division (IITA)
rep	replicate
r.p.m.	revolutions per minute
sec. Forest	secondary Forest

SOM	soil organic matter
SOM-ND	soil organic matter related nutrient dynamics
*	significant (5 %)
**	significant (1 %)
***	significant (0.1 %)
ϕ	diameter

1 Introduction

Soil degradation and concomitant decline in soil fertility and quality is often emphasized as constraint to crop productivity in tropical Africa (Moorman and Greenland, 1980; Edwards et al., 1990; Okali,1992; Babalola and Opara-Nadi, 1993; Vlek, 1993; Ley et al., 1993; Kayombo and Lal, 1993; Hoffman and Carroll, 1995). Soil degradative processes are interrelated and constitute physical, chemical and biological mechanisms (Lal et al., 1990; Theng, 1991; Lal, 1993; Hoffman et al., 1995; Halvorson et al., 1995) where the processes leading to destructive land use may be gradual (Vlek, 1993). In managing degraded tropical soils for improved productivity much emphasis was placed on enhancing soil physical and chemical fertility whereas less is known of the associated changes in soil microbiological and soil biochemical properties and how such changes influence plant productivity and sustainability of a system (Swift and Sanchez, 1984; Eswaran et al., 1993; Doran and Parkin, 1994; Pankhurst and Lynch, 1995; Jordan et al., 1995; Kennedy and Smith, 1995; Yakovchenko et al., 1996).

Primary soil degradative processes in Alfisols in Nigeria were often equated with physical and chemical soil properties and have been used as indicators of soil degradation (Wilkinson and Aina, 1976; Juo and Lal, 1977; Aweto 1981; Lal et al., 1990; Laflen et al., 1990; Hulugalle and Maurya, 1991; Hulugalle, 1992; Mbagwu, 1992; Nwosu et al., 1995). However, even after optimizing the soil chemical and physical properties, expected high crop yields were not obtained on many soils in West-Africa, as direct correlations between soil organic matter and nutrient status with crop yield were not always evident (Jones and Wild, 1975; Babalola and Opara-Nadi, 1993). Moreover, quantitative studies that linked productivity with soil conditions could only roughly predict crop yields under various cropping conditions (Roder et al., 1995 a; Kleinman et al., 1995; Buol, 1995; Hoffman and Carroll, 1995; Yakovchenko et al., 1996).

Intercropping woody species with field crops is thought to contribute to the sustainability of land use intensification by offering an effective means of enhancing soil conditions and reducing the degradative effects of cropping (Kang et al., 1990; Kang, 1993; Kleinman et al., 1995; Palm, 1995).

Improved fallow management systems were developed to prevent soil from degradation or to restore degraded soils. The proposed sustainable management systems include (1) alley cropping or hedgerow intercropping systems as defined by ICRAF as an agroforestry system in which food or forage crops are grown in the „alleys“ between hedgerows of trees or shrubs (AFNETA, 1992, pp. 8-9); (2) herbaceous *in situ* mulch systems (live mulch) in

which food crops are planted directly in low growing cover crops (Akobundu, 1980; Mulongoy and Akobundu, 1990, 1992).

Low growing leguminous cover crops that are grown simultaneously with field crops are thought to protect the soil surface from incoming radiation, precipitation and wind. They are also thought to sustain acceptable yields by restoring soil nitrogen pools and enhancing soil organic matter levels without deterioration of the environment (Akobundu, 1980; Mulongoy and Akobundu, 1990, 1992; Kleinman et al., 1995).

Application of plant residues, particularly by N_2-fixing woody leguminous species and nutrient recovery from layers below the rooting depth of the food crops as well as prevention of nutrient leaching by hedgerows is considered favorable to soil fertility improvement and sustaining crop productivity of the system. However, the restorative capability and the soil improvement potentials of planted fallows or alley cropping systems were more pronounced on high than on low base status soils. Moreover, studies revealed that the establishment of some fast growing trees may cause depletion of soil fertility and productivity (Lundgren, 1983 as cited by Lal 1989; Wilson et al., 1986; Kang and Wilson, 1987; Kang et al., 1990; Kang, 1993; Haggar et al., 1991; Hulugalle, 1992; Kühne, 1993; Palm, 1995; Juo et al., 1995; Juo and Manu, 1996).

Objectives

The present study was undertaken to link soil microbiological and soil biochemical parameters with soil quality conditions and crop productivity and to identify those parameters or processes that are affected most by long-term management. Degradation is defined by land-use history and is reflected in the soil quality status and the productive potential. A degradation index is used to discriminate between three selected sites varying in time and intensity of land use based on the continuously cropped controls of long-term experiments. Various improved fallow management systems are evaluated for their potential as low-input continuous crop production systems by comparing them to sole cropping.

2 State of the Art

2.1 Soil quality indicators

Soil is a dynamic, natural resource critical to the sustainability of any terrestrial ecosystem. It is an important component of the earth's biosphere for the production of food and fiber and the maintenance of environmental quality (Doran et al., 1996; Halvorson et al., 1996). The quality of soil is rather dynamic and can affect the sustainability and productivity of land use. It is the end product of soil degradative or conserving processes and is controlled by chemical, physical, and biological components of a soil and their interactions (Kennedy and Papendick, 1995; Elliott et al., 1996). Consequently, the manner in which soils are managed has a tremendous impact on productivity and sustainability (Scholes et al., 1994).
The concept of soil quality changed consistently with an increase of the understanding of soils and soil quality concerns (Warkentin, 1995). The quality of soils was mainly defined (Larson and Pierce, 1991, pp. 176) by the soil's function as "the capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem. Under this definition, soil quality is a key factor in the four sustainability objectives as described by Lourance (1990), namely agronomic sustainability, ecological sustainability, microeconomic sustainability and macroeconomic sustainability". A minimum data set (MDS) was proposed to measuring soil quality and its changes due to current soil management practices by a selection of key indicators such as soil texture, organic matter, pH, nutrient status, bulk density, electrical conductivity and rooting depth (Larson and Pierce, 1991).
This definition was conceptualized more qualitatively by combining different resources which impact on the sustainability by Doran and Parkin (1994, pp. 7) as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". It was postulated that basic soil quality indicators should reflect (1) ecosystem processes and relate to process oriented modeling, (2) integrate soil physical, chemical, and biological properties and processes, (3) be accessible to many users and applicable to field conditions, (4) be sensitive to variations in management and climate and (5) where possible, be components of existing soil data bases (Doran and Parkin, 1994, pp. 9). Based on these propositions a list of basic soil properties that should be indicative of soil quality was established and included in the MDS by Larson and Pierce (1991), and expanded with a few biological aspects of soil quality, namely microbial biomass C and N, and soil respiration by Doran and Parkin (1994).

The identification of biological indicators of soil quality was reported as critically important by several authors (Doran and Parkin, 1994; Elliott et al., 1996) because soil quality is strongly influenced by microbiological mediated processes (nutrient cycling, nutrient capacity, aggregate stability), whereby the key is to identifying those components that rapidly respond to changes in soil quality (Scholes et al., 1994; Elliott et al., 1996). Indicators, however, will vary according to the location, and the level of sophistication at which measurements are likely to be made. Wylie (1994) and Smyth and Dumanski (1995) concluded therefore, that it is not possible to develop a single short list which is suitable for all purposes. Syers et al. (1995) also emphasized the range of likely indicators rather than the use of a single indicator. Within the Framework for Evaluation of Sustainable Land Management (FESLM) initiated by an International Working Group (IWG; Smyth and Dumanski, 1995) evaluations to assessing the sustainability of current and alternative land-use systems are based on changes in indicators of productivity over time rather than land suitability classes. Within this context, the terms “indicators” and “thresholds” have been defined (Smyth and Dumanski, 1995) as: (1) indicators are “attributes that measure or reflect environmental status or conditions of sustainability”, whereas (2) thresholds are “levels of indicators beyond which a system undergoes significant change, that is, points at which stimuli provoke significant response”. In terms of sustainable land management, the threshold value may be considered as the level of a specific indicator beyond which the particular system of land management is no longer sustainable (Syers et al., 1995). However, according to Syers et al. (1995) our understanding of likely thresholds is not well developed, except for a limited number of environmental indicators such as soil acidity, and nutrient status of P and K for a given soil type or some biophysical indicators such as bulk density. It simply would be expecting too much for a single threshold value to represent the boundary or cut-off between sustainable and unsustainable. Consequently, a range of threshold values and temporal trends for particular indicators is required (Syers et al., 1995).

2.2 Biological significance of the soil microbial biomass

The microbial biomass in soil is made up of bacteria, fungi, actinomycetes, algae, protozoa and some nematodes, and is estimated to contribute about ¼ of the total biomass on earth (Roper and Gupta, 1995; Pankhurst et al., 1995). The microbial biomass contributes to the maintenance of soil fertility and soil quality in both natural and managed terrestrial ecosystems in that it controls major key functions in soil (Turco et al., 1994; Elliott et al.,

1996). The microbial biomass is part of the soil organic matter (SOM). Soil organic matter plays a major role in terrestrial ecosystem development and functioning. In both undisturbed and cultivated systems, potential productivity is directly related to the SOM concentration and turnover (Smith et al., 1993). Soil organic matter is a complex mixture of living, dead, and decomposing material, and inorganic compounds (Smith et al., 1993). The living component makes up about 4 % of the total soil organic C and has been subdivided into three components, (1) plant roots (5-10 %), (2) macroorganisms or fauna (15-30 %), and (3) microorganisms (60-80 %). The non-living component of the total SOM has traditionally been broken down into macroorganic matter or light fraction (plant residues in varying stages of decomposition), and humus including non-humic (carbohydrates, lipids, organic acids, pigments, and proteins) and humic substances (fulvic acid, humic acid, and humin) (Theng et al., 1989). However, no sharp boundary exists between these fractions in terms of physical-chemical properties. Moreover it is difficult to relate this fractionation scheme to dynamic processes (Theng et al., 1989). However, a number of models have been proposed to describe SOM-dynamics. In soil-crop models, e.g. CENTURY for tropical ecosystems, SOM was separated into conceptual pools with distinct turnover times: (1) the active (0.14 yr.), slow (5 yr.) and passive (150 yr.) fractions (Parton et al., 1994). The living soil organic matter pool, or the soil microbial biomass is considered to be a part of the active SOM. The quality and quantity of the organic matter of soils normally changes at slow rates which are difficult to detect in the short term because of the large pool-size of organic matter and the spatial variability of soils. However, the soil microbial biomass as active fraction of the organic matter responds much more rapidly than soil organic matter as a whole to changes in management, climate etc. For that reason, soil microbial biomass and the ratio between microbial biomass and SOM has been proposed as an indicator of the state and changes of total soil organic matter (Dick, 1992; Powlson, 1994; Pankhurst and Lynch, 1995; Pankhurst et al., 1995). Under temperate conditions Powlson et al. (1987) could demonstrate in long-term straw amended field experiments over 18 yrs. that the relative increases in biomass-C (37-45 %) and biomass-N (46-50 %) were much greater than those in total soil organic C (5 %) or N (10 %). Hence, the authors considered the changes in the microbial biomass as early indication for changes in SOM (Powlson et al., 1987). Similar results were reported by Saffigna et al. (1989) for an sub-tropical Australian Vertisol cropped with sorghum under different tillage and residue management practices. The combination of residue retention and zero tillage caused a relatively larger increase (31 %) in the microbial biomass than in the total soil

organic matter (15 %). The application of farmyard manure (15-90 t $hā^{-1}$ $year^{-1}$) under sub-tropical and semi-arid conditions in India was also found to increase the microbial biomass without appreciably increasing soil organic C levels (Goyal et al., 1993).

Soil microorganisms are continually changing and adapting to changes in the environment. This dynamic nature makes them a sensitive indicator to assess changes and to predict long-term effects of changes in soil resulting from management practices (Kennedy and Papendick, 1995; Kennedy and Smith, 1995).

Soil microorganisms also contribute to the maintenance of soil quality in that they control many key processes in soils. They are involved in the decomposition and accumulation of SOM, nearly all mineral nutrient transformations in soils related to plant nutrition and soil fertility (Apsimon et al., 1990 as cited by Roper and Gupta, 1995; Pankhurst et al., 1995; Kennedy and Papendick, 1995).

Soil microbial biomass also serves as a source and sink for mineral nutrients and organic substrates in the short term, and as a catalyst to convert plant nutrients from stable organic forms to available mineral forms over longer periods (McGill et al., 1986). Anderson and Domsch (1980) reported that the microbial biomass of soils contain substantial quantities of both C and plant nutrients, whereby the nutrients temporarily held in the biomass largely contribute to the pool of available plant nutrients in soils. The microbial biomass content in agricultural soils under temperate conditions in Germany ranged from 0.27 to 4.8 % of the total soil C and the average quantities of N, P, K and Ca were about 108, 83, 70 and 11 kg/ha, respectively (Anderson and Domsch, 1980).

Furthermore, microbes contribute to the formation of the soils structure in that they help to aggregate the soil by polysaccharide production (Kennedy and Papendick, 1995; Anderson, 1991). Soil organic matter consists of 25 % of carbohydrates with polysaccharides (about 40 %) as the main fraction. The polysaccharides are predominantly of microbial origin and are very important to forming stable micro-aggregates in the soil with clay minerals, multivalent cations and humic substances because they are not readily decomposed as compared to plant polysaccharides (Anderson, 1991).

Finally, the microbial biomass is releasing and containing enzymes which are responsible for nutrient cycling (Saffigna et al., 1989; Srivastava and Singh, 1991, Carter, 1991; Ocio et al., 1991).

The size and activity of the microbial biomass is regulated by the soil organic matter quantity and quality and has been related to climatic conditions (Insam, 1990), soil moisture content (Van Veen et al., 1985; Doran et al., 1990; Van Gestel et al., 1996), soil

temperature (Joergensen et al., 1990), soil pH (Jenkinson and Powlson, 1976; Roper and Gupta, 1995), soil structure and texture (Ladd, 1992; Jocteur-Monrozier et al., 1992) and to soil and crop management practices (Aoyama and Nozawa, 1990; Ocio et al., 1991; Ritz et al., 1992; Mueller et al., 1992; Amato and Ladd, 1992; Srivastava and Lal, 1994).

2.3 C_{mic}/C_{org} ratio

The ratio of microbial biomass-C to soil-C (% C_{mic}/C_{org}) is the microbial-C content per unit soil carbon (Anderson and Domsch, 1989; Sparling, 1992). The ratio has been proved to be a sensitive indicator of quantitative changes in soil organic matter due to changing management conditions and climate (Anderson and Domsch, 1989; Insam et al., 1989). C_{mic}/C_{org} was found to be higher in crop rotations than in monocropping soils of 26 long-term experiments (134 plots) under temperate conditions in Central Europe, and was attributed to the two management systems applied (Anderson and Domsch, 1989). Mean C_{mic}/C_{org} was 2.3 % and 2.9 % under permanent monoculture and continuous crop rotations, respectively. Soils that exhibit a ratio higher or lower than these proposed equilibrium values would therefore be accumulating or loosing C, respectively (Anderson and Domsch, 1989). However, to establish whether the C_{mic}/C_{org} ratio of a soil is in equilibrium, thus whether a soil has achieved equilibrium in organic matter status, it will be necessary to establish a baseline or reference values for each soil and a set of conditions to which the tested soil can be compared (Sparling, 1992). For a range of soils in New Zealand it appeared that these values were not readily transferable, particularly for soils that differed widely in organic matter content and mineralogy (Sparling, 1992).

In long-term experimental sites under temperate conditions in Alabama, USA 78 % of the variability of the C_{mic}/C_{org} ratio could be explained by the climatic conditions (precipitation/evaporation quotient) (Insam et al., 1991). Thus, the ratio was smallest under a balanced precipitation and evaporation regime (P/E = 1) and higher in drier (P/E < 1) or more humid climates (P/E > 1) (Insam et al., 1989). However, the P/E-quotient as suggested by Insam et al.(1989) to predict equilibrium levels of C_{mic}/C_{org} did not give useful results when applied to a range of New Zealand soils (Sparling, 1992). Under New Zealand conditions factors other than climate seemed to contribute to the relationship between C_{mic} and C_{org} (Sparling, 1992).

One problem associated with the C_{mic}/C_{org} ratio is that both components have a common origin, and are not independent of each other. Also, changes in organic carbon will impact more on the ratio than changes in microbial biomass since the former is quantitatively

much more abundant.

2.4 Biological significance of soil enzymes

2.4.1 Activity and stability of soil enzymes

Enzyme activity in the soil environment is considered important to contributing to the overall soil microbial activity and to soil quality (Jordan et al., 1995). The total enzymatic activity of soils is made up of enzymes that are associated with metabolically active or non proliferating cells (biontic enzymes), and those that are attached to dead cells and plant debris or being immobilized on the soil clay and humic colloids (abiontic enzymes; Skujins, 1976; Burns, 1982; Dick et al., 1988). Enzymes in the soil solution are generally short-lived because they are readily inactivated by physical adsorption, denaturation or degradation (Sarkar and Burns, 1984).

Enzyme activities are an important index of the biological activity of a soil because they are involved in the dynamics of soil nutrient cycling and energy transfer. Enzymatic processes are closely associated with soil fertility as they mediate the conversion of unavailable forms of nutrients to forms that are readily assimilable by plants and microbial biomass (Sarathchandra et al., 1984; Sarkar et al., 1989; Dick et al., 1988; Dick, 1992; Martens et al., 1992; Sinsabaugh, 1994).

Soil enzymes participate in the decomposition and synthesis of organic substances and are important for the formation of recalcitrant organic molecules (Galstian, 1974; Martens et al., 1992).

Enzymatic activity of soils reflect the intensity and direction of biochemical processes in the soil matrix. Hence, the activity indicates the biological capacity of a soil to carry out the biochemical processes which are important to maintaining the soil fertility (Galstian, 1974; Dkhar and Mishra, 1983; Burns, 1986; Garcia et al., 1994) as soil fertility depends not only on nutrient status and availability but also on the turnover of N, P and other nutrients (Lopez-Hernandez, 1989).

From inversely proportional relationships between P-availability and phosphatase activity and N-availability and N-acquiring enzyme activities, Sinsabaugh (1994) concluded that measurements of specific enzyme activities can be used as indicators of relative nutrient limitation.

As enzymes do not react readily to environmental changes like the soil microbial biomass, their activity is a more stable indicator of biological processes (Galstian, 1974). Those enzymes in the soil that are associated with humic substances and to a lesser extent with

clay particulates are protected against thermal denaturation, proteolysis, dehydration or decomposition and are part of a persistent extracellular enzyme pool that is independent of the existing microbiota (Burns, 1982; Sarkar and Burns, 1984; Miller and Dick, 1995). The humic-enzyme fractions retain the original properties of the enzymes (Busto and Perez-Mateos, 1995) as stable enzyme-organic matter complexes were found to allow diffusion of substrates to the active enzyme site (Burns, 1982). Therefore, soil can be considered as a sink and source of indigenous and persistent enzymatic capacity which is independent of current or recent microbial and plant activity (Galstian, 1974; Burns, 1986; Lähdesmäki and Piispanen, 1992; Busto and Perez-Mateos, 1995). Moreover, the enzymatic activity of a soil is conditioned by land use history since enzymes are produced by living organisms and plants which contribute to the biological soil formation.

The activity and stability of enzymes in soil is regulated by pH (Frankenberger and Johanson, 1983; Trasar-Cepeda and Gil-Sotres, 1987; Dick et al., 1988), microbial biomass (Saffigna et al., 1989; Häussling and Marschner, 1989; Srivastava and Singh, 1991; Carter, 1991), vegetation (Juma and Tabatabai, 1978; Harrison, 1983; Perucci et al., 1984; Helal et al., 1987; Tarafdar et al., 1987), soil and crop management practices (Perucci and Scarponi, 1985; Beck, 1990; Martens et al., 1992; Kandeler and Eder, 1993), soil organic matter (Juma and Tabatabai, 1978; Chhonkar and Tarafdar, 1984; Sparling et al., 1986), clay minerals (Makboul and Ottow, 1979; Huang et al., 1995) and to the soil moisture content (Harrison, 1983; West et al., 1988 a,b).

2.4.2 Acid and alkaline phosphomonoesterase

Orthophosphoric monoester phosphohydrolases (acid and alkaline phosphatases) particularly catalyze the hydrolysis of P-ester bonds binding P to C (C-O-P ester bonds) in organic matter. Inorganic P is released from organically bound P (leaf litter, dead root systems and other organic debris) without concomitant release of C (Harrison, 1983; Clarholm, 1993). Barrett-Lennard et al. (1993) reported that soil phosphatases may also mediate the hydrolysis of P-esters leaked from plant roots. Phosphatases are concentrated in the surface layer and rhizosphere where most of the fresh and less humified organic matter is prevailing (Trasar-Cepeda and Gil-Sotres, 1987; Rojo et al., 1990; Asmar et al., 1995). Acid phosphatase is mainly produced by plants but also soil microorganisms release acid phosphatases. Acid phosphatase was detected in rhizodermal and root cap cells, in soil fungi and bacteria, in mucilage covering roots, and in microbial membranes in soil (Fraser et al., 1991). The production of acid phosphatase by fungal hyphae, however, is discussed

controversially in the literature. Häussling and Marschner (1989) and Tarafdar and Marschner (1994) found a positive correlation of phosphatase and mycelial hyphae length, whereas others reported no difference in activity between soils with or without fungal mycelium (Joner et al., 1995). Alkaline phosphatase is produced by soil microorganisms and soil fauna (Chhonkar and Tarafdar, 1984; Nakas et al., 1987) whereas higher plants are devoid of alkaline phosphatase (Tarafdar and Claassen, 1988; Juma et al., 1988). The optimal pH for acid and alkaline phosphatase activity was reported as pH 6-6.6 (Nakas et al., 1987) and pH 9-11 (Tabatabai and Bremner, 1969), respectively.

2.4.3 ß-Glucosidase

ß-Glucosidase belongs to a group of enzymes that catalyze the hydrolytic conversion of cellulose to glucose. Cellulose is quantitatively the most important organic compound and its mineralization and degradation in soil is a major process within the carbon cycle (Sinsabaugh et al., 1991). Plant biomass, for example, consist of 40-70 % of cellulose which is constantly replenished by photosynthesis (Enari and Markkanen, 1977; Enari, 1983). The microbial decomposition of cellulose is a complex process mediated sequentially by at least three types of enzymes (Enari and Markkanen, 1977; Enari, 1983; Hayano and Tubaki, 1985; Busto and Perez-Mateos, 1995). The (1) endo-ß-1,4-glucanases catalyze the hydrolysis of ß-1,4 -bonds within the cellulose molecule. At the free endings within the chain (2) further hydrolysis by exo-ß-1,4 glucanase releases cellobiose (disaccharide) that is finally decomposed by (3) ß-1,4-glucosidase to yield glucose. However, the complete decomposition of cellulose to glucose is only mediated in the presence of ß-glucosidase which catalyses the limiting step in the degradation of cellulose materials by removing cellobiose. Cellobiose, in turn, suppresses exo-ß-glucanases by end-product inhibition (Enari and Markkanen, 1977). Electron microscopic observations of the enzymatic hydrolysis of cellulose confirmed this hypothesis (White and Brown, 1981 as cited by Enari, 1983). Hence, ß-glucosidase activity is considered an indicator for biomass turnover (Garcia et al., 1994; Gander et al., 1994) as it is the driving force in the decomposition of carbohydrates in soils (Deng and Tabatabai, 1996). The primary producers of ß-glucosidase are mucoraceous fungi such as*Actinomucor* sp. and *Mortirella* sp. (Hayano and Tubaki, 1985), whereas bacteria do not produce exo-ß-1,4-glucanases and extracellular ß-glucosidase (Enari, 1983). ß-Glucosidase is concentrated in organic debris of the soil surface and in the fine soil fraction (< 2 mm) where fungal hyphae prevail (Hayano and Tubaki, 1985; Eivazi and Tabatabai, 1990; Foster, 1994 as cited by Miller

and Dick, 1995). Busto and Perez-Mateos (1995) could demonstrate that ß-glucosidase is extracellular and stabilized in soil by associations with humic materials. The optimal pH of ß-glucosidase activity was reported to be pH 6.0 (Eivazi and Tabatabai, 1988).

2.4.4 Protease

The hydrolysis of proteins (proteolysis) is an important step in the organic nitrogen cycle (ammonification and nitrification) of soils (Skujins, 1976; Ladd and Butler, 1972; Hayano, 1993) and is essential to maintaining soil fertility (Loll and Bollag, 1983; Takeuchi and Hayano, 1994). Proteases decompose proteins into smaller membrane-permeable peptides (oligopeptides) and amino acids which microorganisms can assimilate and metabolize to ammonia and carbondioxide (Loll and Bollag, 1983; Hayano, 1996). The main mineralization processes of biomass-N involve amino acid formation from protein and ammonification from amino acids (Hayano, 1996). Most of the N present in unfertilized soils is organic in nature and represents an important nutrient reservoir. Protein-N is the major form of soil organic nitrogen and often makes up 1/3 of total soil N (Loll and Bollag, 1983). This is of particular importance in many areas of the tropics where plant residues, household wastes and manure are often the only nutrient sources available (Ruthenberg, 1976; Palm and Sanchez, 1991). Thus, soil proteases are considered to reflect the proteolytic potential of a soil and hence, to indicate protein degradation capacity (Loll and Bollag, 1983; Kuprevich and Shcherbakova, 1971). Most proteases are extracellular since a direct uptake of proteins does not occur as such (Loll and Bollag, 1983; Law, 1980). Proteases constitute a heterogeneous mixture of enzymes with different molecular weights, structures and substrate specificities (Ward, 1983). Therefore, the characteristics of proteolytic enzymes are difficult to analyze (Ladd, 1972; Loll and Bollag, 1983; Law, 1983; Hayano, 1996). According to Sinsabaugh (1994) relationships between organic N content and extracellular enzyme activities are complex and diffuse as N is associated with nucleic acids, polysaccharides, proteins and humic complexes, whereby each of these N-pools is accessed by discrete enzyme systems. Based on the type of action and catalytic mechanism, proteases are classified according to the system of Hartley (1960 as cited by Law, 1980) into acid protease, serine or alkaline protease, thiol protease and metalloproteases. The origin of proteases in soil and their contribution by animal, plant and microbiological sources is discussed controversially in the literature. Badalucco et al. (1996) found highest protease activity in the root hairzone of wheat plants and concluded therefore a contribution of root-hair-enzymes to the overall protease activity at the soil-

root-interface (Badalucco et al., 1996). Similar results were reported by Nannipieri et al. (1983), stating that the addition of ryegrass resulted in higher protease activity due to the addition of exogenous enzymes with the ryegrass as compared to glucose amended soils. Based on observations by Rempe et al. (1965) and Hayano et al. (1983) that aseptically grown plants released invertase and peroxidase but not proteases and that tomato plants exhibited much lower protease activity per root dry weight as compared to phosphatase and ß-glucosidase, respectively, Hayano (1996) concluded that the contribution of proteases derived directly from plants is probably negligible or much less significant than that of other soil enzymes. Law (1980) stressed that extracellular proteolytic enzymes derive from various bacteria, although it is not always clear whether the enzymes described are truly extracellular or are released by lysing cells. And Glenn (1976 as cited by Law, 1980) suggested that only gram-positive bacteria produce truly extracellular enzymes. These findings are supported by Hayano (1996). Selective inhibition of bacteria and actinomycetes revealed that the soil contained no fungal protease (Hayano, 1996). Watanabe and Hayano (1994 a,b), Watanabe et al., (1994) and Hayano et al. (1990 as cited by Watanabe and Hayano, 1996) reported Bacillus sp. (gram-positive) as the numerically dominant proteolytic bacteria derived from paddy fields and both Andosols and gray lowland soils that were cultivated to sweet potato and a rice-wheat rotation or remained as uncultivated grassland in Japan, regardless of substrate specificity. Depending upon the soil, the optimal pH is reported as 6.8-8.8 (Ladd, 1972).

2.5 Limitations of bioassays

One constraint in using biological assays for soil quality indication is the lack of standard methodology. Considerable variation exists among assay procedures used by various researchers, making actual activity comparisons between sites difficult. It was thus emphasized that if bioassays are to be used as soil quality indicators, soil sample pretreatment, assay procedures and units of measurement must be standardized (Dick, 1994).

Soil enzymes are studied indirectly by measuring the activity via assays since it is difficult to extract enzymes from soils (Dick, 1992). In vitro assays, however, measure a potential activity under defined but artificial conditions rather than an activity under natural conditions of substrate supply. The incubation conditions used ensure near optimal rates of catalytic substrate conversion, thus making it difficult to relate the activities to those occurring in soils (Suttner, 1990; Nannipieri, 1994). Another constraint was related to the

inaccuracy of methods to discriminating between intracellular and extracellular activities of soil enzymes (Nannipieri, 1994). Nonetheless, studying soil enzyme activities is considered to provide insight into biochemical processes in soils, and is believed to be sensitive as a biological index (Frankenberger and Johanson, 1983; Dick, 1992; Garcia et al., 1994).

3 Materials and Methods

3.1 Study sites

The experimental sites were located at the research farm of the International Institute of Tropical Agriculture (IITA; 7° 30`N, 3° 54`E, 213 m.a.s.l.) at Ibadan in the forest-savanna transition zone of south-western Nigeria. The area has a bimodal distribution of rainfall and receives on average 1250 mm of rain, with two peaks in rainfall distribution that occur in June and September and a period of lower precipitation in August (Figure 1).

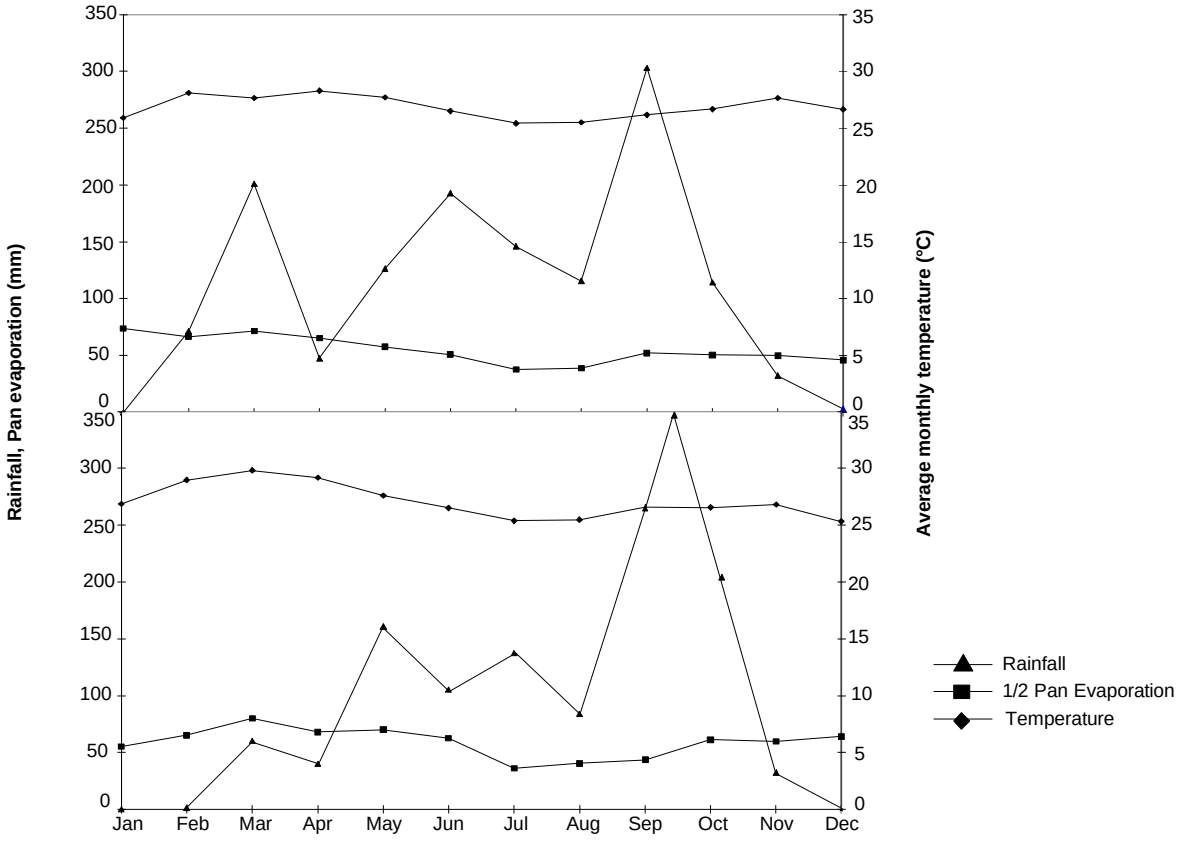


Figure 1. Climatic diagrams at IITA for 1993 (top) and 1994 (bottom)
(source: modified from Vielhauer and Hauser, 1995).

The dry season lasts from November to March. The annual rainfall is highly erratic and single rainfall intensities are high. The bimodal character of rainfall distribution enables two distinct growing seasons, the first season from late April to late August and the second shorter season from September to November. The length of the growing period is 211-270

days. The mean annual temperature is 26.2 °C and ranges from an average minimum of 21.3 °C to an average maximum of 31.2 °C.

The vegetation of the area consists of secondary forest and natural regrowth in various stages of succession. Arable crops constitute mainly maize (*Zea mays*) and cassava (*Manihot esculenta* Crantz) in intercropping but also egusi melon (*Citrullus lanatus* ssp. *mucopermus*), okra (*Abelmoschus esculentus*), yam (*Dioscorea rotundata*) and cowpea (*Vigna unguiculata* ssp. *unguiculata*) are found in mixtures with cassava and maize.

The landscape is undulating, dominant slopes are between 3 and 10 %. The soils at IITA are heterogeneous with changes occurring at distances of a few meters.

The soil at the experimental site is a well-drained Alfisol (oxic Paleustalf: USDA classification) and belongs to the Egbeda-Iwo soil series (Moormann et al., 1975). These upland soils are derived from strongly weathered gneiss's of the pre-Cambrian basement complex (Harpstead 1974; Moormann et al. 1975). The shallow surface horizons are underlain by a pronounced quartz gravel layer 20 to 40 cm below the surface, varying in thickness (up to 60 cm) and in percentage of coarse fragments and stone size with the gravel concentrations ranging from 40 % to 80 % (Wilson et al., 1982). The transition into the bedrock is a heavy clay layer underlined by Saprolite.

The gravel content of the surface soils varies between 1-25 % depending upon the degree of erosion of the profiles (Moormann et al., 1975). They are medium to light textured at the surface and have a low percentage of silt. The pore size distribution is discontinuous and a low structural stability with respect to raindrop impact results in surface sealing followed by runoff losses and erosion. Bulk density values are low to moderately low. The water holding capacity above the gravel horizon is generally low (1.2 mm/cm) on average whereas higher water holding capacities exist in the layers below the gravel horizon.

The soils are slightly acidic and contain only small amounts of exchangeable aluminum. They have a high base saturation (> 80 %), with Ca and Mg as dominant exchangeable cations. The effective CEC at the surface is generally low (6.2 cmol/kg soil) by temperate region standards but higher than for more strongly weathered soils of the tropics (Harpstead, 1974). Quartz, kaolinite and Fe-oxides are the predominant soil minerals in the topsoil. Therefore, the CEC of soil organic matter is important to retain nutrients for plants and microorganisms (Moormann et al., 1975).

3.2 Land use history of the study sites

3.2.1 Westbank 3

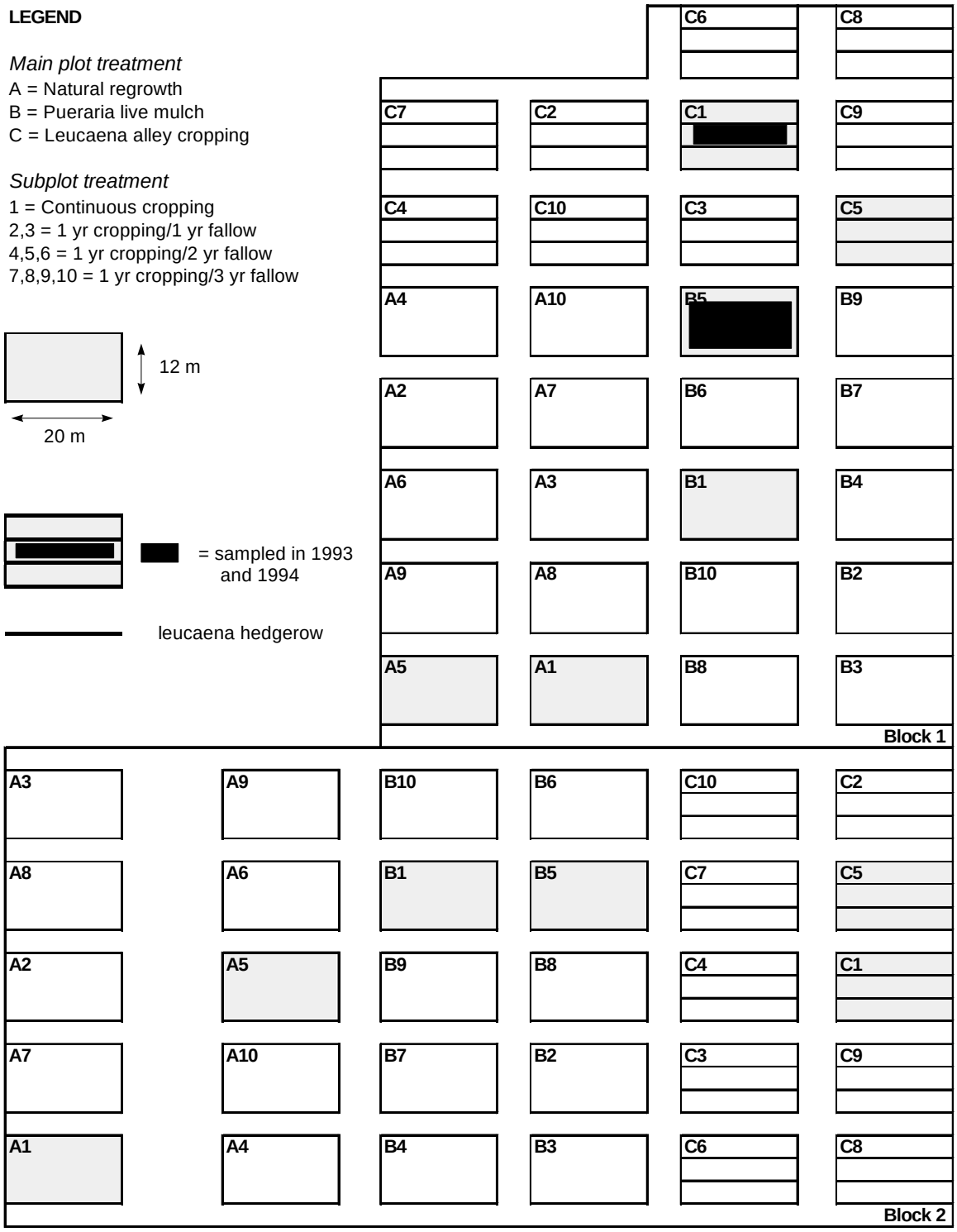


Figure 2. Field layout of Westbank 3 (modified from Vielhauer and Hauser, 1995).

The site was established in June 1989. A 25 year old secondary rainforest was cleared manually by using the traditional method of underbrushing, slashing and burning of the dried litter. Oil palms *(Elaeis guineensis*) and iroko trees (*Telfairia occidentalis*) were left in the plots and were only thinned in areas of high density. As depicted in Figure 2, the design is a split plot with four replications. Three fallow management systems - natural regrowth of the spontaneous vegetation, alley cropping with leucaena (*Leucaena leucocephala* [Lam.] de Wit*)*, a N_2-fixing woody legume and pueraria (*Pueraria phaseoloides)*, a N_2-fixing legume as herbaceous cover crop - were assigned to the main plots. Each fallow management system was operated at four different cropping intensities: (1) continuous cropping (1:1), (2) 1 year cropping, 1 year of fallow (1:2), (3) 1 year cropping, 2 years of fallow (1:3) and (4) 1 year cropping, 3 years of fallow (1:4) as subplots. Each subplot in the experimental treatment measures 12 by 20 meters.

Leucaena (cv. K 636 in replicate 1, cv. K 28 in replicate 2-4) was seeded at a rate of 3 kg/ha using 4 m interhedgerow spacing. Each alley cropping plot consisted of 4 leucaena hedgerows, whereby the 1st and 4th hedgerow were border rows (see Figure 2). Pueraria was planted at a seeding rate of 15 kg/ha. All systems were intercropped with high yielding maize (cv. TZSRW) at a population density of 40,000 plants/ha and cassava (cv. TMS 30572, maturity period 12 months) with 10,000 plants/ha. In the alley cropped system the space occupied by the hedgerows was compensated for by reducing the crop interrow distance from 1 m to 0.80 m (5 rows) for both crops in order to maintain the crop population densities (Vielhauer and Hauser, 1995). The interrow distance of maize and cassava in the pueraria and natural regrowth plots was 1 m. Maize and cassava interrow spacing was 25 cm and 100 cm, respectively. The crops were planted late April or in May depending on the onset of rains. Maize was harvested in August, while cassava was growing on the field around the year and harvested after 12 months of growth.

The plots were managed with minimum tillage, maize and cassava were hand-planted, no fertilizer or pesticides were used, weed control was done by hand weeding and the litter left on the field.

Leucaena was cut back (pruned) 3 to 5 times each year between March and October. The first pruning was done before planting maize and cassava, three times during the first growing season and a last time in October. Leaves and smaller branches remained in the plots as mulch, big branches were removed from the system. Pueraria was cut back at regular intervals to prevent it from climbing and suppressing the crops.

Before crops were planted each year the fallow vegetation in all treatments was slashed and the dried plant residue burnt (IITA/RCMD, 1989; Vielhauer and Hauser, 1995).
Soil and plant sampling was done in the first two replicates of the continuously cropped plots (1:1) as well as in the treatments with a 1 year cropping, 2 years of fallow period (1:3) cycle. Adjacent undisturbed secondary forest served as reference plots.

3.2.2 D 2

In April 1986, 4 fallow management systems (Figure 3) were established on about 1 year old grass fallow, formerly cropped and used by breeders of IITA (Van der Meersch, personal communication): (1) alley cropping with leucaena (*Leucaena leucocephala* [Lam.] de Wit (cv. K 8)), (2) alley cropping with senna (*Senna siamea* [Lam.] Irwin & Barneby) , a non-fixing leguminous tree, (3) mucuna (*Mucuna pruriens* var. *utilis*) as herbaceous cover crop, planted every second year, and (4) continuous cropping of maize and cowpea as the control treatment.

Table 1. Soil chemical and physical characteristics at D 2 in April 1986.

	Depth	
characteristics	**0-5 cm**	**5-10 cm**
C_{org}(%)	1.23	0.73
N_{tot} (%)	0.14	0.08
Bray-I P (mg kg^{-1})	33	28
Ca(1)	2.7	1.7
Mg(1)	0.75	0.43
Mn(1)	0.025	0.036
K(1)	0.44	0.26
Na(1)	0.08	0.06
ECEC(1)	4.03	2.7
Acidity(2)	0.03	0.20
pH	5.7	5.3
Base saturation (%)	99	93
Bulk dens. (Mg m^{-3})	1.32	1.42
Texture (%)		
sand	81	80
clay	9	9
silt	10	11

(1) = $cmol^{+}$ kg^{-1} soil
(2) = KCl exchangeable acidity ($cmol^{+}$ kg^{-1} soil)

At the beginning of the experiment, the surface layers at D 2 were less than 10 cm deep and the stone line cropped out at some spots in the field. Also high gravel contents were measured at some parts of the area (Van der Meersch, 1992). The chemical and physical soil properties at the beginning of the field trial in 1986 are summarized in Table 1 (compiled from Van der Meersch, 1992, pp. 28).

Except for 1990 and 1992 when only single maize was grown in the first season, each fallow system was sequentially planted to maize (cv. TZSR-W, Tropical Zea Streak Resistant White) in the first season and cowpea (*Vigna unguiculata* L. Walp. ssp. *unguiculata*) in the second season. Continuous cropping of maize and cowpea served as control. In 1988 the plots were split into two subplots during the second season, and were either cropped to early maturing maize (cv. DMR-ESR-W, maturity period 100 days) or cowpea as a single modification from the common cropping pattern (Van der Meersch, 1992). Each treatment was operated at two management levels, without and with fertilizer application, as displayed in Figure 3. The field layout was a s factorial (4 x 2) randomized complete block design with five replications, each plot size measuring 10 by 18 meters. The plots received N (120 kg N ha^{-1} as urea), P (90 kg P ha^{-1} as single superphosphate) and potassium (30 kg K ha^{-1} as muriate of potash; Van der Meersch, 1992). Senna and leucaena plots consisted of 5 hedgerows and 4 alleys of 10 m length using 4.5 m interhedgerow spacing. The planting distance of leucaena and senna within the rows was 25 and 50 cm, yielding 8,900 and 4,450 plants per hectare, respectively. Leucaena seeds were inoculated with the rhizobium strain IRc 1050 prior to planting (Van der Meersch, 1992). The crops were grown within each alley at a spacing of 75 cm between each row and to the hedgerows trees. Maize and cowpea within row spacing was 25 cm, achieving 45,000 plants/ha in the senna and leucaena and 55,000 plants/ha in the control and mucuna treatments, respectively. Mucuna was seeded at a distance of 25 by 100 cm (Van der Meersch, 1992).

The plots were managed with minimum tillage, weeding was done several times during the cropping season by hand hoeing. Removal of the weedy fallow vegetation that developed during the dry season and seedbed preparation of maize and cowpea was done by spraying of paraquat (Van der Meersch, 1992; Vanlauwe, personal communication).

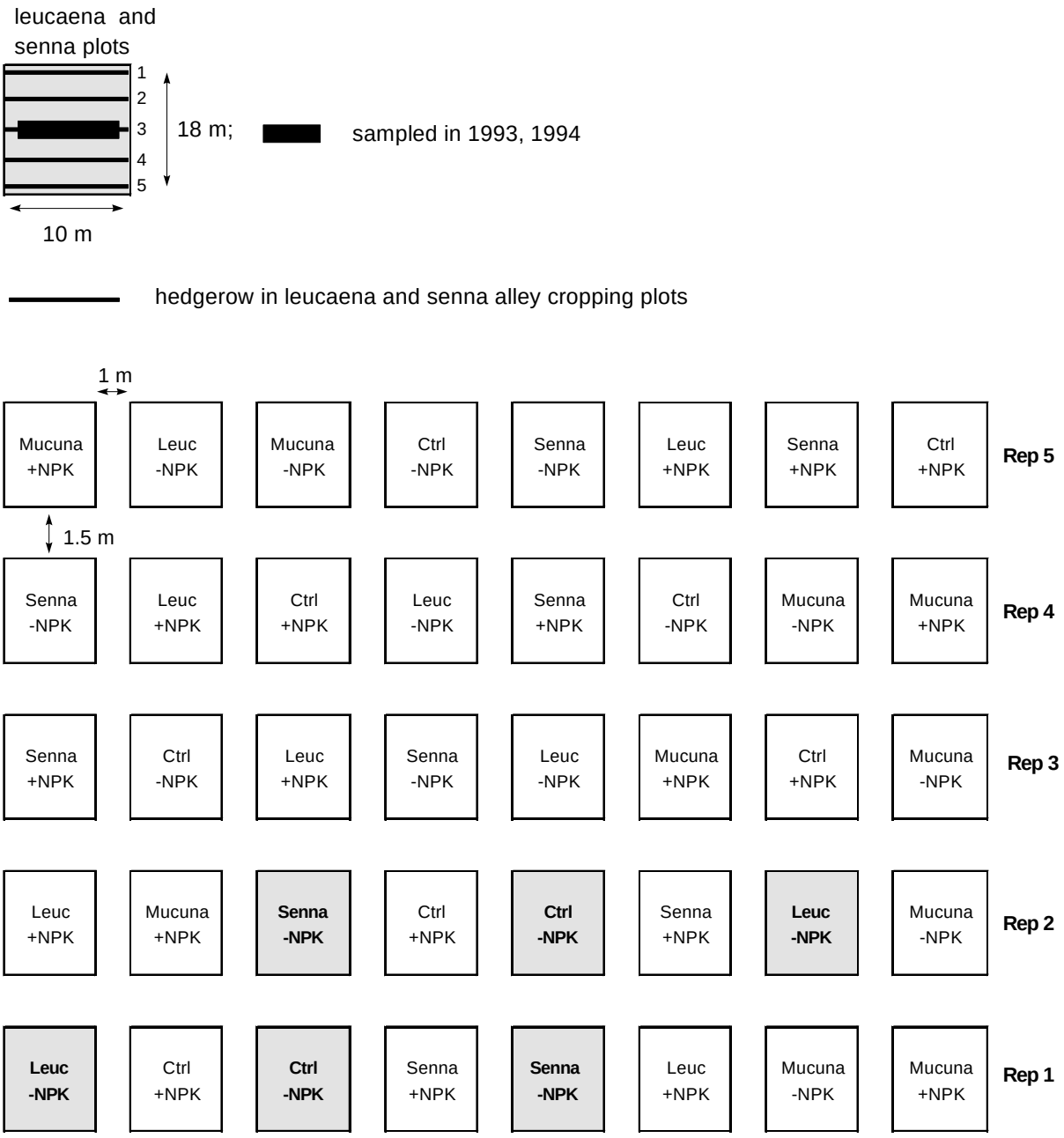


Figure 3. Field layout of the experimental site at D 2 (modified from Van der Meersch, 1992).

One year after establishment, the hedgerow trees were pruned the first time in 1987 and the leaves and twigs were applied to the plots as mulch. Between 1988 and 1990, the trees were pruned and mulched three times a year, once before planting the first season crop, the second time 7 to 8 weeks later during the first season and a last time before planting the second season crop (Van der Meersch, 1992). From 1990 onwards, leucaena and senna were pruned 3 to 5 times during the cropping period and leaves and smaller branches were left on the plots as mulch. Bigger branches were removed. The trees were normally pruned

before planting the first crop, once or twice during the first growing season, before planting the second season crop and a last time during the second growing season (Vanlauwe, 1996).

In 1994 the plots were split into four subplots, each plot size measuring 5 x 4.5 m (Figure 4). The subplots consisted of 3 hedgerows and 2 interrows, and 2 hedgerows were used as border rows of the experiment. Four differing fertilizer treatments were applied, (1) without fertilizer, (2) with NPK, (3) with PK and (4) with N. Phosphorus was applied as single superphosphate at a rate of 30 kg P/ha, N was applied as urea at 60 kg N/ha and K at 30 kg K/ha as muriate of potash (Vanlauwe, 1996).

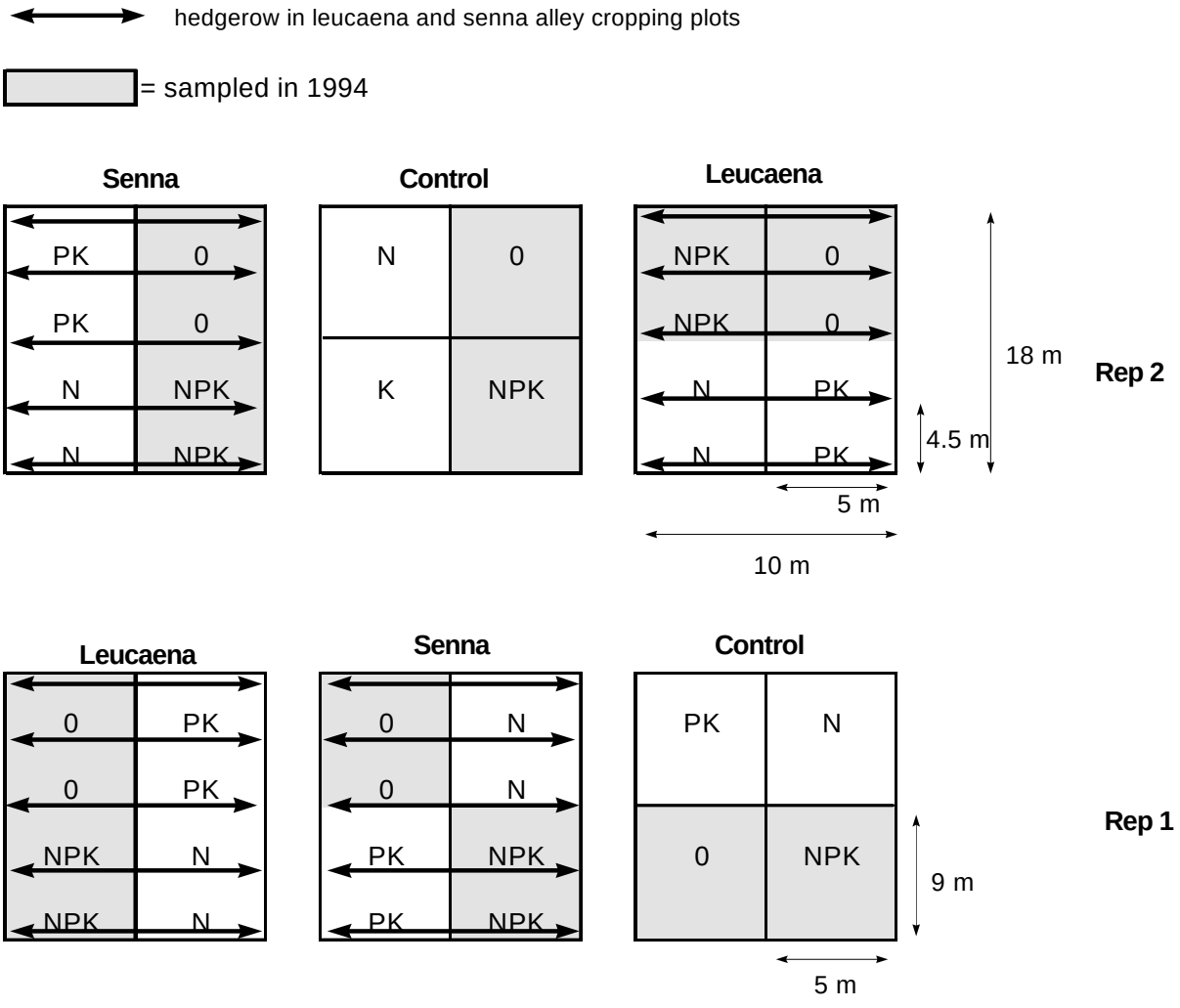


Figure 4. Field layout of D 2 showing subplots with differing fertilizer management of the 1st and 2nd replication in 1994.

In 1993 and 1994 soil sampling was done in the unfertilized control, leucaena and senna treatments of the first two replicates. These treatments were unfertilized since 1986. In 1994, additional sampling was done in the fertilized subplots (Figure 4).

3.2.3 Westbank 1

The experimental site was established in 1979 on a 15 years old secondary rainforest, formerly managed under shifting cultivation. Between November 1978 and March 1979 the area was cleared mechanically with a tree pusher/root rake combination system traveling through the soil to a depth of 50 cm to remove tree roots, stumps and debris. Trees and underbrush material were burnt *in situ* and unburned trees removed (Couper et al., 1981). An intensive mechanized cropping thereafter for a period of ten years resulted in considerable soil disturbance, followed by an exposure of the subsoil at some spots and high spatial soil variability (Lal, 1981; Couper et al., 1981; Lal and Couper, 1990; Lal, 1992).

In April 1979 the plots were intercropped with maize and cassava. The within row spacing of maize was 25 cm and of cassava 100 cm, the between row spacing was 75 cm. From 1980 to 1982 the plots were sequentially grown to maize in the first season and cowpea in the second season. The crops were sown mechanically 25 cm apart in 75 cm rows and conventionally tilled by disc harrowing.

Maize was fertilized with 400 kg/ha of 15/15/15 NPK-fertilizer at sowing; 4 weeks later a top dressing of 45 kg N/ha as calcium ammonium nitrate was applied. No fertilizer was given to cowpea. Graded contour banks were formed to control erosion.

In 1982 mucuna as herbaceous fallow species was planted in the second season to restrict erosion and restore soil fertility (Lal and Couper, 1990; Lal, 1992). Between 1983 and 1986 maize and cowpea were cropped sequentially again. Fertilizer applications corresponded to earlier rates.

Since 1983 the plots were managed by no-tillage. Seedbed preparation and weed control was done by spraying 2,5 l/ha of paraquat and atrazine at a rate of 2,5 kg/ha. Due to accelerated soil erosion problems and low yields, the experimental site was under mucuna fallow again in 1987 and 1988 (Couper et al., 1981; Lal and Couper, 1990; Lal, 1992).

In 1989 woody and herbaceous fallow species were introduced in order to investigate their potential to biologically restoring a severely degraded Alfisol (Hulugalle, 1989, 1992). The sampled fallow species comprised pueraria, leucaena, senna and natural regrowth of the

spontaneous vegetation (Figure 5). Pueraria was planted in rows spaced at intervals of 25 by 75 cm, leucaena and senna were planted in hedges using 4 m interhedgerow spacing. Pre-planting land preparation was by hand hoeing to a depth of 5 cm. Continuous intercropping of maize and cassava on those plots that have been cropped since 1979 served as control. The within row spacing of maize and cassava was 25 cm by 100 cm, respectively, the between row spacing 75 cm. The plot size was 24 by 12 meters.

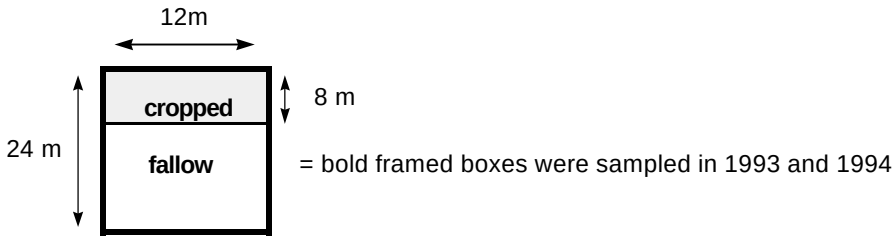
After establishment, fertilizer was applied once in 1989 to each fallow treatment at a rate of 400 kg/ha of 15/15/15 NPK. Between 1989 and 1992 400 kg/ha of 15/15/15 NPK was amended to the control treatments only at planting each year. The plots were managed with a minimum tillage system. Weeding was done at five-week intervals during the rainy season by slashing with cutlasses. Seedbed preparation was done with hand hoes (Hulugalle, 1989, 1992).

In March 1993 one third of each fallow plot (8 by 12 meters) was manually cleared and burnt as displayed in Figure 5. Cassava plant debris of the continuous cropping control was burnt as well before replanting in May 1993. Potential nutrient input of selected fallow species was estimated with 330, 10, 160, 260, 50 kg/ha as N, P, K, Ca, Mg from senna, respectively, 110, 3, 60, 60, 20 kg/ha from leucaena, 230, 6, 80, 180, 30 kg/ha from pueraria and 170, 5, 60, 150, 30 kg/ha from natural regrowth, respectively (Salako, 1993; personal communication). The remaining two third of the plots were left fallow. Maize and cassava was intercropped for two consecutive years in 1993 and 1994.

Plots were maintained by minimum tillage, weeding was done with hand hoes. No fertilizer was applied. In 1993 cassava cuttings, treated with Aldrin-dust, were replanted again two to three weeks after the first planting because of damage by ants and termites (Salako, 1993; personal communication).

Leucaena and senna hedgerows were not burnt completely and removed from the plots after clearance in March 1993. Unburned hedgerow stumps of about one meter height were left in the plots. Stimulated by the onset of the rainy season the stumps coppiced. Consequently, in 1993 a hedgerow effect was still existent. To counteract this unwanted effect the „hedgerows“ were slashed thoroughly in 1994 and the stumps were poisoned with diesel to prevent coppice shoot regrowth.

In 1993 and 1994 soil sampling was done in the cropped and fallow treatments of replicate one and two.



Rep. 1

Cajanus cajan	*Panicum maximum*	*Pueraria phaseoloides*	*Mucuna pruriens* var.*utilis*	Natural fallow	Maize/ Cassava
Centrosema pubescens	*Senna siamea*	*Acacia difficilis*	*Brachiaria lata*	*Lablab purpureus*	*Acacia leptocarpa*
Psophocarpus palustris	*Leucaena leucocephala*	*Stylosanthes hamata*	*Acacia auriculaeformis*	Natural fallow II	*Macroptilium atropurpureum*

Rep. 2

Panicum maximum	Natural fallow	*Leucaena leucocephala*	*Mucuna pruriens* var.*utilis*	Natural fallow II	*Pueraria phaseoloides*
Senna siamea	Maize/Cassava	*Acacia leptocarpa*	*Cajanus cajan*	*Lablab purpureus*	*Brachiaria lata*
Acacia difficilis	*Acacia auriculaeformis*	*Psophocarpus palustris*	*Centrosema pubescens*	*Macroptilium atropurpureum*	*Stylosanthes hamata*

Figure 5. Field layout of Westbank 1 (replicate 1 and 2) in 1993 and 1994.

3.2.4 Screening of the study sites

Land use history impacts on the productivity and susceptibility to degradation of a soil. The extent and severity of soil degradation will depend on the cultivation systems and management intensities that were imposed (Theng, 1991; Kleinman et al., 1995).

In this study the primary cause of degradation was assessed by the length of the cropping period and the management intensity that was applied over time by screening continuous cropping controls of long-term management trial (Table 2).

Except for 1987 and 1988, Westbank 1 was continuously cropped for 14 years prior to the onset of soil sampling in 1993 to either maize and cowpea in sequence or maize and cassava intercropping. In contrast, Westbank 3 was intercropped to maize and cassava only since 1989.

Table 2. Land use history at Westbank 1, D 2 and Westbank 3 as reflected by time of continuous cropping and management .

	year															
	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
cropping pattern																
WB 1	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs
D 2		├	─	─	─	─	┤	M-C	M-C	M-C	M-C	M	M-C	M	M-C	M-C
WB 3											M+Cs	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs
fertilizer																
WB 1[(1)]	-	+	+	+	+	+	+	+	+	-	+	+	+	+	-	-
D 2		├	─	─	─	─	┤	-	-	-	-	-	-	-	-	-
WB 3								-	-	-	-	-	-	-	-	-
tillage																
WB 1[(2)]	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-
D 2		├	─	─	─	─	┤	-	-	-	-	-	-	-	-	-
WB 3								-	-	-	-	-	-	-	-	-
pruning																
D 2								-	+	+	+	+	+	+	+	+
WB 3											-	+	+	+	+	+

M+Cs = maize and cassava intercropping
M-C = maize and cowpea sequential cropping
Mu = mucuna fallow
M-Mu = maize in the 1st season and mucuna fallow in the 2nd season
M = maize in the 1st season only
(1) = fertilizer application at a rate of 400 kg/ha of 15/15/15 NPK-fertilizer at sowing; 4 weeks later a top dressing of 45 kg/ha as calcium ammonium nitrate to maize crops
(2) = conventional tillage, disc harrowing
├─┤ Between 1980 and 1986 D 2 was part of an experimental area used by breeders (maize, cassava, cowpea and soybean) with diverse tillage (ploughing and disc harrowing) and fertilizer managements. In 1986, D 2 was split into two plots. At one site the improved fallow management tria were stablished in 1986. However, the recorded management schedules of the site do not allow a conclusive allocation of the land use history to D 2 (Van der Meersch, pers.com.; Vanlauwe, pers.com.).

The land use practices applied at the study sites are multiple cropping systems that aim at intensifying land use in time and space dimensions by growing two or more crops on the

same field per year. The chronological sequence of the management systems is demonstrated in Figure 6. The prevailing land use practices in south-western Nigeria are maize-cassava-intercropping systems, whereas sequential cropping of maize and cowpea is less important in this area (Heide et al., 1985).

Under sequential cropping managements as practiced at D 2 two or more crops are grown in sequence on the same field per year (Andrews and Kassam, 1976). As depicted in Figure 6 crop intensification is only in the time dimension, since the two crops do not overlap and the second crop is being sown only after the harvest of the first. Cowpea is planted in the shorter second season between September and October when lower rainfall prevails. This short duration crop can escape possible drought at the end of the season (Härdter, 1989; Kayombo and Lal, 1993).

In intercropping systems (WB 3, WB 1), however, crop intensification is in both, space and time dimensions (Andrews and Kassam, 1976). Maize is cropped in the first season and harvested before cassava develops full canopy, whereas cassava with its slow initial growth and a growing period of 9 to 18 months to maturity is in the field throughout the year.

The management intensity of each system differs primarily in the rate to which soil resources are used in time and space. While row intercropping, as practiced at Westbank 3 and Westbank 1, is one of the more extreme means of intensifying land use because inter- and intra-component exploitation of soil resources is high (Oelsligle et al., 1976), sequential cropping is the less intensive form of multiple cropping. As depicted in Figure 6, the soil under intercropping of maize and cassava is covered with a crop almost year round, whereas sequential cropping of maize and cowpea allows a less intensive resource use, including a fallow period from December to late March.

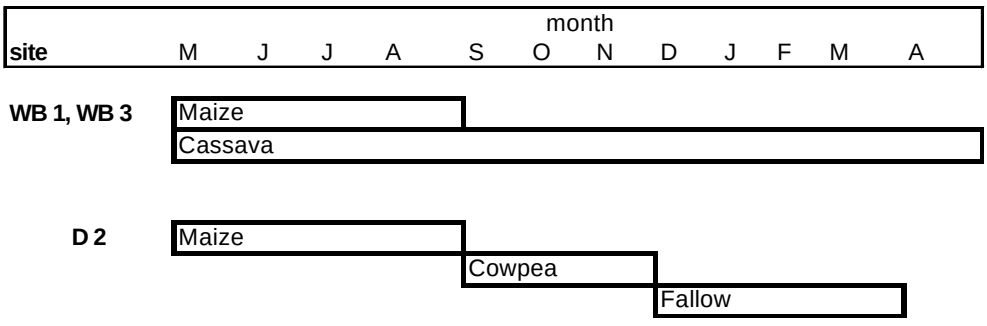


Figure 6. Cropping calendar at the different field trials during 1993 and 1994.

Intercropping of maize and cassava may lead to more rapid mining of natural soil fertility because both crops require large amounts of nutrients (Beets, 1982). Maize plants require high amounts of N for a good yield, but also P and K are essential (Adediran and Banjako, 1995). Although cassava can grow in a wide variety of soil conditions, the cassava crop can rapidly impoverish the soil under good soil fertility conditions (IITA, 1990; Olasantan et al., 1996). Nutrient removals of unfertilized maize/cassava intercropping at IITA, Nigeria was reported as 82, 12, 89, 32 and 13 kg N, P, K, Ca and Mg per hectare per year, respectively (Olasantan et al., 1996). However, part of the nutrients taken up by maize during the early stages of the growing season will be recycled to the soil by decomposition of maize stover after the grain harvest.

In contrast, sequential cropping of maize and cowpea is presumed to be advantageous to maintaining soil fertility as the system retains nitrogen fertility (Eaglesham et al., 1981; Beets, 1982). Although cowpea plants need adequate quantities of N from soil as well, the main contribution to the productivity of this system may be expected from a beneficial crop rotation effect. The N_2 fixing ability of cowpea with subsequent N and also P transfer to the succeeding crop by decomposition of the plant residues may contribute to a better utilization of soil nitrogen (Härdter, 1989). The fallow vegetation growing from December to late March may also sustain the system by restoring nutrient supply of the soil.

Besides influencing the soil fertility status, the management system may also influence the erodibility of the soil. The rate of growth and the extent of canopy cover, especially under high rainfall conditions, regulates the degree to which the soil surface is exposed to raindrop impact, wind and sunlight, and hence runoff and erosion (Lal, 1990). Canopy cover can be increased by intercropping (Reddy, 1987). Monocropped cassava, for example, takes 63 days to provide a 50 % ground cover, as compared to only 50 days for cassava/maize intercropping (Reddy, 1987). Olasantan et al. (1996) reported that intercropping of maize and cassava at IITA, Nigeria resulted in better interception of light, improved moisture content in the top 10 cm, reduced soil temperature, and enhanced earthworm activity. However, intercropping of cassava with maize delayed bulking of storage roots and significantly reduced tuber yield as compared to sole cropping (Olasantan et al., 1996; Kühne, 1993). Monocropping of field crops as practiced at D 2, on the other hand, may be prone to erosion by sediment loss during intense rainfalls during early stages of plant development.

Based on the length of the cropping period and the management intensities applied (Table 2) Westbank 1 is presumed as the most degraded site. D 2 is ranked as intermediate in the

degree of degradation between Westbank 3 and Westbank 1, although the management system at D 2 is less intense and more conservatory in nature as the intercropping systems at WB 3 and WB 1.

However, between 1980 and 1986 D 2 had been cropped and used by breeders of IITA. Data on soil physical and chemical characteristics of the site prior to the experimental implementation in April 1986 (Table 1) show that the soil had a low nutrient status. Based on the proposition by Juo (in: IITA, 1983 cited by Van der Meersch, 1992, pp. 113) degraded soils at IITA's experimental farm are existent when the pH is less than 5, organic carbon less than 1 % and exchangeable Mg less than 0.5 $cmol^+$/kg soil. Surface soil properties in the 0 to 15 cm layer under secondary forest with pH values of 6 to 6.6, organic carbon of 1.5 to 2.3 % and exchangeable Mg of 0.9 to 1.8 $cmol^+$/kg were taken as reference (Van der Meersch, 1992). Van der Meersch (1992) accordingly concluded that the soil was at a low fertility level when the trial started in 1986 and continued to degrade further upon cropping. In 1990, organic carbon, pH and exchangeable Mg in the 0 to 5 cm layer reached concentrations between 1.05 and 1.21 %, 4.9 and 5.2 and 0.44 and 0.6 $cmol^+$/kg, respectively (Van der Meersch, 1992, pp. 165-166) and were, thus, in the proposed magnitude of degraded soils at IITA. Similar results were obtained for WB 1. At the onset of the experimental trial in 1979, total organic carbon, pH and exchangeable Mg in the 0-10 cm layer was 1.56 %, 6.7 and 1.7 $cmol^+ kg^{-1}$, respectively and declined to 1.15 %, 5.6 and 0.62-0.72 $cmol^+ kg^{-1}$, respectively in 1991 (Lal, 1992).

In summary, according to the land use history the state of degradation is ranked in the order WB 1 > D 2 > WB 3.

3.3 Soil sampling

3.3.1 Number of soil cores

In preliminary tests (data not shown) the number of single core samples to be taken from the plots in order to account for soil spatial variability were evaluated. To that end, plots were chosen from the least degraded Westbank 3 (plot size 20 by 12 meter) and the most severely affected Westbank 1 (plot size 12 by 8 meter). The treatments at WB 3 included leucaena, pueraria and natural regrowth and at WB 1 leucaena and senna alley cropping. In the alley cropped plots 20 core samples were taken along the hedgerow from 0-10 cm depth. In both the natural regrowth and pueraria plots 25 samples were selected at random.

Each sample was analyzed separately for ß-glucosidase activity as it was found to fluctuate highly within short distances.

Based on suggestions by Petersen and Calvin (1986) the number of samples needed were estimated by $n = ta^2 \, s^2/D^2$, with n = number of samples, ta = quantile of student's t distribution with (n-1) degrees of freedom at the $\alpha = 0.05$ probability level, s^2 = variance of mean and D = desired precision (5 % deviation of mean). The results obtained revealed that 215, 245, 164, 93 and 70 single core samples had to be taken from leucaena at WB 1, senna at WB 1, leucaena at WB 3, natural regrowth at WB 3 and pueraria at WB 3, respectively. This, however, is not practicable in routine field work.

Similar results were reported by Roder et al. (1995 b) and Pushparajah (1989) cited by Roder et al. (1995 b). The authors assessed the short range soil variability in slash-and-burn systems of northern Laos and concluded from their results that the number of sub-samples ($n = t_a^2 \, s^2/D^2$) required to document changes in available P and K would be unrealistically high (> 300). In order to detect differences of 10 % with a confidence level of 95 % Roder et al. (1995 b) limited the number of sub-samples for 200 m^2 to 15 for pH, N and P_{total} and to 20 for organic carbon.

However, the main emphasis in our research work was focused on potential changes of soil processes over time rather than short-term variability within plots. Thus, sampling was intensified over time by taking soil samples every 6 weeks.

3.3.2 Sampling procedure and sample preparation

Between April 1993 and October 1994 soil cores were taken at random every six weeks from the 0 to 5 and 5 to 10 cm depth. We limited the number of subsamples to 15-25 single soil cores due to capacity restrictions (Table 3). The topsoil was considered only, since mulching systems with minimum tillage are likely to affect only the top layers. Total soil organic carbon, nutrients and microbial biomass were reported to decline rapidly below 10 cm at IITA, Nigeria (Vanlauwe, 1996).

Soil sampling in the leucaena alley cropping treatment at WB 3 was done along the 2nd and 3rd hedgerow and in the interrow (2 m away from the hedges) between the 2nd and 3rd hedge (see Figure 2). In the leucaena and senna alley cropping treatments at D 2 soil samples were taken along the 3rd hedgerow and in the alleys (2.25 m away from the hedgerows) between both the 2nd and 3rd and 3rd and 4th hedgerow (see Figure 3). Soils in the control, pueraria and natural regrowth treatments were sampled from the whole plot.

The random soil cores were taken with a 4 cm ∅ soil auger, bulked and homogeneously mixed in a plastic bucket and subsampled for temporary storage in sealed plastic bags.

Table 3. Number of random core samples from 0-5 cm and 5-10 cm depth every 6 weeks between April 1993 and October 1994.

	Study site		
Management systems	**Westbank 3**	**D 2**	**Westbank 1**
Control	25	25	20
Leucaena			
along hedge	18	18	15
along interrow	18	18	15
Senna			
along hedge		18	15
along interrow		18	15
Nat. regrowth	25		20
Pueraria	25		20

Bulk density measurements were made with undisturbed soil cores. Subsamples for the determination of gravimetric soil moisture content, pH, texture, exchangeable cations, available phosphorus and sequential fractionation of phosphorus were air dried, ground and sieved to pass a 2 mm sieve; subsamples for organic carbon and total nitrogen determination were sieved to pass a 0.5 mm sieve after air-drying.

The soils for enzyme analysis were kept field moist, passed through a 2 mm sieve and stored frozen until analysis. Microbial biomass carbon was determined 1 to 4 days after sampling on field moist and unsieved subsamples.

3.4 Soil analysis

Chemical and physical analysis of the soils were done according to the procedures of the Analytical Service Lab of IITA (1979). The gravimetric water content was determined by oven-drying 10 g soil at 105 ^{o}C for 24 hours and calculated as the ratio of mass of water to the soil dry mass. Particle size distribution was analyzed with the hydrometer method using

sodium hexametaphosphate as a dispersing agent. The soil bulk density was measured with the core method. Soil pH was determined in a 1:2.5 ratio of 10 g soil and 25 ml of 0.01M $CaCl_2$ solution. The soil water was allowed to equilibrate for 1 h and the pH values were measured with a Beckman glass electrode pH meter.

Organic carbon in soil was analyzed by the dichromate oxidation method of Walkley and Black (1954) as cited by IITA (1979) on 1g soil samples, total N by the Kjeldahl digestion and the N content in the digest analysed colorimetrically on the Technicon Model II Autoanalyzer. Available phosphorus was analysed by the Bray No 1 method of Bray and Kurtz (1945, as cited by IITA, 1979). The exchangeable bases Ca, Mg, K , Na as well as Mn were extracted with 1 N ammonium acetate (pH 7) and the cation exchange capacity (CEC) calculated as the sum of exchangeable cations (IITA, 1979).

Phosphorus was fractionated by a sequential extraction according to Hedley et al. (1982) with modifications by Tiessen and Moir (1993). The procedure used is a chemical extraction of decreasingly available phosphorus forms due to stronger adsorption and affinity to soil components. The method aimed at quantifying labile P_i (resin P_i and $NaHCO_3$-P_i), Fe + Al associated P_i, Ca-associated P_i, as well as labile and more stable forms of P_{org} in subsequent steps. Thus, the differentiation of these fractions should reflect their bioavailability. The fractions extracted by this procedure correspond to the following hypothetical soil P-pools:

- resin membrane-Pi: freely exchangeable, adsorbed on surfaces of more crystalline P-compounds, sesquioxides or carbonates,
- $NaHCO_3$-$P_{inorg\ and\ organic}$: labile inorganic and organic P sorbed on soil minerals, plant available,
- NaOH-P_{inorg} : non-occluded phosphorus, associated with amorphous and some crystalline Al and Fe phosphates,
-NaOH-$P_{organic}$: labile organic phosphorus of the fulvic acid fraction, used as indicator of P-status and fertility of soils,
- NaOH sonicated P_i and P_{org}: occluded inorganic P and protected and recalcitrant P_{org},
- HCl-P_i: calcium associated P_i (apatites),
- residual P,

(Tiessen et al., 1992, 1994; Beck and Sanchez, 1994; Paniagua et al., 1995).

The following P-fractions were analysed sequentially on 0.5 g soil samples with slight modification: (1) $NaHCO_3$-P_{inorg}, by shaking the soil with 30 ml 0.5 M $NaHCO_3$ adjusted to pH 8.5 end-over-end for 16 hr at 25 ^oC, followed by 5 min centrifugation at 10000 r.p.m.

and subsequent filtration of the supernatant through a 0.45 µm millipore filter (cellulose acetate filter, Sartorius AG No. 11106-47-N, Germany), (2) $NaHCO_3$-P_{total} by digesting 5 ml of the supernatant with acidified potassium persulfate in the autoclave for 60 min (Environmental Protection Agency, 1971), (3) NaOH-P_{inorg}, by adding 30 ml of 0.1 M NaOH to the soil of step (1) and re-shaking as above. (4) NaOH-P_{total} by digesting 5 ml for 90 min as in step (2).

The organic P-content in the $NaHCO_3$ and NaOH extracts was calculated as the difference between total P and inorganic P in the respective extraction steps. Orthophosphate P in all extracts and digests were determined colorimetrically by the molybdate-ascorbic acid method (Murphy and Riley, 1962, as cited by Olsen and Sommers, 1982) at 712 nm on a spectrophotometer. The spectrophotometer was fitted with a 5 cm and a 1 cm cuvette for the bicarbonate and the NaOH-fraction, respectively.

Labile inorganic phosphorus was immediately extracted with bicarbonate (0.5M $NaHCO_3$), the resin membrane procedure as first step to extract the most labile P_i was left out and was done as a modification from the original methods (Hedley et al., 1982; Tiessen and Moir, 1993). This procedure was applied in accordance to Magid and Nielsen (1992) who reported that a pooling of resin-P_i and bicarbonate-P_i by immediate extraction with 0.5 M $NaHCO_3$ was sensible without interfering with the sequential extraction procedure.

3.5 Enzyme analysis

The Enzyme Commission (EC) numbers and enzyme names are according the recommendations by the Nomenclature Committee of the International Union of Biochemistry (International Union of Biochemistry and Molecular Biology on the Nomenclature and Classification of Enzymes, 1992).

3.5.1 Acid and alkaline phosphatase

[Orthophosphoric monoester phosphohydrolase; Enzyme Commission Number: 3.1.3.2 and 3.1.3.1; 1992]

Acid and alkaline phosphatase activity in the soil was measured according to Tabatabai and Bremner (1969) with slight modifications. The release of p-nitrophenol from a p-nitrophenylphosphate solution (disodium-p-nitrophenylphosphate hexahydrate; Fluka No. 71768, Fluka, 1997/98) added to the soil was determined colorimetrically at 400 nm 1 hour

after incubation at 37 °C. Results of activity are expressed as micrograms p-nitrophenol released over 1 hour by 1 g soil and are averages of triplicate assays.

Toluene was not included in the procedure because it may increase the observed activities of both, acid and alkaline phosphatase (Tabatabai, 1982). The application of toluene as biocide for microorganisms during subsequent incubation is also questionable because it can be used as a source of C by most soil microorganisms (Kaplan and Hartenstein, 1979). Modified from the original method to assaying alkaline phosphatase activity was the application of the modified universal buffer (MUB) of pH 9 rather than pH 11 due to the inaccuracy of the Beckman glass electrode pH meter above pH 9 (Pleysier, 1993; personal communication). However, the optimal activity was not affected since the pH-optimum lies between pH 9 and 11 (Eivazi and Tabatabai, 1977).

3.5.2 ß-Glucosidase

[ß-Glucosidase, Enzyme Commission Number: 3.2.1.21; 1992]

ß-Glucosidase was analyzed according to Eivazi and Tabatabai (1988). The method is based on the colorimetric determination of p-nitrophenol released by ß-glucosidase after the soil is incubated with buffered (pH 6.0) p-nitrophenyl-ß-D-glucoside (Fluka No. 49291, Fluka 1997/98) solution for 1 h at 37 °C. Toluene was not included in the procedure, and was modified from the original method. The extracted p-nitrophenol is measured at 400 nm on a spectrophotometer. Results reported are averages of triplicate assays, expressed on a oven dry basis (drying at 105 °C for 24 h). The results of activity are expressed as micrograms p-nitrophenol released over 1 hour by 1 g soil.

3.5.3 Protease

[Protease, Enzyme Commission Number: 3.4; 1992]

Protease activity of the soil was determined according to Ladd and Butler (1972). Tyrosine released from a submitted sodium caseinate (Sigma No. C 8654; Sigma, 1997) solution buffered at pH 8.1 by soil proteases after incubation for 2 hours at 50 °C was measured colorimetrically at 700 nm. Results of activity are expressed as micrograms tyrosine released per 2 hours and per 1 g soil.

3.6 Microbial biomass carbon

Microbial biomass carbon was determined by the chloroform-fumigation-extraction method for biomass ninhydrin-N after pre-extraction of roots (Mueller et al., 1992). Pre-extraction of the unsieved soil samples is favored in the presence of living roots. The fumigation of soil with chloroform will destruct the cell walls of both, the microbial biomass and the fresh roots, which in turn results in the unwanted extraction of the root cellular content. Sieving and subsequent preincubation for 10 days as alternative to removing roots is unsuitable (Mueller et al., 1992). Pre-extraction was conducted by shaking triplicate soil samples for 20 min with 0.05 M K_2SO_4 and subsequent passing through a 2 mm sieve. Roots on the sieve were washed free of soil with additional 0.05M K_2SO_4 and the soil suspension centrifuged for 15 min at 500 g. The supernatant then was decanted and three drops of liquid chloroform were added to the soils to be fumigated. After pre-extraction, the non-fumigated control samples were immediately extracted according to Brookes et al. (1985 a, b) and Vance et al. (1987). The samples to be fumigated were placed in a desiccator and fumigated under vacuum for 24 hours at 25°C in the dark. After allowing the chloroform to dissipate, the released microbial compounds were then extracted with 0.5 M K_2S0_4 and the α-amino nitrogen containing molecules (amino acids, peptides, proteins; 30 %) as well as ammonium (70 %) were determined colorimetrically at 570 nm in the presence of ninhydrin according to Joergensen and Brookes (1990).

Biomass carbon was calculated by multiplying the ninhydrin-reactive N with 20.6. Ninhydrin-reactive nitrogen (N_{nin}) was calculated by using l-leucine standards as the difference between N_{nin} extracted from fumigated soils and N_{nin} extracted from non-fumigated soils.

3.7 Plant sampling and analysis

Maize grain and stover were subsampled at final harvest in 1994, dried and analyzed for nutrients.

Leucaena and senna prunings (leaves, twigs and smaller branches) were sampled from each pruning at Westbank 3 and D 2, dried and weighed for dry matter determination. Subsamples were analyzed for nutrients.

Plant analysis

Part of the plant material was finely ground and analyzed using the standard methods of IITA (1979).

Determination of total N was done by the micro-Kjeldahl method and the N content in the digest analyzed colorimetrically on the Technicon Model II Autoanalyzer. For K, P, Ca and Mg, concentrations the plant material was digested with perchloric acid. The P content of the digest was analyzed colorimetrically with the Vanado-Molybdate method. Calcium and Mg were determined with atomic absorption spectrometry, K with flame photometry.

3.8 Statistical analysis

Statistical analysis was performed on soil chemical and microbiological parameters by nested (hierarchical) analysis of variance using the General Linear Model procedure of the Systat Program (Systat, 1992). Measurements over time were not considered as repeated measurements because composite soil cores taken within each plot differed at each sampling date. As a result, measurements over time were not treated as fixed but as random effects, and time was nested as subsample within treatments. Thus, 3 sites, 12 treatments and 5 sampling dates during the 1st and 2nd cropping season (April-October) in 1993 and 1994 were combined in the nested analysis of variance. For the dry season 3 sampling dates were nested as subsamples within treatments.

If the overall F-test was significant, planned but nonorthogonal contrasts were applied to the soil chemical and microbiological data. To evaluate which treatments were different from others the Bonferoni adjustment was carried out by dividing α through the number of planned comparisons as the new α-striking significance level, where $\alpha'' = \alpha/k$ with k = number of planned contrasts (Sokal and Rohlf, 1995, pp.241). The number of the planned comparisons used here were 11, and the new significance level, thus, considered was $\alpha/11 = 0.0045$. The planned contrasts or comparisons applied were (1) control versus control at different sites, (2) at WB 3: control versus leucaena, control versus pueraria, and control versus natural regrowth, (3) at D 2: control versus leucaena and senna, and (4) at WB 1: control versus senna, control versus leucaena, control versus pueraria, and control versus natural regrowth.

If not stated differently, data on soil chemical and microbiological properties are the mean of 5 sampling dates of both the 1st and 2nd cropping period (April-October) and the mean of three sampling dates during the dry season (November 1993-March 1994). Data on natural

regrowth at Westbank 3, as exception, are presented only for the 1st cropping period and the dry season. Thereafter a period of bush fallowing for 2 consecutive years commenced in succession after the one year's cropping period in 1994.

A two-factorial ANOVA with treatment and time was applied to maize grain yield data. No significant interactions were obtained between treatment and time, thus yield in 1993 and 1994 was averaged over time.

Cassava tuber yield, nutrient concentration and nutrient uptake were statistically analyzed by one factorial ANOVA using treatments as levels of one factor.

Pearson's product-moment correlation coefficient r was used to describe the degree of the linear association between two variables. The significance of the simple linear correlation was expressed with *** at $P \leq 0.001$, with ** at $P \leq 0.01$ and with * at $P \leq 0.05$. The correlation analysis was based on the coefficient r of 5 sampling dates of both the 1st and 2nd cropping period (April-October) in 1993 and 1994 ($n = 24$).

Principal component analysis (PCA) as multivariate procedure was used to analyze 17 soil chemical, physical and microbiological variables of 24 plots differing in land use and degree of degradation, and 2 undisturbed secondary forest sites. PCA was performed on mean seasonal values of the 2nd cropping season lasting from April-October 1994 at 0-5 cm and 5-10 cm depth, due to the largest available data set. The data were standardized to a mean of zero and a variance of one. Before factoring a correlation matrix was computed. Principal component analysis is intended to reduce the number of variables to a smaller number of underlying factors called principal components (PCs). Hence, PCA creates a minimum number of new variables, which are linear combinations of the original ones such that the new variables contain most or all of the information (Reyment and Jöreskog, 1993). The PCs are extracted by applying the principal or main axis method (Überla, 1977). This procedure maximizes the total variance of the data set on the 1st PC (square sum of the component loadings have a maximum), the remaining variance of the data set on the 2nd PC and so on. The number of PCs considered in PCA is according to their Eigenvalue and should be greater than one (Kaiser-criterium; Überla, 1977). The Eigenvalue indicates the contribution of each PC to explaining the total variance of the data set. The principal components are made up of a discrete set of variables. The correlations of the original variables with the PC is expressed by the component loadings, and range from +1 to -1. The Varimax-rotation was applied to achieve a simple structure among component loadings and PCs. By means of Varimax-rotation the component loadings of the PCs are either large or small. According by the convention component

loadings > | 0.5 | are only considered for interpretation of the principal components (Backhaus et al., 1996). Component scores were computed for each plot in order to show the variation among plots. They are displayed in a coordinate system to visualize how the plots are described by the 1st and 2nd PC. Negative factor scores indicate that the plot is below average with respect to a principal component, whereas zero and positive values show the average and above average expression of a plot, respectively.

4 Results and Discussion

4.1 Characterization of the study sites and their degree of degradation

4.1.1 Crop performance of maize and cassava

Data in Table 4 illustrate the yield of maize and cassava for two consecutive growing seasons in 1993 and 1994. The yields (mean of two replications) fluctuated highly between the two cropping seasons and more so for cassava than for maize.

Table 4. Maize grain and stover (kg DM ha^{-1}) and cassava fresh tuber and biomass (t DM ha^{-1}) yield under continuous cropping in 1993 and 1994 at Westbank 3, D 2 and Westbank 1.

	Westbank 3	D 2	Westbank 1
Maize grain			
1993	1202	1604	400
1994	1134	2374	200
Mean	1168	1989	300
LSD	647.8		
Maize stover			
1993	1323	2628	700
1994	1509	2901(1)	331
Mean	1416	2764	515.5
LSD	927.6		
Cassava tuber			
1993	6.8		5.2
1994	8.2		3.7
1995	n.a.		10.3(2)
Mean	7.5		4.45
LSD	10		

(1) = stover was estimated by harvest index of 45 %;
(2) = not included in statistical analysis;
n.a. = not available;
data on maize and cassava yields for WB 1 and WB 3 were received from RCMD, IITA and for D 2 from Vanlauwe, personal communication.

The average yield for the improved cassava variety TMS 30572 in Nigeria is reported as 11-12 t/ha, the potential yield as 20-25 t/ha (IITA, 1990; Lawani and Babaleye, 1992). Obiagwu (1995) and Hulugalle et al. (1990) cited yields for unfertilized cassava between 5.6 and 15.7 t/ha, in accordance with our results obtained in 1993 and 1994.

The differences in cassava yields were not statistically significant between the sites. At Westbank 1, the yields fluctuated highly between the cropping seasons. In 1994 cassava tuber yielded only 3.7 t/ha compared to 5.2 t/ha in 1993. The poor performance of cassava at Westbank 1 in 1994 may be attributed to losses by rodent attacks. Moreover, cassava treated with Aldrin-dust had to be replanted three weeks after the first planting because of damage by ants and termites (Salako, personal communication). Except for 1994, cassava at Westbank 1 generally performed fairly good as compared to the non-degraded Westbank 3 site and even reached yields of 10.3 t/ha in 1995.

Similar results for Alfisols in Nigeria varying in their degree of degradation after topsoil removal were reported by Lal (1987).

The fairly good performance of cassava at the most degraded Westbank 1 site may be related to the ability of the plant to grow in soils that are acid and too impoverished to support other staple crops (IITA, 1990; Edwards and Kang, 1978). Also, cassava plants are more tolerant to high levels of aluminum and manganese, and low levels of calcium and potassium than many other species (Reddy, 1987). Cassava is a drought resistant crop and able to tolerate long periods of water shortage (Connor et al., 1981). Moreover, the strong mycorrhizal infection under field conditions (Sanders, 1973, as cited by Kang et al., 1980; Howeler et al., 1987) and an extensive mycorrhizal hyphae-root system up to 2 m deep may enable the plant to sustain productivity by utilizing nutrients and water less accessible to other crops (IITA,1990; Kang et al., 1980; Ezumah, 1983, as cited by Kayombo and Lal, 1993; Connor et al., 1981).

In comparison, maize is less tolerant to acid soils (Aldrich et al., 1975, as cited by Duque-Vargas et al., 1994; Kang and Osiname, 1979) and requires a high soil fertility status in the surface layers (Agboola, 1979, pp. 88-89) due to the shallow rooting pattern of the vast majority of maize roots (Kayombo and Lal, 1993; IITA, 1976, as cited by Mueller-Harvey et al., 1985; Hauser, 1990). The average yield at Westbank 3 is below and at D 2 in the range of the reported average yields in Nigeria (1.5-2 t/ha), but much below the potential yield of 3.5-10 t/ha (Lawani and Babaleye, 1992, pp. 29). In contrast, at Westbank 1 maize did not yield more than 400 kg/ha when continuously cropped to maize. This drastic reduction in maize yield is due to the exhaustive crop management for more than 14 years.

Comparable trends were obtained by Lal (1987,1995) on an Alfisol in Nigeria by artificial topsoil removal. The average maize yield of 1.2 t/ha was reduced to 0.7 and 0.2 t/ha upon 10 and 20 cm topsoil removal, respectively. As depicted in Table 4, the performance of maize at the D 2 site was the highest as compared to the least degraded Westbank 3 and the most degraded Westbank 1. The average grain yield (mean of two replications and two cropping seasons) under continuous cropping decreased in the order D 2 > WB 3 > WB 1 and was 1989 kg DM/ha, 1168 kg DM/ha and 300 kg DM/ha, respectively. The better performance of maize at D 2 may be attributed to benefits from cowpea, cropped in the second season. Effective cowpea-rhizobium symbiosis can fix up to 200 kg N/ha within 10 weeks of establishment (Schroder, 1992, as cited by Obiagwu, 1995) and supply 80 to 90 % of the host plant N-requirement (Mulongoy, 1985). Both, maize-cowpea intercropping at IITA, Ibadan and sequential cropping of maize and cowpea in southern Nigeria revealed that under low soil N-fertility status inclusion of cowpea gave significant benefits to the associated or succeeding maize crop (Eaglesham et al., 1981; Heide et al., 1985). Nitrogen fixed by cowpea became available to maize which was grown after senescence of the legume and the decomposition of its residues (Heide et al., 1985). The likelihood of yield improvement and efficient nutrient use by maize rotated with cowpea was also supported by Härdter (1989, 1991) and Horst and Härdter (1994) for Alfisols in the northern Guinea Savanna of Ghana. The beneficial effect was explained by N-transfer from cowpea to maize via mineralization of plant residues with high N content and less removal of inorganic N of the legumes from the soil compared to the cereals. Yields of maize in rotation with cowpea were stable at about 2.5 t/ha throughout 4 years, when no N was applied (Härdter, 1989).

A shortage in supply of phosphorus for the high-yielding maize may have influenced the yield potential at Westbank 3 and Westbank 1. Kang and Osiname (1979) found a good correlation between extractable Bray-I phosphorus and maize grain yield at IITA, Nigeria. A critical soil phosphorus test level for maize production on the Egbeda soils was estimated at about 14 μg P g^{-1} soil (Kang and Osiname, 1979). Adeoye and Agboola (1985) established a critical range for optimum maize production in south-western Nigeria at 10 to 16 μg P/g soil. Only D 2 sustained available Bray-I phosphorus equal to or above this critical range. In comparison, Westbank 3 and Westbank 1 maintained a constant level of 7 μg P/g in the 0 to 5 cm layer and 3.6 μg P/g in the 5 to 10 cm layer. Vanlauwe (1996) reported that P-additions (30 kg P ha^{-1} as SSP) at D 2, IITA in 1995 did not improve maize yield.

4.1.2 Nutrient uptake by maize grain

Nutrient uptake in the aboveground dry matter (stalks and grain) of the control treatments at Westbank 3, D 2 and Westbank 1 is presented in Table 5.

Table 5. Nutrient uptake (kg ha^{-1}) in total dry matter (t ha^{-1}) of maize plants under continuous cropping at harvest 1994.

	dry matter t ha^{-1}	**N**	**P**	**K** **kg ha^{-1}**	**Ca**	**Mg**
Westbank 3	2.6	37.3	30.5	30	10(2)	10.5
D 2	5.3	53	13.3	56.3	38.3	30.2
Westbank 1	0.5	4.3	0.8	4.8	3	2.3
LSD	2.3	30.8	19.3	23.7	n.d.	12.5

n.d. = not determined;
(1) = total dry matter production of the above ground plant material including stalks and grain;
(2) = only stover; data were received from RCMD, IITA.

Generally, differences in total dry matter production (above ground plant material including stalks and grains of maize) corresponded to differences in grain yield (Table 4). The lowest nutrient uptake was found at WB 1 with a low dry matter production of 0.5 t/ha and concomitant low uptake of N, P, K, Ca and Mg. Nitrogen-uptake at D 2 and WB 3 was 53 kg and 37.3 kg/ha, respectively. However, no significant difference between the sites were found and was related to the high inter-plot variability (see Table 1 of the Appendix). Potassium uptake was significantly higher at D 2 as compared to WB 3. However, P-uptake of maize plants did not reflect the differences in the dry matter production. Despite a higher dry matter production at D 2 and higher available inorganic Bray-I P in soil (Table 9) compared to Westbank 3, phosphorus uptake at WB 3 was superior to D 2, although not statistically confirmed due probably to high inter-plot variability at WB 3 (see Table 2 of the Appendix). The results on N-uptake at D 2 are consistent with data reported by Härdter (1989) and Jonsson et al. (1996). Härdter (1989) elaborated that N-uptake of maize was higher after rotation with cowpea due to better N-nutrition of maize in the crop rotation systems as compared to monocropped maize. A more favored N-supply of the soil was attributed to the incorporation of cowpea residues with a high N-content. But also Jonsson et al. (1996) found a strong correlation between maize biomass production and N-uptake in Tanzania.

4.1.3 Soil physical characteristics

As depicted in Table 6, mean bulk densities (Mg m^{-3}, 0-5 cm depth) were 1.26, 1.37 and 1.33 at Westbank 3, D 2 and Westbank 1, respectively and were not significantly different from each other.

Table 6. Soil texture and bulk density under continuous cropping in the 0-10 cm layer, 1993.

		Texture (%)		
site	**bulk density (Mg m^{-3})(1,2)**	**sand**	**silt**	**clay**
Westbank 3	1.26	82.0	9.0	9.0
D 2	1.37	81.0	10.5	8.5
Westbank 1	1.33	73.5	9.0	17.5
SE	0.06	4.1	1.2	3.7

(1) = bulk density of the top 5 cm;
(2) = SE was only determined for WB 1 and WB 3, since mean bulk density of total D 2 was only available by Van der Meersch, 1992.

The mean content of sand, silt and clay (Table 6) were about 81 %, 9.5 % and 9.5 %, respectively at both Westbank 3 and D 2 and 73.5 %, 9 % and 17.5 %, respectively, at Westbank 1. No significant differences were found between the sites. Average contents in the 0-10 cm layer under secondary forest at Westbank 1 before clearing in 1978 were reported as 72.8 %, 10.4% and 16.8 % as sand, silt and clay, respectively (Lal and Couper,1990; Lal, 1992) and are in accordance with the current texture.

The mean gravel contents of the sites were estimated based on results from soil surveys and degradation studies at IITA and surrounding areas (Harpstead, 1974; Moorman et al., 1975; Wilkinson and Aina, 1976; Lal, 1992). Lal (1992, pp. 112,113) reported that the size and content of the gravel under the forest cover in 1978 prior to forest clearing varied considerably. Thus, the gravel content in the surface horizon (0-20 cm) ranged from 1.0-25 %, whereas in the sub-soil often as much as 50 % gravel by weight was observed. Vanlauwe (personal communication) reported the percentage of stones > 4 mm at D 2 in the top 5 cm and 5-15 cm layer as 0.3-11 % and as 0.2-20 %, respectively. Accordingly, the gravel contents (> 2 mm) at 0-10 cm depth was taken as 15 %. Based on land use

history and local experts, the gravel content at Westbank 3 and WB 1 was estimated as 5 % and 30 %, respectively.

4.1.4 Soil chemical characteristics

4.1.4.1 Soil nutrients and pH

Data on soil chemical properties are the mean of 5 sampling dates of both the 1st and 2nd cropping period (April-October) and the mean of three sampling dates during the dry season (November 1993-March 1994). Average concentrations at 0-5 cm and 5-10 cm depth of organic carbon, total nitrogen and pH of the continuing cropping control plots as affected by land use are summarized in Table 7, available cations and manganese are presented in
Table 8.

Table 7. Average soil organic carbon (t ha^{-1}), total nitrogen (kg ha^{-1}) and pH characteristics, corrected for bulk density and gravel content of the control treatments at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	C_{org} (t ha^{-1})			total N (kg ha^{-1})			pH ($CaCl_2$)		
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
0-5 cm									
sec. Forest	19.3	17.5	16.8	1707	1381	1358	6.6	6.9	6.7
Westbank 3	8.8	8.2	9.3	732	713	856	6.8	7.0	6.9
D 2	5.4	6.4	6.1	479	563	537	6.0	5.8	6.0
Westbank 1	4.1	5.0	4.6	408	471	479	5.7	5.7	5.5
LSD	1.6	2.3	2.2	176	123	202	0.36	0.5	0.5
5-10 cm									
sec. Forest	13.5	11.9	11.8	1319	907	1178	6.5	5.7	6.8
Westbank 3	5.2	5.1	5.2	511	513	484	6.7	6.8	6.8
D 2	4.0	4.5	4.9	394	446	438	5.6	5.4	5.5
Westbank 1	3.9	4.0	4.6	411	378	446	5.2	5.3	5.4
LSD	1.3	1.2	2.0	117	122	170	0.3	0.5	0.5

LSD (excluding forest) at $\alpha = 0.05$

Land clearing and prolonged cultivation resulted in a progressive decline in mean soil pH by about one unit from 6.8 under forested conditions to pH 6 and 5.7 at D 2 and Westbank

1, respectively. The decline in pH was somewhat stronger at 5-10 cm depth. In comparison, 4 to 5 years of continuous cropping to maize and cassava caused no decrease in pH at Westbank 3 as compared to secondary forest. The pH at WB 3 was significantly higher compared to WB 1 and D 2, whereas the latter were not significantly different from each other.

The chemical fertility of the soils at 0-5 cm and 5-10 cm depth decreased with time of cropping and was influenced by land use history. Compared to secondary forest, the average total loss of organic C in the 0-5 cm layer after 14, 10 and 4 years of continuous cropping were 76 %, 68 % and 50 % at WB 1, D 2 and Westbank 3, respectively. Similar trends were obtained at 5-10 cm depth, but the levels were generally lower. At both depths, organic carbon was significantly higher at WB 3 compared to both D 2 and WB 1 which were not significantly different from each other. Comparable results were reported by Lal (1989), showing that organic carbon declined by about 70 % from initially 2.37 % to 0.73 % in the 0-5 cm layer after continuous cropping for five years. Mulongoy et al. (1993) and Juo and Fox (1977) concluded also that cultivation of food crops reduced the level of total soil organic carbon even if crop residues were retained in the field. A more drastic decline in C, N, P and S content was achieved when crop residues were removed (Mueller-Harvey et al., 1985).

The data on soil N followed similar trends to those of organic carbon. Total average nitrogen declined in the 0-5 cm layer by 68 %, 65 % and 45 % under continuous cropping at Westbank 1, D 2 and Westbank 3, respectively. These findings are consistent with previous results obtained at IITA, Nigeria (Lal, 1989). Total N declined by 75 % five years after continuous cropping under both no-tillage and plow-till.

Exchangeable basic cations ($cmol^+$ kg) and Mn represent the nutrient status of the sites in October 1993, and are illustrated in Table 8. Data corrected for bulk density and gravel content (kg ha^{-1}) are summarized in Table 3 of the Appendix.

Calcium was the dominant exchangeable basic cation at all sites. The depletion of exchangeable cations in the 0-5 cm layer was highest under continuously cropped soils at Westbank 1, as this site has been cultivated and impoverished the most. WB 3 had significantly higher calcium concentrations in the 0-5 cm layer as compared to D 2 and WB 1. No significant differences at 0-5 cm depth for Mg and K were found between the cropped sites. Exchangeable manganese was only prevalent at the degraded sites at WB 1 and D 2, where prolonged cultivation and soil erosion took place and pH values had fallen

below 6. At both depths, higher exchangeable manganese was obtained at D 2 than at Westbank 1, but the trend was not statistically significant.

Table 8. Average soil nutrient status ($cmol^+ kg^{-1}$) of the control treatments at 0-5 cm and 5-10 cm depth in October 1993.

Site/depth	Ca	Mg	K	Mn
		$cmol^+ kg^{-1}$		
0-5 cm				
sec. Forest	12.15	2.33	0.85	0.000
Westbank 3	5.94	0.66	0.21	0.000
D 2	1.75	0.48	0.23	0.008
Westbank 1	1.30	0.39	0.17	0.007
LSD	1.87	0.43	0.15	ns
5-10 cm				
sec. Forest	6.36	1.46	0.53	0.000
Westbank 3	3.74	0.46	0.12	0.000
D 2	0.88	0.21	0.32	0.059
Westbank 1	1.37	0.32	0.10	0.004
LSD	2.06	0.27	0.21	ns

LSD (excluding forest) at $\alpha = 0.05$;
ns = non-significant

In the 5-10 cm layer, potassium was significantly higher at D 2 compared to Westbank 3 and Westbank 1. The higher K concentrations at D 2 may be attributed to former fertilizer applications when the plots were used for crop breeding under high fertilizer applications. The differences in exchangeable basic cations among the sites were likely related to the soil organic matter contents, as the sites with the lowest content of organic carbon also had the least exchangeable basic cations. This is reflected in the high correlations of Ca and Mg with organic carbon, having a correlation coefficient of $r = 0.78$ and 0.54 ($P \leq 0.01$) at 0-5 cm depth, respectively, and $r = 0.75$ and 0.74 at 5-10 cm depth ($P \leq 0.01$), respectively. Soil organic matter is the major determinant of nutrient availability on these low-activity clay soils (Moorman et al., 1975). The nutrient status of the sites, however, is in agreement

with findings by Juo and Lal (1977) and Lal (1989) for soils of south-western Nigeria. Critical values of 0.15-0.20 $cmol^{+}\ kg^{-1}$ of exchangeable K in surface soils with sandy to loamy texture were reported by Juo (1985) below which cassava (can survive and produce under a wide range of adverse soil and climatic conditions) responds significantly to K-application. Accordingly, at WB 3 and WB 1 exchangeable K in the 5-10 cm depth and both 0-5 cm and 5-10 cm depth, respectively, was below this critical range (Table 8). For Mg Lombin and Fayemi (1976) proposed sufficiency levels between 0.2 and 0.42 $cmol^{+}\ kg^{-1}$, and established a critical Mg:K ratio of 2 or less to reliably predict the plant-available Mg-status of these soils. At 5-10 cm depth D2 and WB 1 exhibited exchangeable Mg-concentrations below this sufficiency level, whereas only D 2 in the 5-10 cm layer had a Mg:K ratio of 0.66 (Table 8) which was below the critical value of 2. Lombin and Fayemi further reported that the Mg-uptake by maize fell sharply below a Mg:K ratio of 2, and suggested that K probably may have suppressed Mg-uptake. This may also hold true for D 2 where heavy fertilization with K likely has induced Mg-deficiency.

The changes in the composition of the exchange complex and the appearance of exchangeable Mn as a function of soil pH and degradation was demonstrated for Egbeda soils (oxic Paleustalf) in south-western Nigeria by Stumpe and Vlek (1991). Thus, Ca and Mg disappeared from the exchange complex at pH 4.2 and 5, respectively, whereas exchangeable Mn increased between pH 6.5 and 5.0.

4.1.4.2 Bray-I phosphorus

Bray-I phosphorus did not follow the trends of organic carbon and total nitrogen as is shown in Table 9. Mean values of available Bray-I phosphorus under continuous cropping ranged from 3.6 to 30.7 µg P/g soil at 0-5 cm and from 2.2 to 27.3 µg P/g at 5-10 cm depth.

Continuous cultivation for 4 and 14 years caused a decline in the 0-5 cm layer by 84 % to 4.8 µg/g on average and by 80 % to 5.8 µg/g on average at the non-degraded Westbank 3 and the most degraded Westbank 1, respectively. However, both sites did not differ significantly in available Bray-I phosphorus. Compared to secondary forest, available phosphorus at D 2 decreased by only 10 % and reached 26.6 µg/g in the 0-5 cm layer, 10 years after continuous cropping of maize and cowpea in sequence. Bray-I phosphorus concentrations similar to our data were reported by Adepetu and Corey (1976), Kang and Osiname (1979) and Lal (1989) for soils of south-western Nigeria. Lal (1989) for example

determined average available Bray-I phosphorus contents at IITA of 7 to 30 ppm in the top 5 cm and of 4 to 20 ppm at 5-10 cm depth. Similar to our results for WB 3 and WB 1, consecutive cropping of maize for four seasons at IITA, Nigeria resulted in a decline of Bray-I phosphorus by 63 % from initially 7.5 ppm to 2.8 ppm (Kang and Osiname, 1979).

Table 9. Available Bray-I phosphorus (μg g^{-1} and kg ha^{-1}) under continuous cropping controls at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Bray-I P (μg g^{-1})			**Bray-I P (kg ha^{-1})**		
site/depth	1st season	dry season	2nd season	1st season	dry season	2nd season
0-5 cm						
sec. Forest	25.7	30.7	29.2	14.3	15.5	16.6
Westbank 3	5.0	3.6	5.4	3.0	2.1	3.1
D 2	24.2	25.8	29.5	12.8	14.3	15.1
Westbank 1	5.9	5.1	6	3.0	2.4	2.8
LSD	3.3	6.2	8.4	1.7	3.4	3.9
5-10 cm						
sec. Forest	27.3	22.1	26.1	17	12.6	14.8
Westbank 3	2.9	2.2	4.2	1.7	1.3	2.4
D 2	16.3	17.7	14.8	9.0	9.8	8.4
Westbank 1	4.4	2.9	4.6	2.0	1.4	2.3
LSD	1.8	6.2	4.7	0.9	2.4	2.6

LSD (excluding forest) at $\alpha = 0.05$

The significant higher available Bray-I phosphorus content at D 2 as compared to WB 3 and WB 1 should be attributed to fertilizer applications by breeders prior to the implemented improved fallow managements in 1986. The sustained residual effect of inorganic phosphorus applied to Alfisols in south-western Nigeria is mentioned by several authors. It is thought to be caused by the low P-sorption capacity of these soils with concomitant low standard P-requirements (= the amount of P sorbed by soil to attain the standard concentration of 0.2 ppm P in solution after 6 days) of about 32 μg P/g soil (derived from acid rocks) on average (Juo and Fox, 1977; Kang and Osiname, 1979; Lal, 1989; Osodeke et al., 1993). Even low rates of fertilization of 26 kg P/ha led to a substantial build-up of available P and the residual effect of the applied P was still observed after 4 cropping cycles (Kang and Osiname, 1979). The authors concluded for

the Egbeda soil series at IITA, Nigeria that adequate levels of Bray-I P above 14 ppm for 5 high yielding maize crops (cultivar TZAxTZB), which were cleared from bush fallow and supplemented with 120, 50 and 4 kg ha^{-1} N, K and Zn-fertilizer, respectively, could be maintained by applications of 52 to 104 kg P/ha.

In contrast, fertilization of 60 kg P ha^{-1} as SSP between 1979 and 1986 and from 1989 until 1992, respectively, at the most degraded Westbank 1 site did not lead to a substantial build-up of available inorganic P as determined by the Bray-I extraction method, possibly due to higher P-sorption at WB 1. According to Juo and Fox (1977) the standard P-requirement of these soils increase due to increasing sesquioxide and clay contents with depth. Moreover, high erosion rates at WB 1 (Lal, 1992) may have stripped of partially the lighter textured top soil and exposed the more clayey subsoil (Juo and Fox, 1977).

But also differences in resource quality, i.e. differences in the chemical compositions and amounts of reactive and stable groups of the soil organic matter-clay-complex that are active in ion exchange may have caused the low available inorganic P at WB 1. Probably, not as much inorganic P (Bray-I P) was held in readily exchangeable forms at WB 1 as compared to D 2, where more favorable organic complexes are thought to be existent.

The prevailing surface adsorption of P to monomeric or polymeric Al/Fe hydroxy ions below pH 6 (Lindsay et al., 1989) may also contribute to less available inorganic phosphorus at WB 1. Since 1986, the pH at the site was between pH 5.3 and 5.7 (Lal, 1992). However, also D 2 had pH values ranging from pH 4.9 to 5.7 from 1986 until 1990 (Van der Meersch, 1992), and reached average values of pH 6 in 1993 and 1994.

4.1.4.3 $NaHCO_3$ and NaOH-extractable inorganic and organic phosphorus pools

Data on $NaHCO_3$ and NaOH-extractable inorganic and organic phosphorus pools are the mean of 3 sampling dates (January, May and August) of 1994 and are presented in Table 10.

After land clearing and prolonged cultivation the labile P_i-fraction ($NaHCO_3$-extractable) followed similar trends to those of Bray-I extractable phosphorus. Generally, the decline of available phosphorus was more pronounced at Westbank 3 and Westbank 1 as compared to D 2 and reached lower average total amounts in the 5-10 cm layer. At both depths, D 2 had significantly higher $NaHCO_3$-extractable inorganic P-contents as compared to both WB 1 and WB 3. Labile organic phosphorus ($NaHCO_3$-extractable, plant available) under continuous cropping declined by 50-65 % at 0-5 cm depth compared to secondary forest.

At both depths, $NaHCO_3$-organic phosphorus (μg g^{-1}) at the non-degraded WB 3 site was significantly lower as compared to the degraded Westbank 1 and D 2 sites. However, after correcting the data for bulk density and gravel content (kg ha^{-1}) no significant differences were found in the top 5 cm, whereas at 5-10 cm depth D 2 had significantly higher $NaHCO_3$-P_{org} than both WB 3 and WB1 which, in turn, were not significantly different from each other.

Table 10. $NaHCO_3$ (1) and NaOH-extractable inorganic and organic phosphorus pools (μg g^{-1} and kg ha^{-1}) under continuous cropping controls at 0-5 cm and 5-10 cm depth in 1994.

site/depth	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}
	μg g^{-1}				kg ha^{-1}			
0-5 cm								
sec. Forest	19.9	22.4	24.3	62.9	9.3	11.9	11.1	38.9
Westbank 3	13.2	14.0	8.3	46.1	6.3	7.6	4.6	26.3
D 2	28.1	41.6	11.4	70.2	13.2	23.0	6.2	38.8
Westbank 1	9.1	30.5	11.8	62.5	3.9	14.5	5.5	29.7
LSD	10.7	15.9	2.5	19.5	5.9	8.7	ns	10.3
P contrasts(2)								
WB 3 vs. WB 1				0.033				
5-10 cm								
sec. Forest	33.9	49.6	9.2	77.9	19.3	28.3	5.3	44.4
Westbank 3	3.7	9.2	6.1	45.8	2.1	5.2	3.5	23.8
D 2	17.6	37.3	11.7	71.5	9.7	20.6	6.5	39.5
Westbank 1	7.9	21.2	10.0	50.0	3.5	10.3	4.6	24.3
LSD	5.5	12.3	3.1	24.1	2.9	6.6	1.6	12.9

LSD (excluding forest) at $\alpha = 0.05$
ns = not significant
(1) = includes resin extractable P
(2) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

Organic phosphorus (NaOH-extractable) has been used as an indicator of the P-status and fertility of soils. This pool is thought to represent overall changes in soil organic matter and organic phosphorus levels by functioning as an active reservoir and source and sink of P when the soil is stressed by cultivation and net P-export (Stewart and Tiessen, 1987; Tiessen et al., 1992, 1994; Magid and Nielsen, 1992; Beck and Sanchez, 1994; Paniagua et al., 1995).

Land clearing and continuous cultivation for 14, 10 and 4 years reduced organic phosphorus (µg g^{-1}) in the 0-5 cm layer most at the least degraded Westbank 3 site by 30 % from initially 62.9 µg/g under forested conditions to 46.1 µg/g. This effect was less clearly visible in the 5-10 cm layer. Organic phosphorus data corrected for bulk density and gravel content (kg ha^{-1}) showed for the top 5 cm that D 2 was significantly higher than WB 3 but did not differ significantly from WB 1. WB 3 and WB 1 were not significantly different from each other. In the 5-10 cm layer D 2 had significantly higher NaOH-extractable organic phosphorus as compared to both WB 3 and WB 1, which were not significantly different from each other. Since WB 3 never was fertilized, plant and microbiota available labile inorganic P ($NaHCO_3$ and NaOH-extractable organic phosphorus) was most likely dependent on the mineralization of the organic P-pools. Other studies in south-western Nigeria confirmed a mineralization of total organic phosphorus (fractionated according to Chang and Jackson, 1957 as cited by Adepetu and Corey, 1977) by 25 % in the 0-15 cm layer during two consecutive cropping seasons of about 8.5 months total duration from initially 142 ppm to 106 ppm (Adepetu and Corey, 1976, 1977). The likelihood of organic P-mineralization as plant available source is also supported by Omotoso (1971). In comparison, fertilization of inorganic phosphorus at Westbank 1 and D 2 at a rate of 60 kg/ha and 90 kg/ha per year until 1992 and 1986, respectively, may have contributed to increasing short- and long term P-fertility with subsequent maintenance of the organic P-pool. Fertilization until 1986 at D 2 built up to the organic P-pool, and $NaHCO_3$-P_i and NaOH-P_i, whereas at WB 1 its fertilizer P was largely recovered in the NaOH-P_i and NaOH-P_{org} fraction. Moreover, the $NaHCO_3$-P_i-pool is depleted since 1992 with the redistribution by the NaOH-P_i pool prevented. Tiessen et al. (1992) obtained similar results in Brazil. Organic phosphorus (NaOH-extractable) in soils cropped to sorghum and millet for 12 consecutive years was not significantly depleted as compared to the native vegetation because of P_i-fertilization.

4.1.5 Microbial biomass

4.1.5.1 Microbial biomass carbon

Average soil microbial biomass content (µg g^{-1} and kg ha^{-1}) of the continuous cropping control treatments as affected by land use at 0-5 cm and 5-10 cm depth is depicted in Table 11. Mean extractable biomass under continuous cropping ranged from 58µg g^{-1} to 147 µg g^{-1} in the 0-5 cm layer and from 39 to 86 µg g^{-1} in the 5-10 cm layer.

Land clearing and prolonged cultivation resulted in a progressive decline in mean microbial biomass. Compared to secondary forest, the total loss of the biomass (μg g^{-1}) in the 0-5 cm layer after 14, 10 and 4 years of continuous cropping was 50 %, 70 % and 75 % at Westbank 3, D 2 and Westbank 1, respectively, and correspond to the total loss of organic C (see Table 7). Similar trends were obtained in the 5-10 cm layer, but the microbial biomass was generally lower.

Table 11. Average soil microbial biomass carbon (μg C g^{-1} soil and kg C ha^{-1} soil) under continuous cropping controls at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Microbial biomass					
	μg g^{-1}			kg ha^{-1}		
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
0-5 cm						
sec. Forest	291	234	359	166	134	206
Westbank 3	145	115	147	83	65	84
D 2	93	61	61	51	44	34
Westbank 1	72	58	58	34	28	28
LSD	61	73.5	48.5			
P contrasts (1)						
WB 3 vs. D 2	0.008					
5-10 cm						
sec. Forest	141	122	186	81	70	106
Westbank 3	80	86	75	46	49	43
D 2	47	71	39	26	39	18
Westbank 1	51	52	41	25	25	19
LSD	32	ns	29			

LSD (excluding forest) at $\alpha = 0.05$
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

At both depths, during the 1st and 2nd cropping season, microbial biomass was significantly higher at the least degraded WB 3 site compared to both D 2 and WB 1. During the dry season from November till March, no statistically significant difference ($\alpha = 0.05$) between WB 3, D 2 and WB 1 was obtained. Trends at 0-5 cm depth, however, indicate that the biomass was higher under the least degraded WB 3 as compared to D 2 (P= 0.109) and

WB 1 (P=0.093). D 2 and Westbank 1, continuously cropped to maize and cowpea in sequence and maize/cassava intercropping since 10 and 14 years, respectively, did not differ significantly from each other throughout the research period.

Similar microbial biomass contents were reported by Fugger (1997) for Ghana at 0-30 cm depth (chloroform-fumigation-extraction method) and Ayanaba et al. (1976; chloroform-fumigation-incubation method) for Nigeria at 0-15 cm depth. The likelihood of microbial biomass decline after deforestation and land cultivation was also reported by Ayanaba et al. (1976) for 13 soils at IITA, Ibadan, Nigeria. Microbial biomass (chloroform-fumigation-incubation method) decreased by 37 % from initially 480µg g^{-1} under forested conditions to about 270-340 µg g^{-1} under bush regrowth, by 50 % to 180-300 µg g^{-1} under maize with stover returned, by 70 % to 60-230µg g^{-1} under maize with stover removed and by 65 % to 170 µg g^{-1} under maize/cassava intercropping with stover returned. Clearing of a 20 year old secondary forest in Costa Rica also resulted in rapid changes of the microbial biomass content (chloroform-fumigation-extraction method; Henrot and Robertson, 1994). Under bare soil conditions 50 % of the biomass declined within the first 6 months.

The seasonal course of the microbial biomass between April 1993 and October 1994 at 0-5 cm depth is displayed in Figure 7.

Temporal fluctuations of the microbial biomass is reported to be controlled by variations in organic matter input, quality of organic substrates, moisture conditions, temperature, crop growth and phenology, fertilization and soil texture (Santruckova, 1992; Ritz et al., 1992; Raghubanshi, 1991; Jocteur-Monrozier et al., 1992; Ladd, 1992).

The seasonal fluctuation of the microbial biomass was more pronounced in the 5-10 cm layer (data not shown) as compared to the top 5 cm (Figure 7). During the dry season the microbial biomass decreased at all sites and most at D 2, due probably to the sparse weedy vegetation that developed and covered the soil after the harvest of cowpea in November. At both WB 3 and WB 1 sites soil cover provided by growing cassava plants reduced soil heating by solar radiation. However, a significant correlation of microbial biomass and gravimetric soil moisture content during our research period was only obtained for the 2nd cropping season in 1994 at 0-5 cm depth ($r = 0.79$, $P \leq 0.001$). It appeared that the microbial biomass increased with maize crop growth and easily available organic substrates with root slash at the end of the growing season, and decreased after maize harvest.

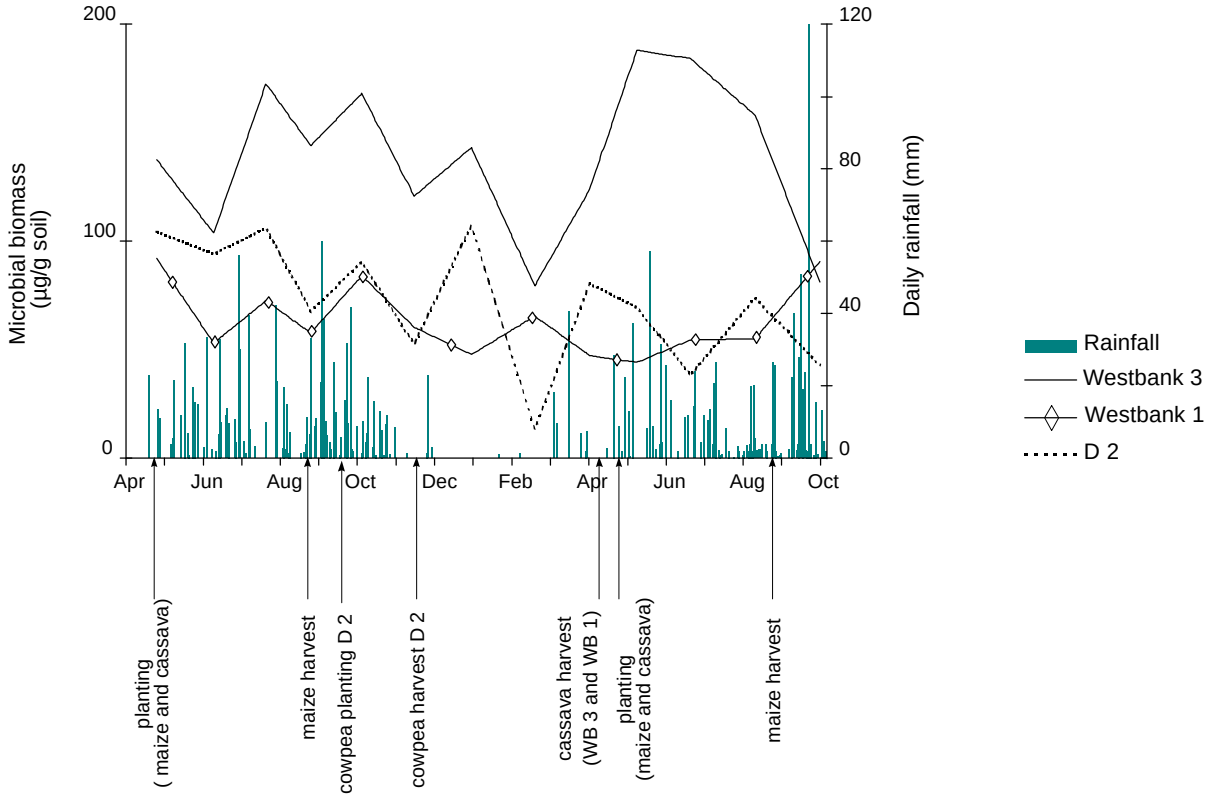


Figure 7. Seasonal course of the microbial biomass under continuous cropping at WB 3, D 2 and WB 1 in the 0-5 cm layer.

According to investigations by Mazzarino et al. (1993) and Srivastava and Lal (1994) in Costa Rica and India, respectively, the microbial biomass was highest during stages of rapid crop growth and lowest at the end of the cropping period. This was related to an increased availability of root derived organic substrates in the early cropping season and mortality of the plants at the end of the cropping season. The impact of soil moisture on microbial biomass content is discussed controversially in the literature. Several authors concluded that the soil moisture content controlled the short-term biomass dynamics (Bottner, 1985; Sparling et al., 1985; Van Gestel et al., 1996) with soil moisture and soil moisture changes accounting for 46-90 % of the variability in microbial biomass (McGill et al., 1986). Others (Kaiser et al., 1995; Mazzarino et al., 1993) found no obvious relation between microbial biomass and soil moisture content under temperate conditions and in the humid tropics of Costa Rica, respectively.

4.1.5.2 C_{mic}/C_{org} ratio

The C_{mic}/C_{org} ratio was calculated on a weight/weight basis to correct for differences in bulk density and gravel content and is expressed as percentage. The data for the two rainy seasons and the dry season in between are given in Table 12, and range from 0.37 to 1.22 %. The C_{mic}/C_{org} ratio under forest cover and at WB 3 was rather stable over seasons but declined at D 2 and WB 1, the more degraded sites.

Table 12. C_{mic}/C_{org} ratio (%) under continuous cropping at 0-5 cm and 5-10 cm depth in 1993 and 1994.

site/depth	1st season	dry season	2nd season
0-5 cm			
sec. Forest	0.85	0.76	1.22
WB 3	0.93	0.79	0.90
D 2	0.94	0.69	0.55
WB 1	0.83	0.55	0.60
LSD	1.07	ns	0.77
P contrasts (1)			
WB 3 vs. D 2			0.003
WB 3 vs. WB 1			0.004
5-10 cm			
sec. Forest	0.6	0.58	0.89
WB 3	0.87	0.95	0.81
D 2	0.64	0.87	0.37
WB 1	0.62	0.62	0.41
LSD	0.76	ns	0.76
P contrasts (1)			
WB 3 vs. D 2			0.009
WB 3 vs. WB 1			0.005

LSD (excluding forest) at $\alpha = 0.05$
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

The percentage of organic C tied up in the microbial biomass under a 25 year old secondary forest was not consistently higher as compared to the control treatments at WB 3, D 2 and WB 1, which were continuously cropped since 4, 10, and 14 years, respectively. This is in contrast with results obtained for both temperate and tropical forest cover (Anderson and Domsch, 1989; Basu and Behera, 1993). Anderson and Domsch (1989) suggested that a higher microbial C content per unit of soil organic carbon under forest may be due to a more diversified organic substrate production and higher input. However, in tropical Alfisols at IITA, Nigeria soil textural conditions appeared to have a more striking impact on the C_{mic}/C_{org} ratio than substrate quality alone.

The poorly structured Alfisols do not protect the soil microbial biomass enough, resulting in high turnover rates and limited incorporation of C and N into the biomass. Sparling (1992) reported also that the ratio was greatly influenced by texture and mineralogy of soils in New Zealand due to the larger amount of non-microbial C in the C_{org} fractions of clay soils. However, the quantity and quality of organic matter applied also affected the ratio. Thus, under native forest the ratio was 1.36 % as compared to 1.63 % and 1.55 % under unimproved and fertilizer amended pastures, respectively, due to increased organic matter input at the latter sites.

No consistent trend on the impact of long-term management on the C_{mic}/C_{org} ratio under continuous cropping control treatments was obtained as compared to either C_{mic} (Table 11) or C_{org} (Table 7) alone. At both depths the C_{mic}/C_{org} ratio at WB 3 was only significantly higher during the 2nd cropping season as compared to both D 2 and WB 1. The temporal changes in the ratio were not entirely reflected by quantitative changes of the soil organic matter content. Total soil organic matter (Table 7) in 1994 was similar to or slightly higher than in 1993 (spatial variability) whereas microbial biomass (Table 11) decreased slightly. However, small changes in soil microbial biomass content are superimposed by concomitant small changes of total soil organic carbon due to the proportional higher quantity of the latter fraction. Thus, under the prevailing conditions it is rather questionable whether the C_{mic}/C_{org} ratio as sole parameter can reflect changes of the soil organic matter status.

4.1.6 Acid and alkaline phosphatase

4.1.6.1 Acid phosphatase

The average acid phosphatase activity (µg g^{-1}) of the continuous cropping controls treatments at 0-5 cm and 5-10 cm depth in 1993 and 1994 is summarized in Table 13.

Table 13. Average acid phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under continuous cropping at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Acid phosphatase activity (µg p-nitrophenol g^{-1} h^{-1})		
Site/depth	**1st season**	**dry season**	**2nd season**
0-5 cm			
sec. Forest	450	676	618
Westbank 3	195	313	192
D 2	312	285	275
Westbank 1	291	351	273
LSD	ns	ns	118
P contrasts (1)			
WB 3 vs. D 2			0.01
WB 3 vs. WB 1			0.012
5-10 cm			
sec. Forest	370	520	450
Westbank 3	139	277	179
D 2	196	252	196
Westbank 1	247	412	232
LSD	134	104	ns
P contrasts (1)			
WB 3 vs. WB 1	0.000		

LSD (excluding forest) at $\alpha = 0.05$
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

It ranges from 139 to 412 µg p-nitrophenol $g^{-1} h^{-1}$ and are according the results reported for Alfisols and Ultisols in Nigeria by Mulongoy and Bedoret (1989). Acid phosphatase activity in the top 5 cm was only significantly lower at the least degraded WB 3 site as compared to both D 2 and WB 1 during the 2nd cropping season. No statistical difference was obtained between D 2 and WB 1. In the 5-10 cm layer this trend was not followed: Westbank 3 had a significantly lower acid phosphatase activity during the 1st cropping season and the dry season as compared to WB 1, whereas WB 3 and D 2 were not different from each other. The results obtained did not reflect a close correlation between phosphatase activity and both available P at the sites and P-uptake by the crops. Phosphorus uptake at harvest 1994 was 30.5, 13.3, and 0.8 kg ha^{-1} at WB 3, D 2, and WB 1, respectively. However, the correlation (r = -0.37) between phosphorus taken up by maize plants at harvest 1994 and phosphatase activity was non-significant at both depths.

Moreover, available soil phosphorus contents under the continuous cropping control treatments (Table 9 and 10) were highest at D 2 and comparable in both WB 1 and WB 3. However, acid phosphatase activity at 0-5 cm depth was lowest at WB 3 as compared to both D 2 and WB 1 during the 2nd season. In the 5-10 cm depth the activity did not differ between D 2 and WB 3, and was highest at WB 1. As discussed in more detail later (Chapter 4.3.3) no significant correlation between the inorganic and organic P-pools and acid phosphatase was obtained at the sites. Phosphatases are considered as inducible enzymes, as their production is regulated by end-product inhibition (Juma and Tabatabai, 1978; Margesin and Schinner, 1994).

The activity of acid phosphatases, thus increases under P-deficient conditions as a widespread adaptive mechanism of plants to compensate for P-deficiency (Skujins, 1976; Nakas et al., 1987; Häussling and Marschner. 1989; Tadano et al., 1993). Since phosphatases are adaptive enzymes, the intensity of their exudation by plant roots is, to some extent, influenced by the P-demand of plants, and hence their P-status (Silberbush et al., 1981 as cited by Tarafdar and Jungk, 1987). Similar to our results Clarholm (1993) reported low needle-P content in Norway spruce trees in Sweden despite enhanced phosphatase activity. She concluded therefore, that the enzymes activity were reduced due to lacking appropriate organic substrate.

Apparently, despite lower inorganic and organic phosphorus pools at WB 3 than at D 2, both sites exhibited similar acid phosphatase activity. This may be attributed to more easily accessible phosphorus-soil organic matter complexes as compared to WB 1, where adverse

resource conditions prevail. Thus, the plants at the latter sites released high amounts of acid phosphatases in order to satisfy the P-demand.

The seasonal course of acid phosphatase activity under continuous cropping in the 5-10 cm layer is displayed in Figure 8.

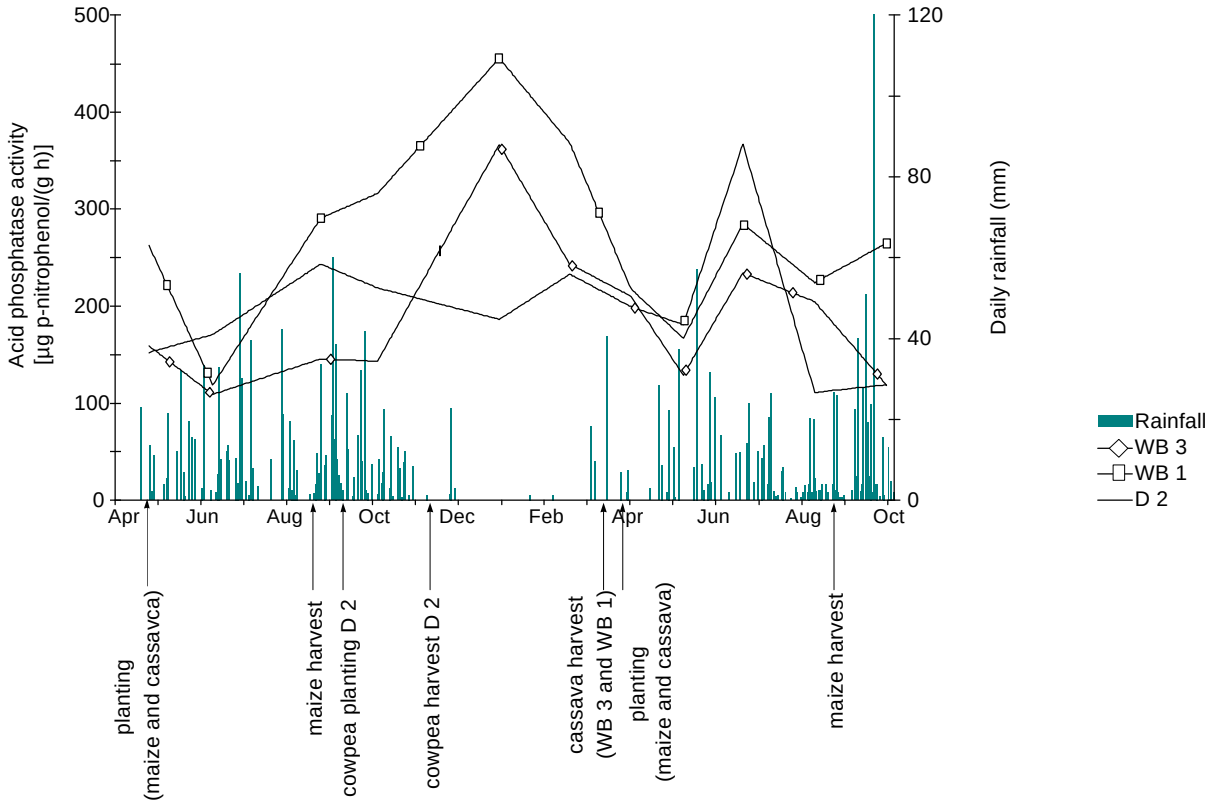


Figure 8. Seasonal course of acid phosphatase activity under continuous cropping at WB 3, D 2, and WB 1 in the 5-10 cm layer

Acid phosphatase activity fluctuated highly throughout the sampling period which could not be attributed to temporal variations in gravimetric soil moisture content and microbial biomass as both parameters were not correlated with the enzymes activity. The likelihood of non-significant impacts of seasonal variations in microbial biomass and soil moisture contents on enzyme activity was also reported by Dkhar and Mishra (1983) and Rastin et al. (1988). Since acid phosphatase is mainly produced by plant roots an increase and decrease in activity is probably related to both crop growth and total root surface area (Tarafdar and Jungk, 1987). During the dry season acid phosphatase activity was highest at WB 1 and lowest at D 2 and was attributed to crop growth and P-demand of the plants: D 2

was only sparsely covered by weedy vegetation whereas cassava plants at WB 1 and WB 3 might have produced surplus acid phosphatase in order to compensate for higher P-requirements.

4.1.6.2 Alkaline phosphatase

The activities of alkaline phosphatase at 0-5 cm and 5-10 cm depth are shown in Table 14, and range from 102 to 365 µg p-nitrophenol g^{-1} h^{-1} in the top 5 cm and from 55 to 293 µg p-nitrophenol g^{-1} h^{-1} at 5-10 cm depth. They are according to the results (20-360µg g^{-1}, 0-15 cm depth, after Tabatabai and Bremner, 1969) reported by Mulongoy and Bedoret (1989) for Nigeria.

Table 14. Average alkaline phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under continuous cropping at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Alkaline phosphatase activity (µg p-nitrophenol g^{-1} h^{-1})		
Site/depth	**1st season**	**dry season**	**2nd season**
0-5 cm			
sec. Forest	740	631	611
Westbank 3	341	365	242
D 2	139	135	127
Westbank 1	104	122	102
LSD	158	70	114
5-10 cm			
sec. Forest	522	508	399
Westbank 3	250	293	178
D 2	55	77	59
Westbank 1	139	136	120
LSD	108	66	84
P contrasts			
D 2 vs. WB 1	0.016		

LSD (excluding forest) at $\alpha = 0.05$
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

Alkaline phosphatase activity, generally, was higher in the top 5 cm at WB 3 and D 2 as compared to 5-10 cm depth, whereas no pronounced difference in activity with soil depth was obtained at the most degraded Westbank 1 site.

Deforestation and prolonged cultivation resulted in a marked decline of alkaline phosphatase activity by 54 %, 82 %, and 86 % at WB 3, D 2, and WB 1, respectively, and was more pronounced than the decline in microbial biomass carbon (Table 11). At both depths alkaline phosphatase activity was significantly higher at the least degraded WB 3 site than at D 2 and WB 1. In the top 5 cm no significant difference in alkaline phosphatase activity was found between D 2 and WB 1. In the 5-10 cm layer, however, alkaline phosphatase activity was significantly higher at WB 1 as compared to D2 during the 1st cropping season, although the α striking significance level after Bonferoni adjustment was not reached (Table 14). No significant difference ($\alpha = 0.05$) was obtained for the 2nd season, whereas during the dry season D 2 was significantly lower at $P = 0.100$ as compared to WB 1.

Since alkaline phosphatase activity is only produced by soil microorganisms and soil fauna (Chhonkar and Tarafdar, 1984; Nakas et al., 1987) the differences in the rate of phosphorous recycling from organic matter at WB 3, D 2, and WB 1 can be related to the quantity and activity of the microbial biomass at the differently degraded sites. Compared to microbial biomass carbon (Table 11) alkaline phosphatase activity appeared a more sensitive parameter to characterize the sites and their degree of degradation as shown by the constancy to reveal highly significant differences between sites.

The seasonal course of alkaline phosphatase activity at 0-5 cm depth is depicted in Figure 9.

Temporal fluctuations in potential activity were less pronounced as compared to microbial biomass (Figure 7) due to stabilization by humic substances. As already mentioned in Chapter 2.3 the activity of soil enzymes may remain rather stable despite the influence of environmental changes as compared to microbial biomass. No decline in activity was found during the dry season, confirming a protection of the enzyme by the SOM-pool. The seasonal course of the enzymes potential activity was somewhat related to the gravimetric moisture content during the 1st season ($r = 0.6$, $P \leq 0.001$) and 2nd season in 1994 ($r = 0.68$, $P \leq 0.001$) at 0-5 cm depth. For the 1st and 2nd cropping season a high positive correlation coefficient of 0.87 ($P \leq 0.001$) and 0.93 ($P \leq 0.001$), respectively, was found between alkaline phosphatase activity and microbial biomass at 0-5 cm depth, and will be discussed in more detail in Chapter 4.3.3.

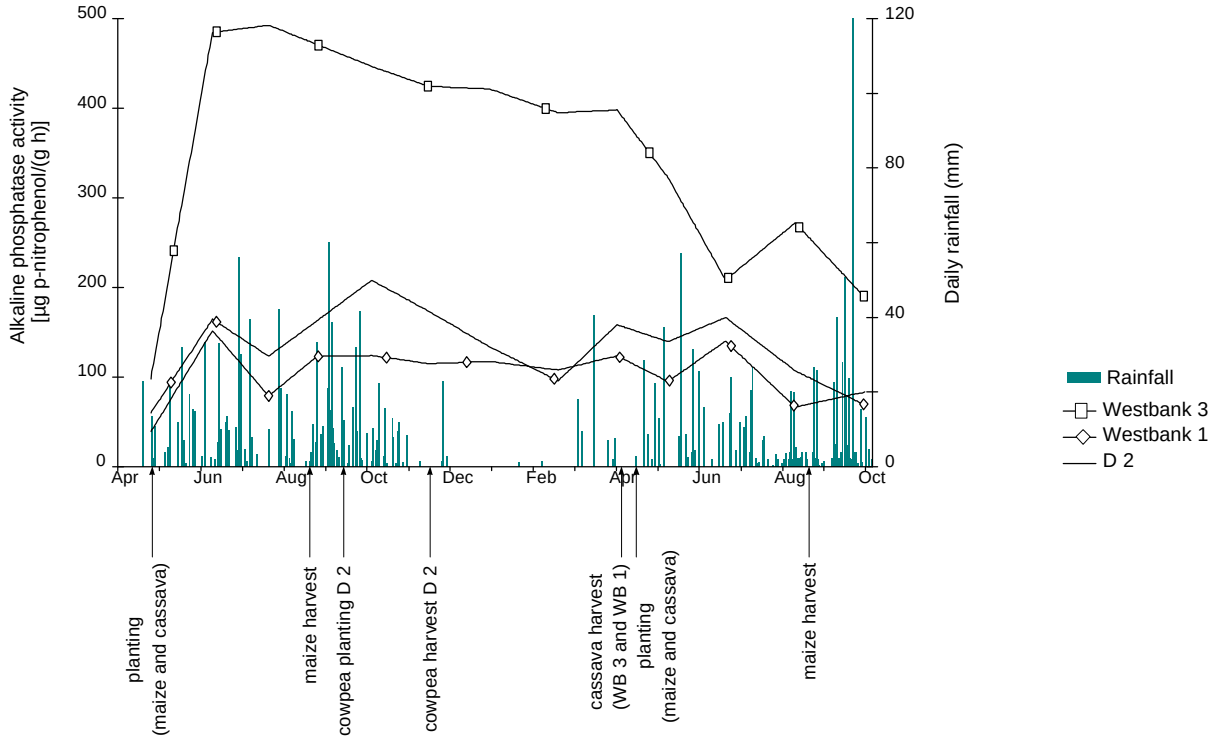


Figure 9. Seasonal course of alkaline phosphatase activity under continuous cropping at WB 3, D 2, and WB 1 in the top 5 cm.

4.1.7 ß-Glucosidase

The seasonal average activity of ß-glucosidase at 0-5 cm and 5-10 cm depth in 1993 and 1994 is summarized in Table 15. The average activity of ß-glucosidase (according to the method of Eivazi and Tabatabai, 1988) for Alfisols and Ultisols in Nigeria is reported as 20-309 µg g^{-1} in the 0-15 cm layer (Mulongoy et al., 1989), or as 10-17µg g^{-1} for Alfisols in northern Ghana at 0-30 cm depth (Fugger, 1997). Our results obtained in 1993 and 1994 are in agreement with these published data.

Deforestation and continuous cultivation for 4, 10, and 14 years resulted in a decline of ß-glucosidase activity by 70 %, 72 % and 80 % in the 0-5 cm layer at WB 3, D 2, and WB 1, respectively. In comparison, total loss of organic carbon was 50 %, 70 %, and 75 % at WB 3, D 2, and WB 1, respectively, as compared to secondary forest (Table 7).

Table 15. Average ß-glucosidase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under continuous cropping at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	ß-Glucosidase activity (µg p-nitrophenol $g^{-1}h^{-1}$)		
Site/depth	**1st season**	**dry season**	**2nd season**
0-5 cm			
sec. Forest	169	181	180
Westbank 3	50	59	47
D 2	47	49	44
Westbank 1	36	30	31
LSD	43	29	36
5-10 cm			
sec. Forest	49	55	62
Westbank 3	21	20	19
D 2	15	13	16
Westbank 1	22	12	22
LSD	23	12	14

LSD (excluding forest) at $\alpha = 0.05$

Contrary to the results obtained for total soil organic carbon (Table 7) and microbial biomass (Table 11) no significant differences in ß-glucosidase activity was achieved at both depths and throughout the sampling period. WB 3 was only significantly higher in the top 5 cm during the dry season as compared to WB 1. Generally, potential ß-glucosidase activity in the 5-10 cm layer was much smaller than the activity at 0-5 cm depth. Similar to our data a more pronounced decrease of ß-glucosidase activity was reported for a legume-vegetable rotation and a traditional vegetable rotation with winter fallow at Oregon, USA. After 2 years ß-glucosidase activity declined by 50 % as compared to organic carbon which declined by 6.5 % and 11.9 %, respectively (Miller and Dick, 1995). Friedel et al. (1996) reported that the impact of tillage management was larger on ß-glucosidase activity than on organic carbon under temperate agricultural conditions in Germany. However, Garcia et al. (1994) reported for degraded soils in south-eastern Spain that ß-glucosidase activities were lower at the most degraded soils, and was attributed to both reduced organic matter mineralization and reduced activity of the carbon cycle (Garcia et al., 1994).

Although a significant positive correlation coefficient of 0.81*** and 0.9*** in the top 5 cm and 0.6*** and 0.83*** at 5-10 cm depth in 1993 and 1994 was obtained between ß-glucosidase and organic carbon, respectively, the activity of the enzyme is primarily dependent upon available cellulosic substrates. Despite great differences in dry matter production of 2.6 t/ha, 5.3 t/ha and 0.5 t/ha at WB 3, D 2, and WB 1, respectively, it appears that no marked differences of available cellulytic substrates by the residues were existent under continuous intercropping of maize and cassava at both WB 3 and WB 1 and the maize and cowpea sequence at D 2.

The seasonal course of the ß-glucosidase activity between April 1993 and October 1994 at 0-5 cm depth is depicted in Figure 10.

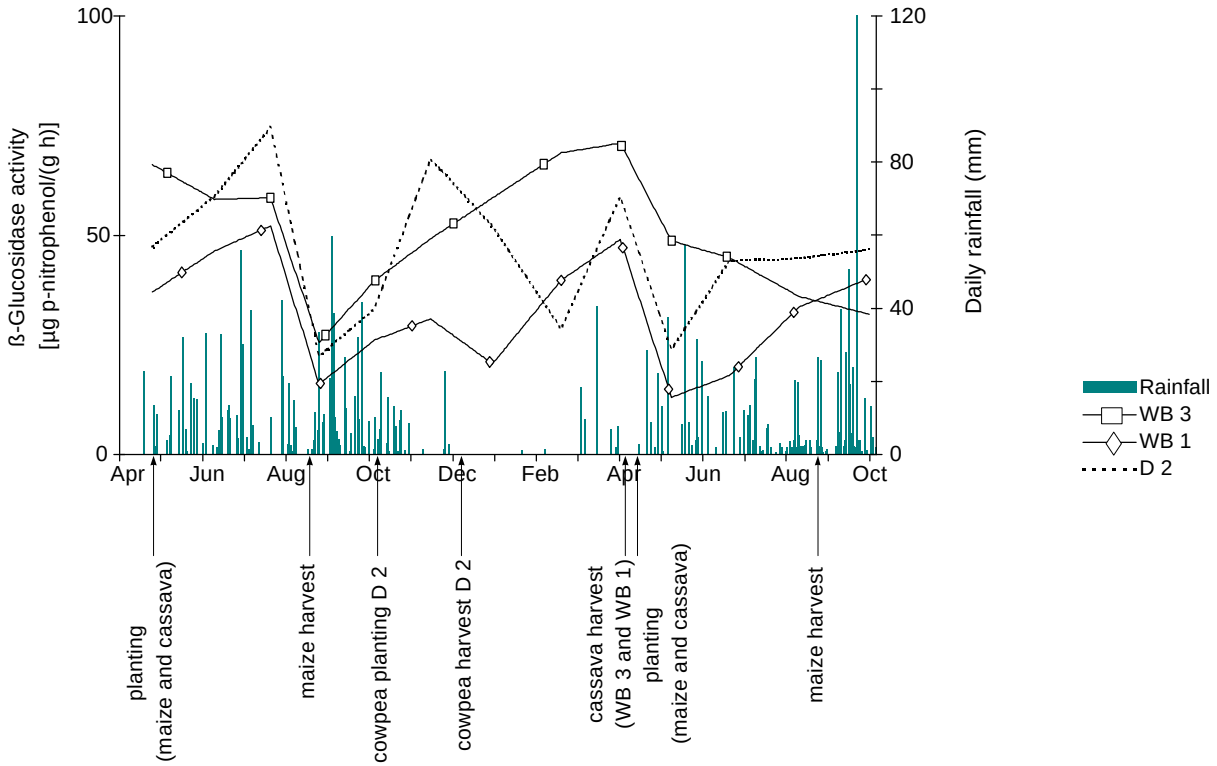


Figure 10. Seasonal course of ß-glucosidase activity under continuous cropping at WB 3, D 2 and WB 1 at 0-5 cm depth.

During the dry period ß-glucosidase activity increased at both WB 3 and WB 1, whereas at D 2 a marked decline in activity towards the end of the dry season was found. This was attributed to a reduced plant cover at D 2, and is discussed in more detail for microbial biomass in Chapter 4.1.5.1. The higher activity at WB 3 and WB 1 during the dry season is

due probably to an increase in the ratio of fungal biomass to bacterial biomass (Shields et al., 1973). Since fungal spores and mycelial fragments survive under very low soil moisture conditions, decomposition of dead roots and cassava litter commenced upon decrease in soil moisture (Ross et al., 1984; Griffin, 1969).

The temporal fluctuation of ß-glucosidase activity was not controlled by the gravimetric soil moisture content as the relation was non-significant (data not shown). Similar results were reported by Eivazi and Tabatabai (1990) and Rastin et al. (1988) that ß-glucosidase was significantly increased upon air-drying of soils in Iowa, USA, while no correlation was found in a beech forest in Germany, respectively. The seasonal activity of ß-glucosidase is related to organic carbon and microbial biomass and is controlled by the availability of the residues added.

4.1.8 Protease

Average seasonal protease activities at 0-5 cm and 5-10 cm depth are depicted in Table 16. Protease activities ranged from 15 to 179 µg tyrosine g^{-1} 2 h^{-1} in the top 5 cm, and from 21 µg to 152 µg g^{-1} 2 h^{-1} in the 5-10 cm layer. Similar to our results Fugger (1997) reported mean protease activities of 20-74 µg g^{-1} 2 h^{-1} at 0-30 cm depth for Alfisols in northern Ghana.

No consistent trend in protease activity as related to site degradation was obtained. In the top 5 cm protease activity decreased in the order WB 3 = D 2 > WB 1 only during the 1st season, whereas no significant differences were found for the dry season and the 2nd season. At 5-10 cm depth, WB 3 had significant higher protease activity during both the 1st and the dry season. D 2 and WB 1 were not significantly different from each other. The results obtained for protease activity at 5-10 cm depth are according to the total soil nitrogen, decreasing in the order WB 3 > D 2 = WB 1.

Table 16. Average protease activity (µg tyrosine g^{-1} soil 2 h^{-1}) under continuous cropping at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Protease activity (µg tyrosine g^{-1} 2 h^{-1})		
Site/depth	**1st season**	**dry season**	**2nd season**
0-5 cm			
sec. Forest	325	202	230
Westbank 3	179	82	94
D 2	127	39	87
Westbank 1	55	15	131
LSD	92	ns	ns
P contrasts(1)			
D 2 vs. WB 1	0.014		
5-10 cm			
sec. Forest	195	132	150
Westbank 3	152	75	66
D 2	29	41	28
Westbank 1	36	21	145
LSD	58	54	ns

LSD (excluding forest) at $\alpha = 0.05$
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

The seasonal course of mean protease activity under continuous cropping at WB 3, D 2 and WB 1 in the 5-10 cm layer is displayed in Figure 11.

Protease activity fluctuated highly during the cropping seasons. A pronounced decline in activity was observed during the dry season. Similar results were reported by Loll and Bollag (1983) and Watanabe and Hayano (1996) confirming that low soil moisture contents restrict proteolysis. However, no significant correlation of gravimetric soil moisture content and protease activity could be established for 1993 and 1994. Microbial biomass, total N, and organic carbon correlated with protease activity with differing correlation coefficients in 1993 and 1994. Thus, the correlation coefficient between microbial biomass, total N, and organic carbon with protease in 1993 was 0.85***, 0.76***, and 0.77*** and in 1994 was 0.59***, 0.5***, and 0.45**, respectively.

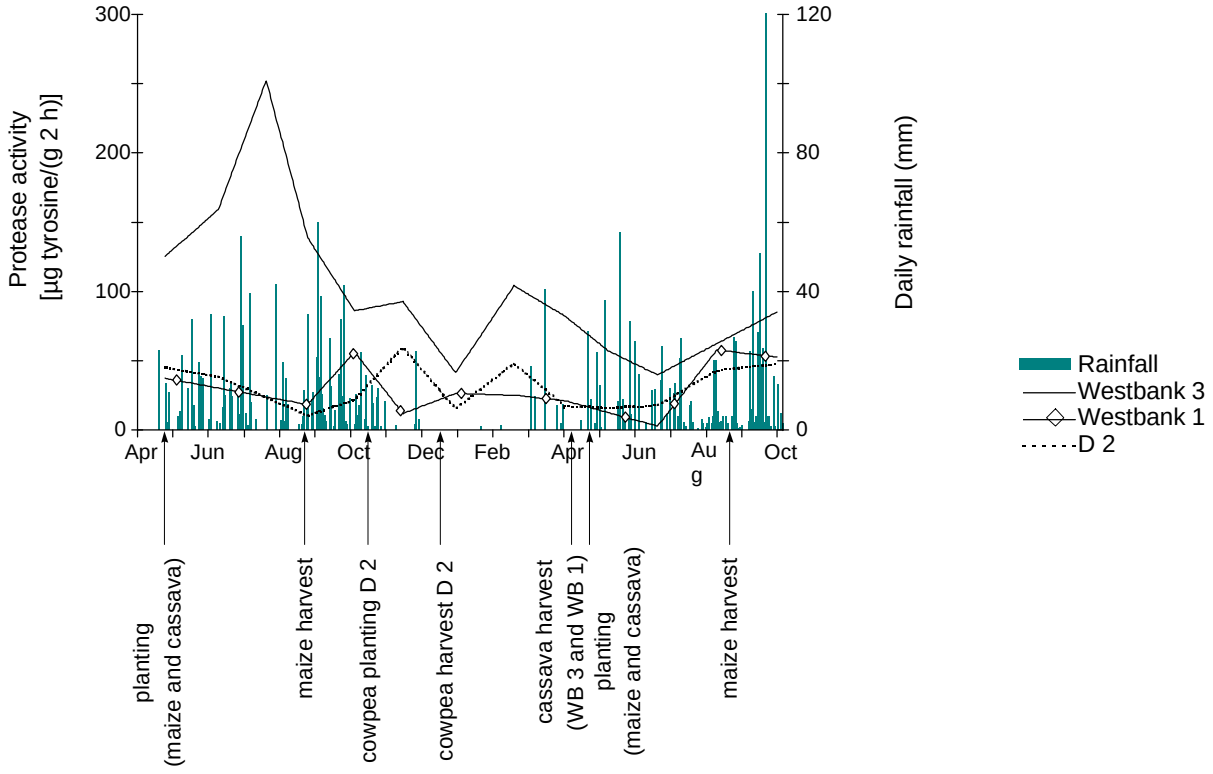


Figure 11. Seasonal course of protease activity under continuous cropping at WB 3, D 2, and WB 1 in the 5-10 cm layer.

4.1.9 Summary

The productivity of maize decreased in the order D 2 > WB 3 > WB 1. No difference in the measured soil physical properties (bulk density, particle size distribution) were obtained among the sites. Soil chemical conditions (pH, C_{org}, total N, exchangeable basic cations) decreased in the order WB 3 > D 2 = WB 1. Inorganic phosphorus (Bray-I and $NaHCO_3$-extractable) was significantly higher at D 2, compared to both WB 3 and WB 1, which were not different from each other. Organic phosphorus ($NaHCO_3$ and NaOH-extractable) in the 0-5 cm layer was highest at D 2 and WB 1 as compared to WB 3, whereas in the 5-10 cm layer D 2 was significant higher as compared to WB 3 and WB 1. Soil microbial biomass behaved similar to total SOM and decreased in the order WB 3 > D 2 = WB 1 at both depths. Alkaline phosphatase at 0-5 cm depth decreased in the order WB 3 > WB 1 = D 2 and at 5-10 cm depth in the order WB 3 > WB 1 > D 2 during the 1st season and in the order WB 3 > WB 1 = D 2 during the dry and the 2nd season. Acid phosphatase was not

significantly different in the top 5 cm, whereas at 5-10 cm depth acid phosphatase activity increased in the order WB 1 = D 2 > WB 3 during the 1st season, and WB 1 > D 2 = WB 3 during the dry season. No significant differences were found for the 2nd season. ß-Glucosidase activity was not different among the sites. Protease activity was not significantly different at 0-5 cm depth except WB 3 = D 2 > WB 1 during the 1st season. At 5-10 cm depth the activity decreased in the order WB 3 > D 2 = WB 1 during both the 1st and dry season. No significant differences were found for the 2nd season.

In summary, WB 3 was characterized by medium maize productivity, high amounts of soil organic matter related properties, low phosphorus status and acid phosphatase activity, high microbial biomass, alkaline phosphatase and protease activity. D 2 was characterized by high maize productivity, low values of soil organic matter related properties, high phosphorus status, low microbial biomass as well as low alkaline phosphatase and protease activity. Characteristic for Westbank 1 was low maize productivity, low amounts of soil organic matter related properties, low inorganic phosphorus status and high organic phosphorus content at 0-5 cm depth, high acid phosphatase activity, low microbial biomass and alkaline phosphatase activity as well as low protease activity in 1993.

Differences between the degraded D 2 and Westbank 1 sites as reflected in maize productivity were largely due to inorganic Bray-I phosphorus at both depths and organic phosphorus at 5-10 cm depth. Differences in relation to soil microbiological properties were due to alkaline phosphatase activity at 5-10 cm depth. Acid phosphatase activity differed only during the dry season at 5-10 cm depth, and protease activity at 0-5 cm depth during the 1st season.

4.2 Effects of improved fallow management systems on site degradation

The management of the improved fallow systems at each site is depicted in Table 17.

Table 17. Improved fallow managements at Westbank 1, D 2, and Westbank 3

cropping pattern	year															
	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
WB 1																
Ctrl	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs
Leucaena	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	Leuc	Leuc	Leuc	Leuc	M+Cs	M+Cs
Senna	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	Senna	Senna	Senna	Senna	M+Cs	M+Cs
Pueraria	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	Puer	Puer	Puer	Puer	M+Cs	M+Cs
Nat.regrowth	M+Cs	M-C	M-C	Mu	M-C	M-C	M-C	M-C	M-C	Mu	Bush	Bush	Bush	Bush	M+Cs	M+Cs
D 2																
Ctrl		⊢	—	—	—	—	⊣	M-C	M-C	M-C	M-C	M	M-C	M	M-C	M-C
Leucaena		⊢	—	—	—	—	⊣	M-C + Leuc	M-C + Leuc	M-C + Leuc	M-C + Leuc	M + Leuc	M-C + Leuc	M + Leuc	M-C + Leuc	M-C + Leuc
Senna		⊢	—	—	—	—	⊣	M-C + Senn	M-C + Senn	M-C + Senn	M-C + Senn	M + Senn	M-C + Senn	M + Senn	M-C + Senn	M-C + Senn
WB 3																
Ctrl											M+Cs	M+Cs	M+Cs	M+Cs	M+Cs	M+Cs
Leucaena											M+Cs + Leuc	M+Cs + Leuc	M+Cs + Leuc	M+Cs + Leuc	M+Cs + Leuc	M+Cs + Leuc
Pueraria											M+Cs + Puer	M+Cs + Puer	M+Cs + Puer	M+Cs + Puer	M+Cs + Puer	M+Cs + Puer
Nat.regrowth											M+Cs + Bush	M+Cs + Bush	M+Cs + Bush	M+Cs + Bush	M+Cs + Bush	M+Cs + Bush

M+Cs = maize and cassava intercropping
M-C = maize and cowpea sequential cropping
Mu = mucuna fallow
M-Mu = maize in the 1st season and mucuna fallow in the 2nd season
M = maize in the 1st season only

⊢—⊣ Between 1980 and 1986 D 2 was part of an experimental area used by breeders (maize, cassava, cowpea and soybean) with diverse tillage (ploughing and disc harrowing) and fertilizer managements. In 1986, D 2 was split into two subplots. At one site the improved fallow management trials were stablished in 1986. However, the recorded management schedules of the site do not allow a conclusive allocation of the land use history to D 2 (Van der Meersch, pers.com.; Vanlauwe, pers.com.).

At Westbank 3 and D 2 hedgerow intercropping and live mulching were practiced since 1989 and 1986, respectively. At Westbank 1, however, leucaena, senna, pueraria and natural regrowth plants were managed as fallows between 1989 and 1993, slashed and burnt with subsequent cropping to maize and cassava in 1993 and 1994.

4.2.1 Crop performance of maize and cassava

In order to obtain significant yield differences at $\alpha = 0.05$, design measures such as blocking, splitting, repeated sub-sampling are used to increase the precision of the mean estimates. Furthermore the number of replications is more than two. However, as already discussed in Chapter 3.3.1 the main emphasis of our research was focused on potential changes in soil processes over time.

Table 18. Maize grain and stover (kg DM ha^{-1}) and cassava tuber (t DM ha^{-1}) yield under traditional and improved fallow management systems in 1993 and 1994 at Westbank 3, D 2, and Westbank 1 (2 field replicates).

	Maize grain			Maize stover			Cassava tuber(3)	
Management	**1993**	**1994**	**Mean**	**1993**	**1994**	**Mean**	**1993**	**1994**
Westbank 3								
Ctrl	1202	1134	1168	1323	1509	1416	6.8	8.2
Leucaena	1595	979	1286	1711	1455	1583	5	4.8
Pueraria	1368	1355	1361	1519	1272	1395	2.6	9
Nat. regrowth(2)	3990	fallow		4848	fallow		⊗	15
D 2								
Ctrl	1604	2374	1989	2628	2901(1)	2674		
Leucaena	2305	1322	1813	1134	1615(1)	1374		
Senna	2066	1944	2004	1783	2376(1)	2080		
Westbank 1								
Ctrl	400	200	300	700	331	516	5.2	3.7
Leucaena	995	637	816	550	964	757	n.a.	5.3
Senna	750	2165	1457	900	1283	1092	n.a.	8.7
Pueraria	450	436	442	800	1098	949	n.a.	14
Nat. regrowth	650	997	823	950	1495	1222	n.a.	10.2
LSD ($\alpha = 0.05$)			647.8					10

Data presented on maize and cassava for WB 1 and WB 3 were received by RCMD, IITA, and for D 2 by Vanlauwe, personal communication;
(1) = stover was estimated by harvest index of 45 % (Vanlauwe, personal communication);
(2) = not included in Anova; see Chapter 3.8;
(3) = statistical analysis for 1994;
⊗ = cassava was planted in 1993 after 2 years of fallowing and harvested 12 months later in April 1994;
n.a. = not available, data were not submitted by RCMD/IITA.

Overall results of the long-term trials were not made available by RCMD/IITA (Resource and Crop Management Division, IITA) so that they cannot be compared with the results presented here. Due to high inter-plot and seasonal variability of cassava tuber yields no significant differences between treatments was obtained at the 5 % level except for pueraria at Westbank 1 which yielded significantly higher cassava tubers than continuous cropping (Table 18). At Westbank 3 natural regrowth (2:1 year rotation of natural regrowth and maize/cassava intercropping, respectively), leucaena, and pueraria were not significantly different from the control. Also the introduction of planted fallows with leucaena, senna and natural regrowth for four years at WB 1 did not significantly increase cassava tuber yield as compared to continuous cropping. Cassava at WB 1 had to be replanted in 1993 because of damage by ants and termites, while during the cropping period losses occurred by rodent attacks (Salako, personal communication). Thus, higher cassava yields might have been expected in 1994 under more regular conditions. Nonetheless, cassava performed fairly well at the severely degraded Westbank 1, and is discussed in more detail in Chapter 4.1.1.

The performance of maize at the degraded D 2 site was generally superior to that at the most degraded Westbank 1 and the least degraded Westbank 3 (Table 18), although not always statistically significant at the 5 % level. The introduction of pueraria or leucaena at WB 3 and leucaena or senna at D 2 did not improve maize yield significantly over continuous cropping control maize yield. Moreover, total dry matter under leucaena (2.9 t ha^{-1}) was significantly lower than under continuous cropping (5.3 t ha^{-1}; Table 20). At the most degraded Westbank 1 site the introduction of planted fallow with senna yielded significant more maize grain than in the continuous cropping control. Leucaena and natural regrowth yielded significantly more maize only at $P = 0.113$ and $P = 0.108$, respectively, than the control. The improved fallows may contribute to an organic matter build-up due to addition of leaf biomass which subsequently releases nutrients (Mittal et al., 1992). Pueraria fallowing for 4 years, however, had no positive impact on maize productivity which is in agreement with results reported by Luna-Orea et al. (1996) for typic and aquic Dystropept soils in the Bolivian Amazon. More than 50 % of the nutrients in the pueraria residue from 12 month fallow were released within 4 weeks after slashing the cover crops. Thus, the nutrients were potentially available at 6 weeks prior to peak nutrient demand by the succeeding crops (Luna-Orea et al., 1996).

The impact of improved fallow managements to improving maize yield as compared to sole cropping is discussed controversially in the literature. Kühne (1993) reported for

ferrali-haplic Acrisols („Terre de barre non degradé“) in southern Benin reduced maize yields when compared to cropping without leucaena hedges due to competition by roots for water and nutrients. These results are not consistent with data reported by Van der Meersch (1992) for Alfisols at D 2, IITA. She found that maize yields in maize/leucaena alley cropping decreased by 11 % from initially 2270 kg/ha in 1986 to 2033 kg/ha in 1990, whereas both alley cropping with senna and the sole cropping control treatment decreased by 40 % from 2890 kg maize/ha in 1986 to 1754 kg/ha in 1990 and by 70 % from 2389 kg/ha in 1986 to 733 kg/ha in 1990, respectively. The maize grain production in 1990 did not differ in either alley cropping system but was significantly higher than in the monocropping system. Leucaena alley cropping was more stable and maintained maize yields of about 2 t/ha after five years continuous cropping (Van der Meersch, 1992). Tian et al. (1993) stressed that maize grain yield was higher with leucaena prunings supplemented with 45 kg N/ha at IITA, Nigeria, and concluded that the combined addition of plant residue and fertilizer-N were important to improving crop production. Similar results were reported for leucaena alley cropping with maize and cowpea planted in sequence on an Entisol (loamy sand Apomu soil) in southern Nigeria (Kang et al., 1985). Although leucaena contributed about 110 kg N ha^{-1} $year^{-1}$ between 1981 and 1983 on average, supplementary rates of fertilizer-N were still needed for obtaining high maize yields (Kang et al., 1985).

Further discussion on the impact of different management systems and the soil's fertility status on maize grain yields is given in Chapter 4.1.1.

4.2.2 Nutrient uptake by maize grain

Table 20 presents the nutrient uptake in the total dry matter at harvest 1994 as affected by fallow managements and cropping sites.

The introduction of planted fallows with leucaena, senna and pueraria and natural regrowth for four years at the most degraded WB 1 did not significantly increase N, P and K-uptake as compared to continuous cropping except for N-uptake under senna at P = 0.098. At this degraded site increased amounts of residue returns by the planted fallows for 4 years should have improved nutrient availability and uptake by maize crops as is indicated by trends (Table 20). However, due to high inter-plot variability no significant differences could be obtained. The single values for nutrient uptake of N and P in stover and grain at either replicate is given in Table 1 and 2 of the Appendix, respectively.

At the least degraded WB 3 site no significant difference in maize N- and K-uptake as compared to sole cropping was found. Phosphorus uptake of maize plants were higher (P = 0.09) under continuous cropping as compared to both pueraria and leucaena. The reduced P-uptake in the maize crop may be caused by competition by the companion hedgerow trees and the herbaceous in situ cover for phosphorus.

Table 20. Nutrient uptake (kg ha^{-1}) in total dry matter (t ha^{-1})**(1)** of maize plants at harvest 1994 as affected by cropping sites and fallow management systems.

Management system	dry matter t ha^{-1}	N	P	K kg ha^{-1}	Ca	Mg
Westbank 3						
Ctrl	2.6	37.3	30.5	30.0	10.0(2)	10.5
Leucaena	2.4	32.5	14.7	27.2	10.5(2)	10.6
Pueraria	2.1	35.7	18.1	30.2	8.8(2)	11.0
D 2						
Ctrl	5.3	53.0	13.3	56.3	38.3	30.2
Leucaena	2.9	32.2	6.5	35.2	12.9	13.0
Senna	4.3	37.7	8.0	47.7	26.7	16.4
Westbank 1						
Ctrl	0.5	4.3	0.8	4.8	3.0	2.3
Leucaena	1.6	14.8	2.3	19.0	10.9	6.6
Senna	3.4	32.1	9.1	24.7	9.0	11.7
Pueraria	1.5	12.5	2.1	16.6	8.1	6.9
Nat. regrowth	2.5	25.5	4.6	20.9	13.9	13.3
LSD	2.3	ns	ns	23.7	12	12.5

Data on nutrient uptake at WB 1 and WB 3 were received from RCMD, IITA and for D 2 from Vanlauwe (personal communication);
(1) = total dry matter production of the above ground plant material including stalks and grain;
(2) = only stover; data were received from RCMD, IITA.

At D 2 the nutrient uptake of N and K by the maize plants was lower under the alley cropping systems than under sole cropping, which indicated lower available N and K than under non-mulched sole cropping. Thus, N-uptake by maize of both leucaena and senna alley cropping systems were significantly reduced (P = 0.079) due probably to competition

by roots of crops and trees for nutrients and water, and is reflected in the significant lower total DM of leucaena as compared to the control treatments (Table 20). Potassium uptake by maize was only significantly reduced in the leucaena treatment (P = 0.075) Phosphorus uptake under sole cropping was not significantly different from the alley cropping treatments.

The impact of alley cropping systems on maize N-uptake is discussed controversially in the literature. Jonsson et al. (1996) reported that a transfer of fixed N of leucaena to maize in Tanzania was not indicated as determined by the ^{15}N-natural abundance method. Van der Meersch (1992), however, concluded that alley cropping with leucaena and senna significantly increased maize N-uptake at D 2. No differences were found between leucaena and senna, a fast and a slow decomposing material, respectively (Van der Meersch, 1992).

The results obtained for crop P-uptake under improved fallow management systems at WB 3 and D 2 are supported by results presented by Palm (1995), who concluded that phosphorus was not provided in sufficient quantities to meet the demand of intercropped maize as well as leucaena and senna plants. However, these findings contradict to those reported by Hands et al. (1995) and Haggar et al. (1991). Hands et al. (1995) found no differences in maize and bean P-uptake between an unfertilized sole cropping control and alley cropping systems with gliricidia and erythrina on a nutrient depleted Ultisol at Costa Rica. Haggar et al. (1991) reported that crop P-uptake in the field was 50-60 % higher in the alley crops than in the unmulched sole crops on volcanically derived soils in Costa Rica due to a more efficient use of P and higher P-cycling rate within the system. The author further suggested that an increase of organic matter input to the soil by the prunings may block the adsorption of P by soil minerals due to organic anions competing for P-adsorption. Therefore, the buffering capacity of the soil is reduced, thus resulting in decreased adsorption of native soil phosphate. However, this may not hold true for the prevailing conditions at IITA, Nigeria where sustained residual effects of inorganic phosphorus fertilization was observed due to the low P-sorption capacity of these Alfisols (compare with Chapter 4.1.4.2). Consequently, competition by roots of arable crops and trees for nutrients may have caused a reduced nutrient uptake for intercropped maize.

4.2.3 Soil physical properties

Mean bulk densities (0-5 cm depth) of the improved fallow management systems at WB 3, WB 1, and D 2 ranged from 1.14 Mg m^{-3} to 1.38 Mg m^{-3} and are presented in Table 21.

No significant differences in mean bulk density were obtained between treatments and sites.

The mean percentage sand, silt and clay content under the improved fallow management systems were about 80 %, 10 % and 10 %, respectively, at Westbank 3 and D 2. Westbank 1 had lower sand (non-significant) and higher clay contents (significant at P = 0.08), and was in accordance to the site's texture under secondary forest before clearing in 1978 (compare with Chapter 4.1.3).

Table 21. Soil physical characteristics under improved fallow management systems in the 0-10 cm layer, 1993.

	bulk density	texture %		
Management	**Mg m^{-3} (1,2)**	**sand**	**silt**	**clay**
sec. Forest	n.d.	81.0	10.0	9.0
Westbank 3				
Ctrl	1.26	82.0	9.0	9.0
Leucaena	1.18	82.0	9.0	9.0
Pueraria	1.20	80.0	10.5	9.5
Nat. regrowth	1.14	78.5	10.5	11.0
D 2				
Ctrl	1.37	81.0	10.5	8.5
Leucaena	1.37	81.5	9.25	9.25
Senna	1.37	79.0	11.5	9.5
Westbank 1				
Ctrl	1.33	73.5	9.0	17.5
Leucaena	1.36	66.0	9.0	25.0
Senna	1.38	68.5	11.0	20.5
Pueraria	1.35	75.0	8.0	17.0
Nat. regrowth	1.34	71.5	7.5	21.0
SE	0.06	4.1	1.2	3.7

SE = Standard error of the mean;
n.d. = not determined;
data on bulk density at Westbank 3 and Westbank 1 were received by Salako (personal communication) and at D 2 by Van der Meersch (1992);
(1) = bulk density of the top 5 cm;
(2) = SE was only determined for WB 1 and WB 3, since mean bulk density of total D 2 was only available by Van der Meersch, 1992.

4.2.4 Soil chemical characteristics

4.2.4.1 Soil nutrients and pH

Average concentrations of organic carbon, total nitrogen and pH in the 0-5 cm and 5-10 cm layer under improved fallow management at Westbank 3, D 2, and Westbank 1 are depicted in Table 22 and Table 4 of the Appendix, respectively.

The pH under the improved fallow managements were highest at Westbank 3 compared to the degraded Westbank 1 and D 2 sites and this is attributed to the shorter cropping period of the former site.

Table 22. Average soil organic carbon (t ha^{-1}), total nitrogen (kg ha^{-1}) and pH values under improved fallow management systems at 0-5 cm depth in 1993 and 1994.

	org. C (t ha^{-1})			total N (kg ha^{-1})			pH ($CaCl_2$)		
Site/depth	1st season	dry season	2nd season	1st season	dry season	2nd season	1st season	dry season	2nd season
0-5 cm									
sec. Forest	19.3	17.4	16.8	1707	1381	1358	6.6	6.9	6.7
Westbank 3									
Ctrl	8.8	8.2	9.3	732	713	856	6.8	7.0	6.9
Leucaena	9.6	10.7	10.9	969	924	999	6.6	6.8	6.8
Pueraria	12.6	11.6	12.5	1023	1069	1060	6.7	7.1	6.9
Nat. regrowth	11.1	10.0	fallow	937	902	fallow	6.8	7.1	fallow
D 2									
Ctrl	5.4	6.4	6.1	479	563	537	6.0	5.8	6.0
Leucaena	6.3	7.4	7.3	580	671	663	6.1	5.7	5.6
Senna	7.0	7.0	8.1	574	638	656	6.3	6.1	6.3
Westbank 1									
Ctrl	4.1	5.0	4.6	408	471	479	5.7	5.7	5.5
Leucaena	9.8	6.8	7.9	842	681	796	6.1	6.0	6.2
Senna	9.4	8.3	9.7	753	679	804	6.6	6.5	6.7
Pueraria	7.2	6.6	8.0	643	560	715	5.7	5.6	5.7
Nat. regrowth	7.4	5.6	7.6	628	530	690	6.1	5.8	6.0
LSD	1.55	2.2	2.1	176	123	202	0.36	0.53	0.51

LSD (excluding forest) at $\alpha = 0.05$

The soil pH in improved fallow managements at both the non-degraded WB 3 site and the degraded D 2 site were not significantly different compared to the continuous cropping controls. Mulongoy et al. (1993), however, reported significant lower soil pH values under leucaena hedgerow intercropping than in sole cropping in Nigeria. He suggested that the decomposition of the applied prunings may have some acidifying effect on soils. At WB 1, however, the introduction of planted fallows with leucaena, senna, and natural regrowth for 4 years significantly increased soil pH in comparison to the control treatments and this was most pronounced for senna fallowing between 1989 and 1993. Pueraria was not significantly different from the continuously cropped controls. Particularly at this degraded site, these relatively small increases in pH may alleviate Mn toxicity.

At WB 3 the mean soil organic carbon content was significantly higher under pueraria throughout the sampling period whereas the 2:1 year rotation of natural regrowth and maize/cassava intercropping was only significant higher than the continuous cropping controls during the 1st season. Leucaena was not significantly different from the continuous cropping controls. Similar results were obtained at D 2, where the introduction of leucaena hedgerow intercropping did not maintain significantly higher amounts of total organic carbon than the continuous cropping control. Senna alley cropping, however, had significantly higher total soil organic matter contents during the 1st and 2nd season as compared to the control. Only at the most degraded Westbank 1 site the introduction of planted fallows with leucaena, senna, pueraria, and natural regrowth significantly increased soil organic carbon as compared to the continuous cropping control. These findings are in accordance with the results obtained by Kang et al. (1981), Kang and Doguma (1985), Wade and Sanchez (1983), and Lal (1989), who all found that higher C and N levels were sustained by continuous additions of leucaena prunings and pueraria mulch than on plots receiving no prunings. The results obtained at D 2 are partly consistent with those reported by Van der Meersch (1992). She found that despite repeated applications of organic material by either prunings of leucaena and senna, soil organic carbon did not increase as compared to the control treatments and was lower than the bush regrowth of the same age.

Despite the introduction of improved fallow managements, the soil organic carbon content in the 0-5 cm layer at the degraded WB 1 and D 2 sites was 50-65 % and 52-67 % lower, respectively, as compared to secondary forest. The decline was more pronounced under the senna and leucaena alley cropping systems at D 2 as compared to the more severely degraded Westbank 1. At the least degraded Westbank 3 site, organic carbon decreased by

35-50 % under the improved fallow management systems in the 0-5 cm layer, 4 years after forest clearing.

The data on soil nitrogen followed similar trends to those of organic carbon. Under secondary forest the mean N content was 1.4 t/ha in the 0-5 cm layer and declined most (55 %) under leucaena alley cropping at D 2 and least (25 %) under pueraria at WB 3. Similar results were found by Lal (1989) at IITA, who reported total N decline of 75 % five years after continuous cropping under no-tillage, plow-tillage, and contour hedgerows with leucaena and gliricidia from initially 0.28 % to 0.07 % in the 0-5 cm layer. The introduction of leguminous or non-leguminous trees in simultaneously cropped fields (agro-silviculture) failed to significantly restore soil organic matter and total N at various sites in southern Nigeria (Mulongoy et al., 1993), in accordance with the results obtained by us in 1993 and 1994. Compared to the continuous cropping control treatments only at WB 3 and WB 1 significant differences in total soil nitrogen were found by the introduction of improved fallow management systems. At D 2 no significant treatment effects were obtained. This is in accordance to results reported by Van der Meersch (1992), who found that at D 2 none of the alley cropping systems with leucaena and senna restored soil N fertility to the same extent as a 4 year old bush fallow. The author concluded that organic N applied with senna prunings could not sufficiently compensate for the N taken up by the companion maize crop or for N losses from the system. Thus, the recycling capacity of the senna trees was not high enough to maintaining soil organic nitrogen. Although leucaena did not sustain soil N as well as a 4 year old bush fallow, the application of leucaena pruning material was suggested to replace fertilizer-N because total N and organic C were sustained at the same level in both, fertilized and unfertilized leucaena alley cropping systems at D 2 (Van der Meersch, 1992). Gaiser (1992) reported that the efficiency of leucaena leaves to increase the amount of organic N in the soil was less than with maize stover. The amount of soil N in the light organic matter fraction had been increased significantly but not the amount of N in the heavy fraction.

Data on exchangeable basic cations ($cmol^{+}\ kg^{-1}$ and $kg\ ha^{-1}$), and Mn are summarized in Table 23 and Table 5 of the Appendix. They represent the nutrient status of these sites in October 1993.

Similar to the continuous cropping control treatments the predominant exchangeable basic cation at all sites was Ca. The introduction of improved fallow managements at WB 3 and D 2 did not sustain higher exchangeable soil nutrient concentrations than the controls. These findings contradict the results reported by Van der Meersch (1992) for D 2 at IITA,

who found increased exchangeable basic cation levels in alley cropping systems with leucaena and senna. The author further suggested a high nutrient "pumping" capacity of senna for Ca and of leucaena for Ca, K, and Mg.

At the most degraded Westbank 1 site, however, significantly higher concentrations of Ca and Mg were obtained after leucaena, senna, and natural regrowth fallowing for four years, whereas pueraria was not different from the continuous cropping control. Potassium was significantly higher only in the senna and leucaena systems.

Table 23. Average soil nutrient status ($cmol^+ kg^{-1}$ and $kg\ ha^{-1}$) under improved fallow management systems at 0-5 cm depth in 1993.

Management	Ca	Mg	K	Mn	Ca	Mg	K
	$cmol^+ kg^{-1}$				$kg\ ha^{-1}$		
0-5 cm							
sec. Forest	12.2	2.33	0.85	0.000	1385	159	188
Westbank 3							
Ctrl	5.94	0.66	0.21	0.000	677	45	47
Leucaena	5.24	0.73	0.26	0.000	597	50	57
Pueraria	6.78	1.00	0.27	0.000	772	68	61
Nat. regrowth	6.87	0.90	0.26	0.000	782	62	58
D 2							
Ctrl	1.75	0.48	0.23	0.008	193	32	50
Leucaena	1.48	0.35	0.30	0.020	163	23	65
Senna	3.00	0.55	0.37	0.008	332	37	80
Westbank 1							
Ctrl	1.30	0.39	0.17	0.007	124	22	32
Leucaena	5.57	1.64	0.46	0.001	531	94	86
Senna	7.3	1.29	0.67	0.000	695	74	124
Pueraria	2.71	0.72	0.15	0.003	258	41	28
Nat. regrowth	3.30	1.02	0.24	0.003	314	58	45
LSD	1.87	0.43	0.15	ns	134	19	22

LSD (excluding forest) at $\alpha = 0.05$

Trends, however, reveal a higher nutrient status 4 years after fallowing with pueraria and natural regrowth compared to the control treatments. Investigations by Kang et al. (1981), Wilson et al. (1982), Lal (1989), and Hulugalle et al. (1990) confirmed an increase of

exchangeable cations by alley cropping treatments compared to a no-tree control due to nutrient "pumping" from deeper layers. Wade and Sanchez (1983) reported similar results for acid Ultisols in Peru, where pueraria cover maintained nutrient concentrations similar to an unmulched but fertilized treatment.

The proposed critical Mg:K ratio of 2 or less beyond which Mg-uptake by maize fell sharply (Lombin and Fayemi, 1976) was reached under leucaena and senna alley cropping in the 0-5 cm and 5-10 cm layer at D 2 (Table 23 and Table 5 of the Appendix), for senna fallowing at WB 1 (both depths), and for leucaena and natural regrowth at 5-10 cm depth. Similar to the continuous cropping control at D 2 (Table 8) K may likely have suppressed Mg-uptake.

Exchangeable manganese was only found at both the degraded Westbank 1 and D 2 sites (Table 17 and Table 4 of the Appendix).

4.2.4.2 Bray-I phosphorus

Data on available Bray-I phosphorus (µg g^{-1}) under improved fallow management systems in the 0-5 cm and 5-10 cm layer, corrected for bulk density and gravel content (kg ha^{-1}) are shown in Table 24 and Table 6 of the Appendix, respectively.

The introduction of improved fallow management systems at the sites did not cause any clear trend. At both WB 3 and WB 1 they generally did not sustain significantly higher Bray-I inorganic phosphorus contents than in the control treatments. As an exception, the 2:1 year rotation of natural regrowth and maize/cassava intercropping at the non-degraded WB 3 was significantly higher during the 1st cropping season as compared to continuous cropping. The introduction of senna fallow for four years at Westbank 1 also led to significant higher available Bray-I phosphorus contents during the 1st cropping season at 0-5 cm depth. The likelihood of enhanced phosphorus availability at sites with improved residue managements is discussed by several authors. One of the mechanisms advanced to explain the increased P-availability when the soil is amended with organic residues is the prevention of P-adsorption by soil minerals due to released organic anions competing for P-adsorption sites (Singh and Jones, 1976; Iyamuremye and Dick, 1996). Investigations by Sharif et al. (1974) showed that inorganic P could be used more efficiently in soil that had received animal manure. The authors further hypothesized that organic matter may increase the availability of inorganic P by suppressing the conversion of inorganic P to less soluble compounds.

Table 24. Available Bray-I phosphorus (μg g^{-1} and kg ha^{-1}) under improved fallow management systems at 0-5 cm depth in 1993 and 1994.

	Bray-I P (μg g^{-1})			Bray-I P (kg ha^{-1})		
site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
0-5 cm						
sec. Forest	25.7	30.7	29.2	14.3	15.5	16.6
Westbank 3						
Ctrl	5.0	3.6	5.4	3.0	2.1	3.1
Leucaena	6.3	3.9	8.6	3.7	2.2	4.9
Pueraria	5.8	4.3	8.6	3.5	2.5	4.9
Nat. regrowth	9.6	5.6	fallow	5.9	3.2	fallow
D 2						
Ctrl	24.2	25.8	29.5	12.8	14.3	15.1
Leucaena	11.6	17.2	20.9	5.6	9.5	11.5
Senna	19.9	18.8	29.1	10.4	10.4	14.8
Westbank 1						
Ctrl	5.9	5.1	6.0	3.0	2.4	2.8
Leucaena	7.6	3.1	4.6	3.8	1.5	2.2
Senna	17.7	8.9	11.3	7.7	4.3	5.3
Pueraria	7.8	5.1	8.0	4.0	2.4	3.6
Nat. regrowth	8.3	3.3	5.5	3.8	1.5	2.6
LSD	3.3	6.2	8.4	1.7	3.4	3.9

LSD (excluding forest) at $\alpha = 0.05$

Singh and Jones (1976) concluded that organic materials with high phosphorus concentrations may increase the amount of P in soil solution due probably to a higher contribution of mineralized P. The likelihood of differences in the availability of phosphorus is also supported by Le Mare et al. (1987). No differences in Bray-I P were found on a dark-red latosol in Brazil between green manured and unmanured treatments. However, amendments with pueraria increased the proportion of added P that was exchanging between soil particles and solution. The authors assumed that the adsorbed phosphorus was more labile under green manured than under unmulched sole cropping due to a change of the phosphorus kinetics in the soil (Le Mare et al., 1987).

Generally, inorganic Bray-I extractable phosphorus at D 2 was significantly higher than at the Westbank 1 and Westbank 3 sites (Chapter 4.1.4.2). The introduction of improved

fallow management systems at D 2, however, did not lead to higher inorganic Bray-I phosphorus concentrations when compared to the continuous cropping control. In fact, both alley cropping systems with leucaena and senna had significantly lower inorganic Bray-I phosphorus than the continuous cropping control. This is in accordance to results reported by Van der Meersch (1992) and Haggar et al. (1991) for D 2 and at CATIE, Costa Rica, respectively. Both authors concluded that the hedgerow trees competed with the crops for phosphorus in unfertilized systems. Moreover, Haggar et al. (1991) reported that alley cropping for seven years maintained P-levels in the soil that were lower compared to other treatments and assumed that there was a net removal of phosphorus from the soil by the hedgerow-trees.

4.2.4.3 $NaHCO_3$- and NaOH-extractable inorganic and organic phosphorus pools

Data on $NaHCO_3$- and NaOH-extractable inorganic and organic phosphorus pools are the mean of 3 sampling dates at 0-5 cm and 5-10 cm depth (January, May and August) in 1994 and are summarized in Table 25 and Table 7 of the Appendix, respectively.

At Westbank 3 no significant differences were obtained between the improved fallow managements and continuous cropping. At D 2, however, the introduction of leucaena and senna alley cropping led to a significant reduction of extractable $NaHCO_3$-P_i, which is discussed for Bray-I-P in Chapter 4.2.4.2. At the most degraded WB 1 site only senna fallowing for four years significantly increased $NaHCO_3$-P_i compared to continuous cropping, whereas leucaena, pueraria, and natural regrowth fallowing was not significantly different from the control. The introduction of improved fallow management systems at all sites had no impact on the $NaHCO_3$-extractable organic phosphorus pool as compared to the controls. This is in agreement with results reported by Tiessen et al. (1991, 1992) for semi-arid northeastern Brazil and northern Ghana. Similar results were obtained for the NaOH-extractable organic P-pool. The introduction of woody and herbaceous legumes at WB 3 and D 2 was not significantly different from continuous cropping. These results are consistent with investigations by Paniagua et al. (1995) and Beck and Sanchez (1994). A decline of NaOH-organic phosphorus was found under non-fertilized but mulched plots when compared to fertilized treatments (Paniagua et al., 1995). Beck and Sanchez (1994) postulated that the incorporation of erythrina and gliricidia prunings in alley cropping systems on a typic Paleudult in Costa Rica had no effect on the organic phosphorus pools. Both authors concluded that inorganic phosphorus fertilization rather than organic

additions regulated the size and distribution of organic phosphorus accumulation. However, in our experiment planted senna fallow at Westbank 1 for four years resulted in significantly higher organic P when compared to continuous cropping, thus implying a contribution of P from the prunings to the soil organic phosphorus pool.

Table 25. $NaHCO_3$ (1) and NaOH -extractable inorganic and organic phosphorus pools (µg g^{-1} and kg ha^{-1}) under improved fallow management systems at 0-5 cm depth in 1994.

site/depth	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}
	µg g^{-1}				kg ha^{-1}			
0-5 cm								
sec. Forest	19.9	22.4	24.3	62.9	9.3	11.9	11.1	38.9
Westbank 3								
Ctrl	13.2	14.0	8.3	46.1	6.3	7.6	4.6	26.3
Leucaena	8.5	22.5	9.3	44.8	4.8	12.1	5.3	25.6
Pueraria	8.9	14.7	7.7	37.0	4.8	8.4	4.3	21.1
D 2								
Ctrl	28.1	41.6	11.4	70.2	13.2	23.0	6.2	38.8
Leucaena	15.3	37.1	11.7	60.7	8.1	20.5	6.2	33.5
Senna	19.2	41.3	9.3	63.1	9.6	22.8	5.3	34.9
Westbank 1								
Ctrl	9.1	30.5	11.8	62.5	3.9	14.5	5.5	29.7
Leucaena	8.8	21.8	10.5	68.3	4.2	10.5	5.0	32.5
Senna	18.6	46.3	9.3	87.2	8.8	22.3	4.4	41.5
Pueraria	9.0	26.3	9.9	57.9	4.2	12.4	4.7	26.8
Nat. regrowth	8.1	21.7	9.7	54.4	3.7	10.8	4.5	27.5
LSD	10.7	16	2.5	19.5	5.9	8.7	ns	10.3
P contrasts(2)								
D 2: Ctrl vs. Senna	0.007							
WB 1: Ctrl vs. Senna	0.006							

LSD (excluding forest) at $\alpha = 0.05$;
(1) = includes resin extractable P;
(2) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

In general, Westbank 3 tended to sustain smaller mean organic phosphorus pools as compared to the degraded sites at D 2 and Westbank 1, irrespective of cropping system (which is in accordance with the data obtained for the continuous cropping control).

4.2.5 Microbial biomass under improved fallow managements

4.2.5.1 Microbial biomass carbon

The effect of improved fallow management systems at WB 3, D 2, and WB 1 on soil microbial biomass (μg g^{-1}) is illustrated in Table 26. Microbial biomass (kg ha^{-1}) corrected for bulk density and gravel content is depicted in Table 8 of the Appendix.

At Westbank 3, mean microbial biomass under pueraria was significantly higher at both depths than in the continuous cropping except during the dry season at 5-10 cm depth. The introduction of leucaena hedgerow intercropping and the 2:1 year rotation of natural regrowth and maize/cassava intercropping were not significantly different from the continuous cropping control. The beneficial impact of pueraria on microbial biomass was also consistent with results reported by Mulongoy and Bedoret (1989) for an Ultisol in southern Nigeria.

Pueraria at Westbank 3 developed both a thick leaf canopy and a dense rooting down to 50 cm soil depth (Vielhauer and Hauser, 1995). The annual dry matter production of pueraria was reported as 1.5-9.5 t ha^{-1} $year^{-1}$ with a maximum rate of dry matter accumulation at 12-18 months after planting (Mulongoy and Akobundu, 1992; Vesterager et al., 1995; Luna-Orea et al., 1996). The litter of pueraria probably returned organic material and nutrients to the soil to favorably contribute to microbial biomass growth. The dense rooting pattern added to this effect by high production of root exudates and root litter.

At D 2 the introduction of leucaena alley cropping did not significantly improve the microbial biomass which is in accordance with the results obtained for organic carbon (Table 23). Senna maintained significantly higher soil microbial biomass in the top 5 cm at both cropping seasons, whereas at 5-10 cm depth only significantly higher microbial biomass was sustained during the 2nd cropping season. No difference with the continuous cropping control was obtained for the dry season. Microbial biomass levels of the secondary forest were not maintained under the improved fallow managements at Westbank 3 and D 2. The smallest decrease (34 %) was found after 4 years under pueraria at WB 3 and the largest decrease by 75 % after 10 years under leucaena at D 2.

Table 26. Average soil microbial biomass carbon (µg C g^{-1} soil) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Microbial biomass (µg g^{-1})					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	291	234	359	141	122	186
Westbank 3						
Ctrl	145	115	147	80	86	75
Leucaena	158	154	192	78	74	91
Pueraria	220	207	238	126	120	140
Nat. regrowth	153	169	fallow	102	87	fallow
D 2						
Ctrl	93	61	61	47	71	39
Leucaena	137	108	83	68	73	38
Senna	169	102	129	74	101	78
Westbank 1						
Ctrl	72	58	58	51	52	41
Leucaena	137	111	122	76	92	48
Senna	165	109	144	78	81	63
Pueraria	101	63	83	57	84	52
Nat. regrowth	102	73	103	57	54	60
LSD	60.9	73.5	48.5	32.3	ns	29

LSD (excluding forest) at $\alpha = 0.05$

The effect of long-term organic residue additions on microbial biomass to 4 annual maize-bean rotations in the humic tropics of Costa Rica was studied by Mazzarino et al. (1993). Two alley cropping systems with erythrina and gliricidia pruning mulch resulted in significantly higher microbial biomass than in the no tree controls (Mazzarino et al., 1993). However, the increase in microbial biomass was only 20 % after 9 years of pruning addition. Mazzarino et al. (1993) concluded that the differences between alley cropped (62 µg g^{-1}) and control treatments (50 µg g^{-1}) were rather small considering that in the alley cropping 3-6 times higher cumulative additions of organic C were applied than in the no-tree controls.

Similar results were reported by Sakamoto and Oba (1991) for various soils in Japan. The increase of microbial biomass did not remain constant under continuous application of organic material. The increase of microbial biomass (ATP-content, direct microscopy method) was higher in fields with short term application of organic material (4 years) as compared to long-term application for 10-12 years. This was attributed to an increased demand of maintenance energy of the microbial cells, and an increased inhibitory effect of toxic substances contained in the organic amendments.

According to Suttner (1990) microbial activities in soil increase with increasing amounts of total SOM. However, if adequate organic carbon is available in the soil the microbial biomass is not dependent upon freshly amended organic additions and subsequent decomposition. Soils that are deficient in total SOM, organic substrates are mineralized much faster because the C-content is the limiting factor for microbial growth. Thus, Suttner (1990) concluded from straw amended trials under temperate conditions in Germany that the decomposition after 1 year was dependent on total SOM present in soil rather than new organic additions.

At the most degraded Westbank 1 site improved fallows for 4 years significantly increased microbial biomass under both leucaena and senna in the 0-5 cm layer during the 1st and 2nd cropping season. No statistically significant differences could be found for the dry season sampling. Organic carbon contents, however, were significantly improved by all treatments (Table 22). At 5-10 cm depth, improved fallow did not significantly enhance microbial biomass over the continuously cropped control treatments. Pueraria and natural regrowth fallowing for 4 years did not lead to significantly higher microbial biomass compared to continuous cropping, probably since direct organic amendments by either root or leaf litter stopped after slashing and burning in 1993. The lower level of microbial biomass following pueraria and natural regrowth fallow was attributed to the reduced input of plant residues and hence organic carbon by maize and cassava crops. Thus, the nutrient poor site and the unfavorable physical and chemical residue quality did not allow for higher microbial biomass levels. Leucaena and senna hedgerows were not burnt completely and removed from the plots after clearance in 1993. The hedges still coppiced and could contribute organic substrates to the microbial biomass by decaying below and aboveground plant biomass.

The seasonal course of the microbial biomass at WB 3, D 2, and WB 1 in the top 5 cm is displayed in Figure 12.

Seasonal fluctuations due to environmental conditions are already discussed in more detail in Chapter 4.1.5.1. As depicted in Figure 12, highest levels of microbial biomass were consistently found under pueraria and senna at Westbank 3 and, D 2 and Westbank 1, respectively. Control treatments had lowest levels of biomass. During the dry season the microbial biomass tended to converge at a reduced level in all treatments. Our results obtained at WB 3 (top) and D 2 (middle) showed an higher increase of biomass under improved fallow managements as the season went on than under the control, which might be attributed to the supply of nutrients and organic carbon by pruning application. Van der Meersch (1992), however, reported a decrease in soil microbial biomass during the first 60-70 days of maize growth at D 2. She inferred that the application of organic substrates by prunings could not compensate for the competition by roots and microbial biomass for nutrients during early maize growth. At WB 3 and D 2 seasonal patterns under improved fallow managements and continuously cropping controls were similar in all treatments and support findings by Mazzarino et al. (1993) for 2 alley cropping treatments with erythrina and gliricidia and 2 no-tree controls in Costa Rica. Seasonal pattern were similar in all treatments. There was no apparent effect of the addition of prunings in the short term. Both Mazzarino et al. (1993) and McGill et al. (1986) suggested that the effects of organic residues on the active soil organic matter are cumulative and become more pronounced after long-term applications. At the most degraded WB 1 site less pronounced seasonal dynamics in microbial biomass was obtained for senna fallowing for 4 years prior to cropping in 1993. The microbial biomass under continuous cropping and pueraria remained rather stable and at a minimum level due to poor substrate availability.

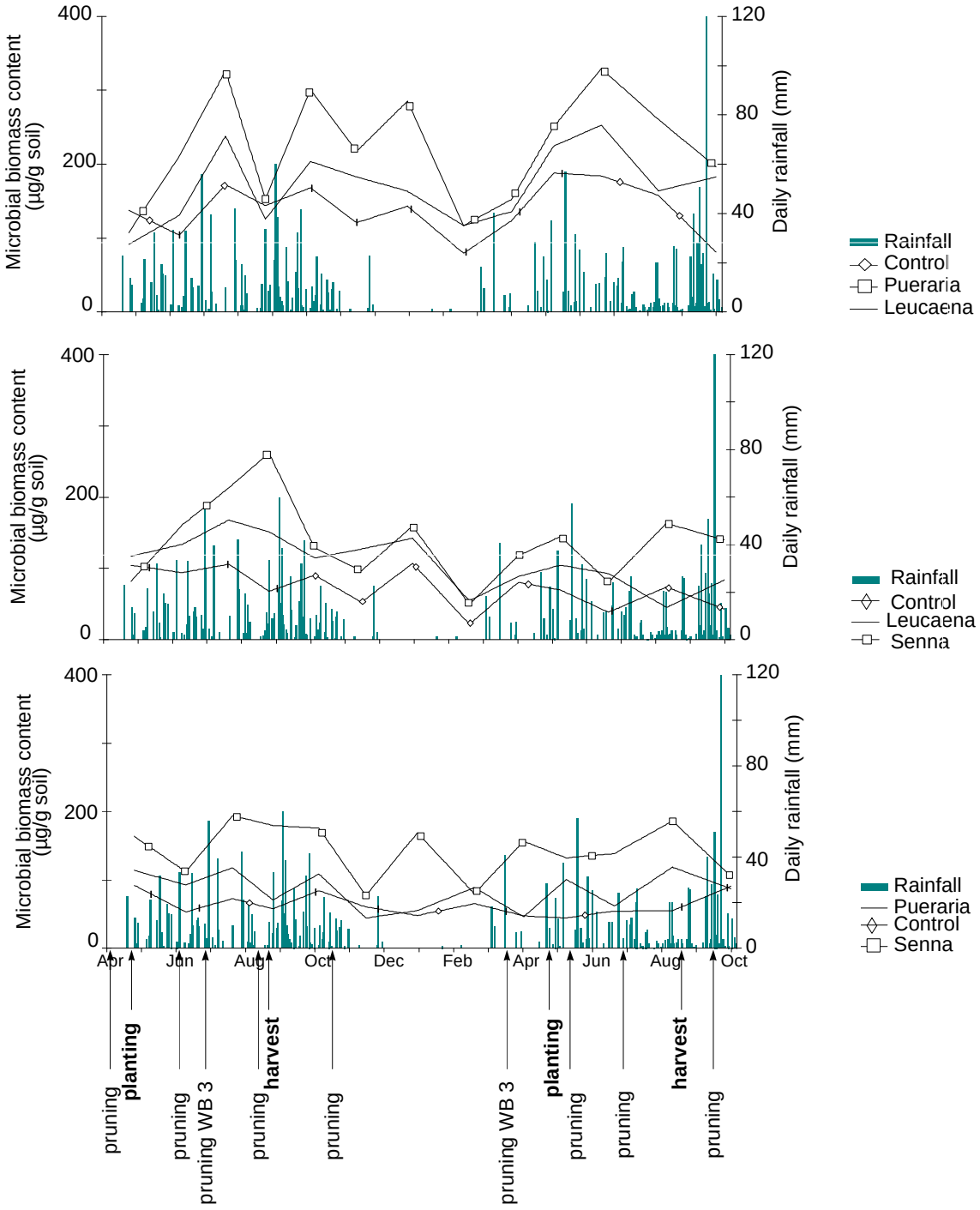


Figure 12. Seasonal course of microbial biomass (µg g^{-1}) at WB 3 (top), D 2 (middle), and WB 1 (bottom) in the 0-5 cm layer ("pruning" applies only for leucaena at Westbank 3 and for senna and leucaena at D 2; "pruning WB 3" means that none was applied to D 2 at that time).

4.2.5.2 C_{mic}/C_{org} ratio (%)

The proportion of soil organic carbon tied up in the microbial biomass (% C_{mic}/C_{org} ratio) at 0-5 cm and 5-10 cm depth is summarized in Table 27.

There was no significant effect of improved fallow managements on the C_{mic}/C_{org} ratio at the 5 % level for the least degraded WB 3 site.

Table 27. C_{mic}/C_{org} ratio (%) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	C_{mic}/C_{org} (%)					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	0.85	0.76	1.22	0.6	0.58	0.89
Westbank 3						
Ctrl	0.93	0.79	0.9	0.87	0.95	0.81
Leucaena	0.93	0.82	1.00	0.93	0.71	0.8
Pueraria	0.99	1.01	1.08	1.03	0.87	1.01
Nat. regrowth	0.78	0.96	fallow	1.15	0.77	fallow
D 2						
Ctrl	0.94	0.69	0.55	0.64	0.87	0.37
Leucaena	1.21	0.81	0.63	0.91	0.9	0.37
Senna	1.33	0.8	0.88	0.8	1.37	0.73
Westbank 1						
Ctrl	0.83	0.55	0.6	0.62	0.62	0.41
Leucaena	0.66	0.77	0.73	0.69	1.12	0.44
Senna	1.00	0.67	0.73	0.53	0.85	0.49
Pueraria	0.66	0.45	0.49	0.58	1.01	0.45
Nat. regrowth	0.65	0.61	0.64	0.58	0.62	0.37
LSD	1.07	ns	0.77	0.76	ns	0.76
P contrasts (1)						
D 2: Ctrl vs. Leuc	0.003					
D 2: Ctrl vs. Senna	0.003					

LSD (excluding forest) at $\alpha = 0.05$;
ns = not significant at 5 % level;
(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

The C_{mic}/C_{org} ratio under leucaena and senna alley cropping at D 2 was only significantly higher during the 1st cropping season at 0-5 cm depth than under the control. C_{mic}/C_{org} ratios at D 2 were higher in 1993 than in 1994 irrespective of fallow management. WB 1, generally, had the lowest C_{mic}/C_{org} ratios of the three sites when compared to secondary forest and was particularly so for pueraria and natural regrowth. The low C_{mic}/C_{org} ratio could be due to low plant biomass input and subsequent dependence of the soil microbial biomass on more stable organic complexes in order to meet their C and N demand. Changes in the ratio at WB 1 reflected the time course of the microbial biomass (Table 26) more closely than that of total SOM (Table 22). Total SOM was 2-4 t/ha higher in the plots that were planted to improved fallows for four years than in the continuously cropped plots.

Similar trends were obtained by Fugger (1997) for calopogonium and pueraria covers in northern Ghana, showing that the seasonal course of the C_{mic}/C_{org} ratio was identical with that of the microbial biomass.

Following the addition of organic amendments, however, small quantitative changes of soil microbial biomass are superimposed by concomitant small changes of soil organic carbon due to the proportional higher quantity of the latter fraction, and will result in a lower C_{mic}/C_{org} ratio. This problem was also stressed by Sakamoto and Oba (1991). They reported for tropical gray lowland soils (dystric Fluvisols), light-colored Andosols (ochric Andosols) and humic Andosols in Japan that the C_{mic}/C_{org} ratio was lower in a field with high total C-contents than in a field with low total C-contents, while the opposite was true for biomass-C.

Also under a range of pasture sites in New Zealand the soils showed a marked decline in the C_{mic}/C_{org} ratio from 1.7 % to 0.29 % upon increase of organic carbon from 5.7 % to 30.4 %, whereas the microbial biomass (substrate-induced-respiration) showed no consistent trend (Sparling, 1992). The author suggested that stabilized C in the organic carbon fraction can greatly influence the C_{mic}/C_{org} ratio, even in soils with similar mineralogy, vegetation, and climate.

Suttner (1990) reported for agricultural, pasture, and nature reserve soils under temperate conditions in Germany that the C_{mic}/C_{org} ratio did not conclusively reflect the C-status of the soils. Whether soils are accumulating or loosing total SOM are likely to be established only from long-term developments of microbial biomass and related activities, rather than single ratios (Suttner, 1990).

4.2.6 Acid and alkaline phosphatase

4.2.6.1 Acid phosphatase

The average activity of acid phosphatase as affected by improved fallow management treatments is given in Table 28, the seasonal course at Westbank 3, D 2, and Westbank 1 is displayed in Figure 13.

Table 28. Average acid phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Acid phosphatase activity (µg p-nitrophenol $g^{-1} h^{-1}$)					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	450	676	618	370	520	450
Westbank 3						
Ctrl	195	313	192	139	276	179
Leucaena	243	407	367	173	240	220
Pueraria	316	448	401	240	348	247
Nat. regrowth	208	352	fallow	134	218	fallow
D 2						
Ctrl	312	285	275	196	252	196
Leucaena	378	425	311	298	380	220
Senna	353	421	308	258	336	218
Westbank 1						
Ctrl	291	351	273	247	412	232
Leucaena	398	453	324	343	394	280
Senna	272	395	282	299	370	268
Pueraria	391	356	346	256	303	236
Nat. regrowth	351	367	351	306	395	294
LSD	ns	ns	118	134	104	ns
P contrasts(1)						
WB 3: Ctrl vs. Puer				0.000		
D 2: Ctrl vs. Leuc				0.000		
D 2: Ctrl vs. Senna				0.007		
WB 1: Ctrl vs. Leuc				0.000		

LSD (excluding forest) at $\alpha = 0.05$

(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

At Westbank 3 pueraria had significantly higher acid phosphatase activities during the 2nd cropping season at 0-5 cm depth and during the 1st season at 5-10 cm depth. This seems to indicate a higher P- demand of pueraria plants combined with crops, than for the crop alone. Leucaena alley cropping exhibited a significantly higher acid phosphatase activity only during the 2nd season sampling at 0-5 cm depth. The 2:1 year rotation of natural regrowth and maize/cassava intercropping was not statistically different from the control. At D 2 no significant differences between either alley cropping treatment and sole cropping was found in the top 5 cm. At 5-10 depth leucaena and senna alley cropping were significantly higher in acid phosphatase activity during both the 1st and the dry season.

At the most degraded WB 1 site senna and natural regrowth fallowing for 4 years prior to cropping did not significantly increase acid phosphatase activity compared to continuous cropping. Leucaena soil samples were significantly higher in activity only during the 1st season at 0-5 cm depth, while acid phosphatase activity in the pueraria soil samples were significantly lower than in the control during the dry season at 5-10 cm depth.

Similar to the continuous cropping controls, the results obtained did not reveal any relation between the P-availability at the sites and the impact of management on phosphatase activity. This aspect is discussed in more detail in Chapter 4.1.6.1.

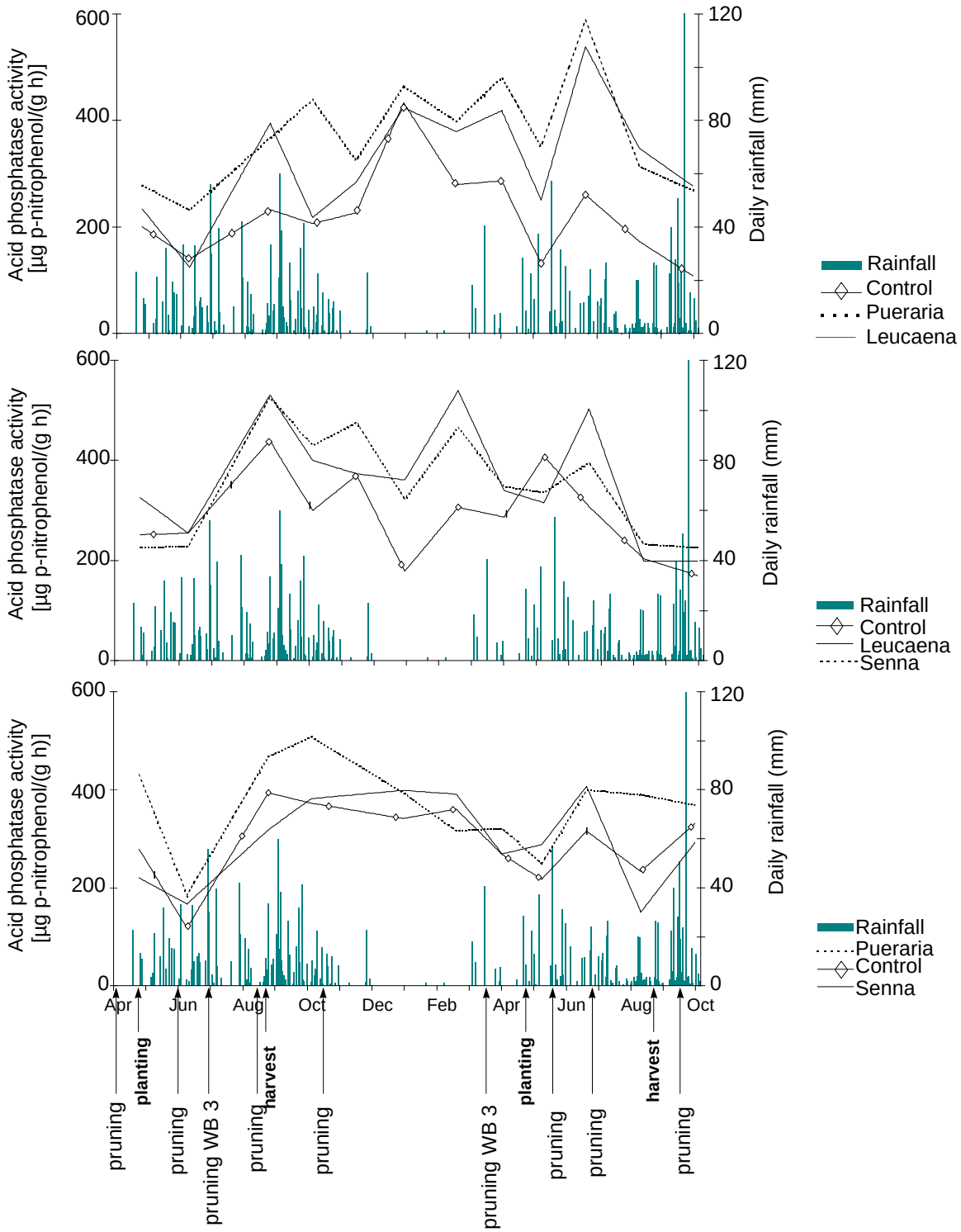


Fig. 13. Seasonal course of acid phosphatase activity (µg p-nitrophenol g^{-1} h^{-1}) at WB 3 (top), D 2 (middle), and WB 1 (bottom) in the 0-5 cm layer ("pruning" applies only for leucaena at Westbank 3 and for senna and leucaena at D 2; "pruning WB 3" means that none was applied to D 2 at that time).

4.2.6.2 Alkaline phosphatase

The average activity of alkaline phosphatase as affected by improved fallow management systems at the different cropping sites is summarized in Table 29, the seasonal course is displayed in Figure 14.

Table 29. Average alkaline phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Alkaline phosphatase activity (µg p-nitrophenol $g^{-1} h^{-1}$)					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	740	631	611	522	508	399
Westbank 3						
Ctrl	341	365	242	250	293	178
Leucaena	394	422	333	258	258	183
Pueraria	541	555	428	349	400	225
Nat. regrowth	437	448	fallow	249	276	fallow
D 2						
Ctrl	139	135	127	55	77	59
Leucaena	219	173	156	128	120	52
Senna	270	191	190	149	116	112
Westbank 1						
Ctrl	104	122	102	139	136	120
Leucaena	324	210	254	173	167	149
Senna	316	271	268	212	200	222
Pueraria	178	122	132	111	105	75
Nat. regrowth	222	149	152	150	161	148
LSD	157	70	114	108	66	84
contrasts						
WB 3: Ctrl vs. Puer				0.003		
D 2: Ctrl vs. Senna	0.012			0.01		

LSD (excluding forest) at $\alpha = 0.05$

(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

Except for the 5-10 cm layer during the 2nd cropping season, the introduction of pueraria at WB 3 significantly increased alkaline phosphatase activity at both depths compared to the continuous cropping controls. This is consistent with the results obtained for microbial biomass (Table 26). Mulongoy and Bedoret (1989) also found higher alkaline phosphatase activity (65 μg g^{-1}) under pueraria cover in an Ultisol in southern Nigeria than under leucaena, treculia (27 μg g^{-1}) and secondary forest (20 μg g^{-1}) at IITA, Nigeria, although the activities were lower than our results obtained in 1993 and 1994. No statistically significant difference in activity at 0-5 cm and 5-10 cm depth was observed between the control and leucaena. The activity of alkaline phosphatase under the 2:1 year rotation of natural regrowth and maize/cassava intercropping was only significantly higher during the dry season at 0-5 cm depth than under continuous cropping. No significant difference was found at 5-10 cm depth.

Alkaline phosphatase activity under leucaena alley cropping at D 2 was not statistically different from continuous cropping. Senna alley cropping supported a statistically higher alkaline phosphatase activity during the 1st cropping season at both depths, and is similar to the results obtained for microbial biomass.

The introduction of planted fallows with leucaena, senna, pueraria, and natural regrowth at the most degraded Westbank 1 site for 4 years consistently and significantly increased alkaline phosphatase activity in the 0-5 cm layer under both leucaena and senna. At 5-10 cm depth alkaline phosphatase activity was only significantly improved with senna fallowing during the 1st and 2nd cropping season. No significant difference was obtained for the dry season. Similar to microbial biomass, alkaline phosphatase activity under pueraria and natural regrowth fallowed for 4 years was not different from continuous cropping. This was attributed to lower microbial biomass due to reduced plant biomass input.

As depicted in Figure 14, alkaline phosphatase activity did not fluctuate highly and remained rather stable at high activities in comparison with microbial biomass (Figure 12).

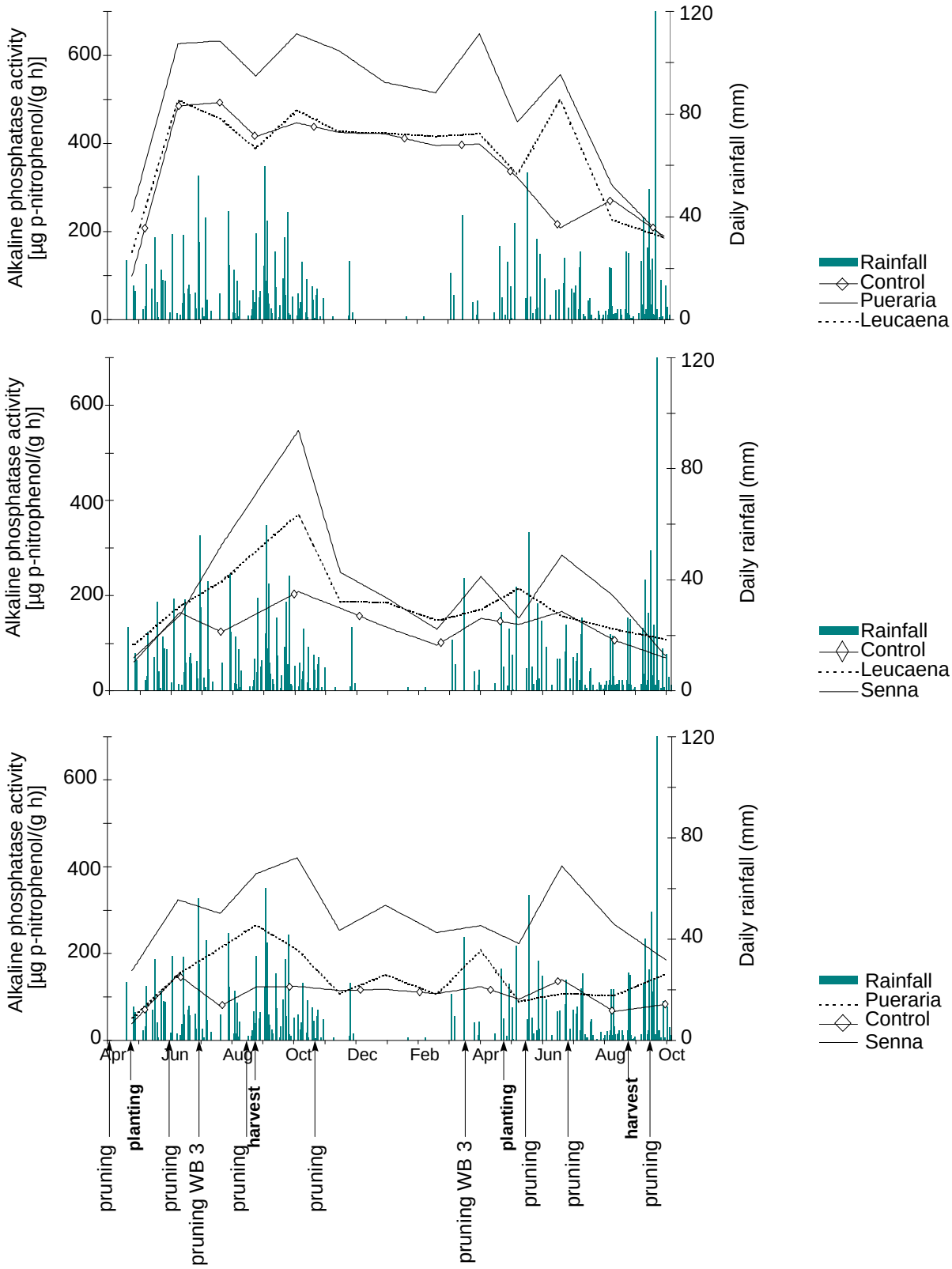


Figure 14. Seasonal course of alkaline phosphatase activity (µg p-nitrophenol g^{-1} h^{-1}) at WB 3 (top), D 2 (middle), and WB 1 (bottom) in the 0-5 cm layer ("pruning" applies only for leucaena at Westbank 3 and for senna and leucaena at D 2; "pruning WB 3" means that none was applied to D 2 at that time).

The impact of organic residue management on alkaline phosphatase activity is discussed controversially in the literature. It was found that cropping systems with higher C-inputs (manure and pea vine) promoted enzyme activity due to enhanced protection of abiontic enzymes (= not associated with viable cells) in the humic complexes of these soils (Dick et al., 1988; Dick, 1994). Increased alkaline phosphatase activity due to long-term applications of manure and pea vine in northwestern USA by 190 % over the control treatments were attributed to greater biological activity and consequently higher enzyme activities accumulated in the soil matrix (Dick et al., 1988). Martens et al. (1992) reported that repeated additions of organic residues (pea vine, 2.4 t ha^{-1}) only increased enzyme activity for the first two additions. The third and fourth addition failed to increase enzyme activity any further due probably to a balance between promoter and feedback mechanisms that favor a constant level of enzyme activity upon regular organic additions (Martens et al., 1992).

4.2.7 ß-Glucosidase

The impact of improved fallow managements on ß-glucosidase activity at WB 3, D 2, and WB 1 in the 0-5 cm and 5-10 cm layer is illustrated in Table 30, the seasonal course in the 0-5 cm layer is depicted in Figure 15.

The introduction of pueraria live mulch at WB 3 significantly increased the activity of ß-glucosidase throughout the research period at both depths as compared to continuous cropping control. This is in line with the results obtained for organic carbon and microbial biomass under simultaneous cropping of pueraria with maize/cassava. Pueraria improved organic carbon (Table 22) and microbial biomass (Table 26) most, as compared to the other treatments and sites. Pueraria at WB 3 developed a thick leaf canopy and dense rooting zone up to 50 cm deep. Thus, accumulation of easily decomposable litter on and beneath the soil surface may have stimulated microbial biomass activity and, hence, enzyme synthesis. Leucaena alley cropping significantly increased ß-glucosidase activity in the top 5 cm during the dry season and 2nd season. The 2:1 year rotation of natural regrowth and maize/cassava intercropping only significantly improved ß-glucosidase in the dry season at 0-5 cm depth (Table 30; Figure 15).

Senna alley cropping at D 2 significantly increased ß-glucosidase activity throughout the sampling period at both depths as compared to the continuous cropping control. Alley cropping with leucaena also significantly improved the activity of ß-glucosidase during the

1st and the dry season as compared to sole cropping. However, no difference in activity was found during the 2nd cropping period at both 0-5 cm and 5-10 cm depth.

Table 30. Average ß-glucosidase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	ß-glucosidase (µg p-nitrophenol g^{-1} h^{-1})					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	169	181	180	49	55	62
Westbank 3						
Ctrl	50	59	47	21	20	19
Leucaena	70	105	79	23	27	20
Pueraria	101	116	120	41	52	44
Nat. regrowth	56	87	fallow	20	23	fallow
D 2						
Ctrl	47	49	44	15	13	16
Leucaena	83	82	62	42	26	13
Senna	97	81	76	44	27	23
Westbank 1						
Ctrl	36	30	31	22	12	22
Leucaena	85	74	68	35	23	28
Senna	95	83	65	47	38	28
Pueraria	43	38	36	19	17	30
Nat. regrowth	66	37	41	21	17	21
LSD	43	28	42	24	13	15
P contrasts (1)						
WB 3: Ctrl-vs. Puer				0.000		
WB 3: Ctrl vs. Leuc			0.008			
D 2: Ctrl vs. Leuc	0.006					
D 2: Ctrl vs. Senna			0.008			0.008
WB 1: Ctrl vs. Leuc			0.003			
WB 1: Ctrl vs. Senna			0.005			

LSD (excluding forest) at $\alpha = 0.05$

(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

The introduction of planted fallows with leucaena, senna, pueraria, and natural regrowth at the most degraded WB 1 site only significantly improved ß-glucosidase activity with leucaena and senna fallowing. In the top 5 cm leucaena and senna significantly enhanced ß-glucosidase activity throughout the research period. In the 5-10 cm layer this trend was not as consistent as in the top 5 cm. Leucaena was not significantly different from continuous cropping, while senna had significantly higher activities during both the 1st and the dry season. Pueraria and natural regrowth were not significantly different from continuous cropping in ß-glucosidase levels.

Similar to our results for pueraria at WB 3 the application of both red clover as green manure in rotational cropping systems at Oregon, USA (Miller and Dick, 1995) and pea vine residue treatments (2.24 t ha^{-1} $year^{-1}$; Dick et al., 1988) was also found to significantly enhance ß-glucosidase activity as compared to mineral fertilizer treatments. Due to a more favorable environment the enzymes of the soil matrix could accumulate by forming stable complexes with soil organic matter, whereas improved conditions for the soil biota by the organic matter applied may have stimulated enzyme production (Miller and Dick, 1995; Dick et al., 1988).

At all three sites, ß-glucosidase activity did not decline during the dry season (Figure 15) and is discussed in more detail in Chapter 4.1.7.

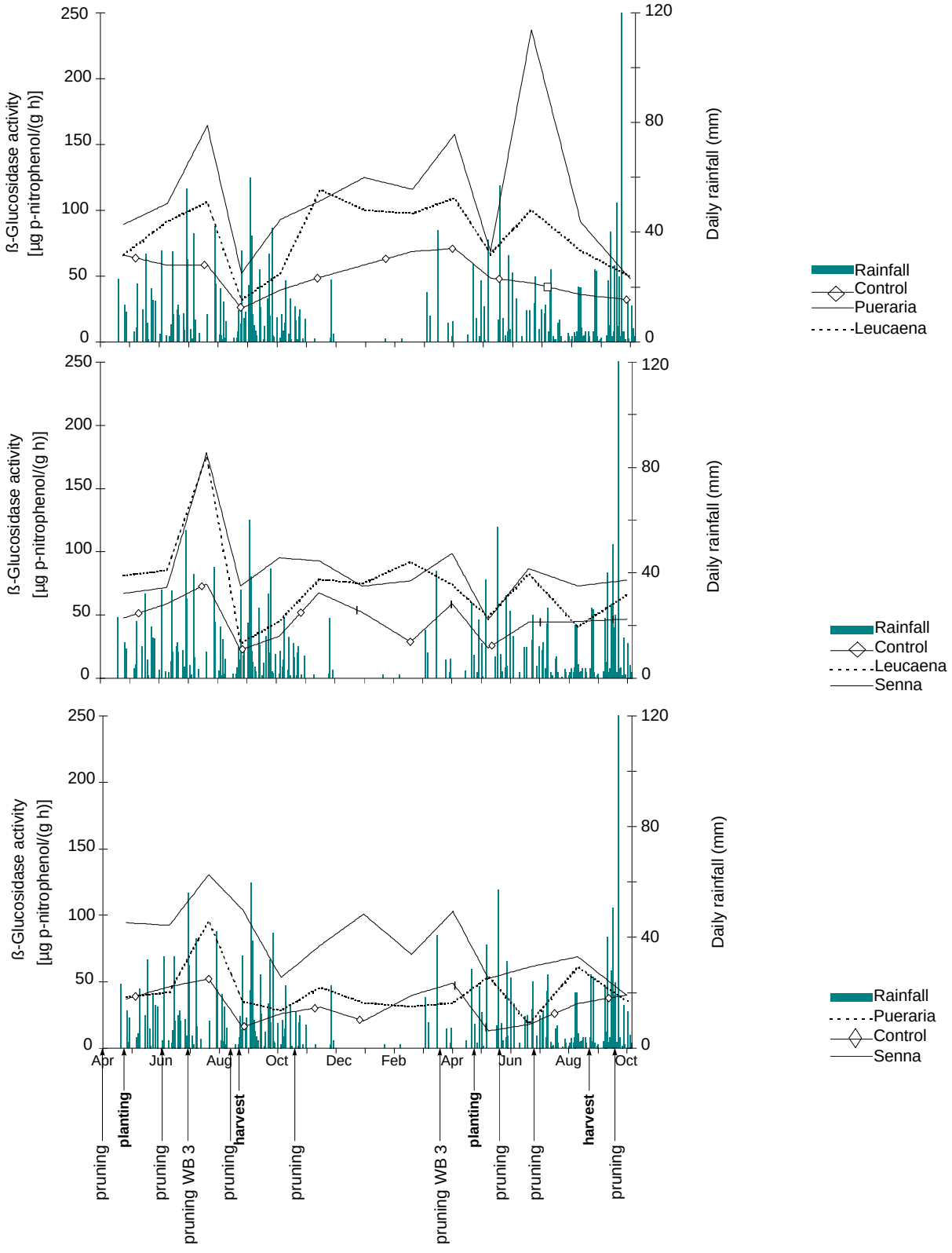


Figure 15. Seasonal course of ß-glucosidase activity (µg p-nitrophenol g^{-1} h^{-1}) at WB 3 (top), D 2 (middle), and WB 1 (bottom) in the 0-5 cm layer ("pruning" applies only for leucaena at Westbank 3 and for senna and leucaena at D 2; "pruning WB 3" means that none was applied to D 2 at that time).

The consistent positive effect of senna alley cropping and senna fallowing on ß-glucosidase activity at D 2 and WB 1, respectively, was due probably to the high litter residue quality provided by planted fallow litter or prunings from its hedgerows in alley cropping systems. The cellulose and hemicellulose content of leucaena and senna leaves were reported as 10.3 % and 5.6 %, and as 18 % and 21.6 %, respectively (Tian et al., 1992), thus indicating a higher supply of readily available carbohydrates by senna. This might explain the greater effect of senna on ß-glucosidase levels. However, the chemical composition of the litter input may also influence ß-glucosidase activity and the decomposition of carbohydrates. Polyphenols such as tannins were reported to inhibit ß-glucosidase activity by blocking cellulase access or by direct inhibition of cellulolytic enzymes (Benoit and Starkey, 1968; Swain, 1979 as cited by Tian et al., 1992). The polyphenol content of leucaena and senna leaves was reported as 4.9 % and 1.5 %, respectively (Tian et al., 1992). The lignin and N-content of the residue material appeared to influence ß-glucosidase activity in experiments reported by Roper et al. (1995). They suggested that the growth of cellulolytic bacteria and fungi was impeded by the lignin content of the residue substrates. Thus, plant material with a higher lignin content tended to decompose more slowly. For leucaena lignin levels were reported as 7.1 % at IITA, Nigeria (Tian et al., 1992) or as 16.2 % in Kenya (leaves and twigs; Jama and Nair, 1996), whereas senna contained 6.5 % IITA, Nigeria (Tian et al., 1992) or 16.7 % in Kenya (leaves and twigs; Jama and Nair, 1996). Since the lignin content of leucaena and senna leaves do not differ markedly, it appeared not to impact on the decomposition of carbohydrates by ß-glucosidase.

4.2.8 Protease

Average protease activity as affected by improved fallow management systems in the 0-5 cm layer and 5-10 cm layer is given in Table 31, the seasonal course at 0-5 cm depth is displayed in Figure 16.

At Westbank 3 only pueraria significantly increased protease activity as compared to continuous cropping. Significantly higher protease activities were obtained for the 1st and 2nd cropping season at 0-5 cm depth, and during the dry season at 5-10 cm depth. Leucaena alley cropping and the 2:1 year rotation of natural regrowth and maize/cassava intercropping were not significantly different from continuous cropping.

Although total N under pueraria and leucaena were significantly higher throughout the sampling period in comparison to the control, the protease activity appears not controlled solely by the total amount of organic C and N present at the sites. Tateno (1988) concluded that protease activity in natural soils was not limited by total but by available substrate concentrations, as proteins are bound to SOM or adsorbed to clay minerals, which, in turn reduced their rate of mineralization by 80 to 90 % (Verma et al., 1975).

Table 31. Average protease activity (µg tyrosine g^{-1} soil 2 h^{-1}) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Protease activity (µg tyrosine g^{-1} 2 h^{-1})					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	325	202	230	195	132	150
Westbank 3						
Ctrl	179	82	94	152	75	66
Leucaena	207	116	142	112	102	75
Pueraria	283	115	154	189	129	93
Nat. regrowth	204	130	fallow	133	78	fallow
D 2						
Ctrl	127	39	87	29	41	28
Leucaena	193	98	77	50	46	27
Senna	191	84	124	77	59	57
Westbank 1						
Ctrl	55	15	131	36	21	145
Leucaena	243	68	194	70	24	100
Senna	199	86	171	106	72	106
Pueraria	119	63	174	40	16	100
Nat. regrowth	149	44	151	94	14	119
LSD	92	ns	ns	58	54	ns
P contrasts(1)						
D 2: Ctrl vs. Leuc+Senna	0.004					

LSD (excluding forest) at $\alpha = 0.05$

(1) = α striking significance level of planned contrasts is $\alpha/11 = 0.0045$.

Generally, non-structural proteins such as casein which was used as substrate in our assay is degraded by most bacterial proteases. However, the rate of mineralization is dependent upon the specificity of the enzymes present in soil to decompose specific substrates (Law, 1980).At D 2, leucaena and senna alley cropping significantly enhanced protease activity only during the 1st cropping season at 0-5 cm depth. At the most degraded Westbank 1 site, pueraria fallowing for 4 years did not significantly improve protease activity over the continuous cropping control. Leucaena significantly improved the activity during the 1st cropping season at 0-5 cm depth, whereas natural regrowth and senna had significantly higher protease activity during the 1st season at both depths. The higher activity of protease was attributed to higher available substrates following slashing and burning of the litter in March 1993.

The impact of improved fallow management on protease activity as compared to continuous cropping (Figure 16) may not be simply due to the higher N yields of leguminous plants. Although N yields between 30 and 300 kg ha^{-1} $year^{-1}$ and between 130 and 270 kg ha^{-1} $year^{-1}$ were reported for N-fixing pueraria and leucaena, respectively (Mulongoy and Akobundu, 1992), the importance of the quality of organic additions to N-dynamics in managed ecosystems as stressed by Palm and Sanchez (1991) should be considered as major control factor of protease activity. It was reported that net mineralization was not correlated to the N - and lignin-content in the leaf material but was found to be negatively correlated to the polyphenolic content or the polyphenolic-to-N ratio (Palm and Sanchez, 1991). Low N -release rates from materials with a high polyphenolic content was attributed to the formation of stable polymers between polyphenolics and amino-groups (Palm and Sanchez, 1991). Similar results were reported by Sivapalan et al. (1985) who concluded that polyphenols form stable complexes with leaf protein and have an adverse impact on N-release. This is due probably to the formation of complex structures with N-containing groups or by acting as tanning agents, thus preventing protein from rapid decay. The polyphenol content of pueraria grown in Colombia and Bolivia was reported as 0.26 % to 0.39 % and 1.39 % to 4 %, respectively (Thomas and Asakawa, 1993; Luna-Orea et al., 1996).

Senna at IITA, Nigeria was found to contain 1.5 % (Tian et al., 1992) and 2.7 % in Tanzania (Jonsson, 1996), whereas the polyphenolics content in leucaena was reported as 4.9 % at IITA, Nigeria (Tian et al., 1992) and as 5.4 % in Tanzania (Jonsson, 1996).

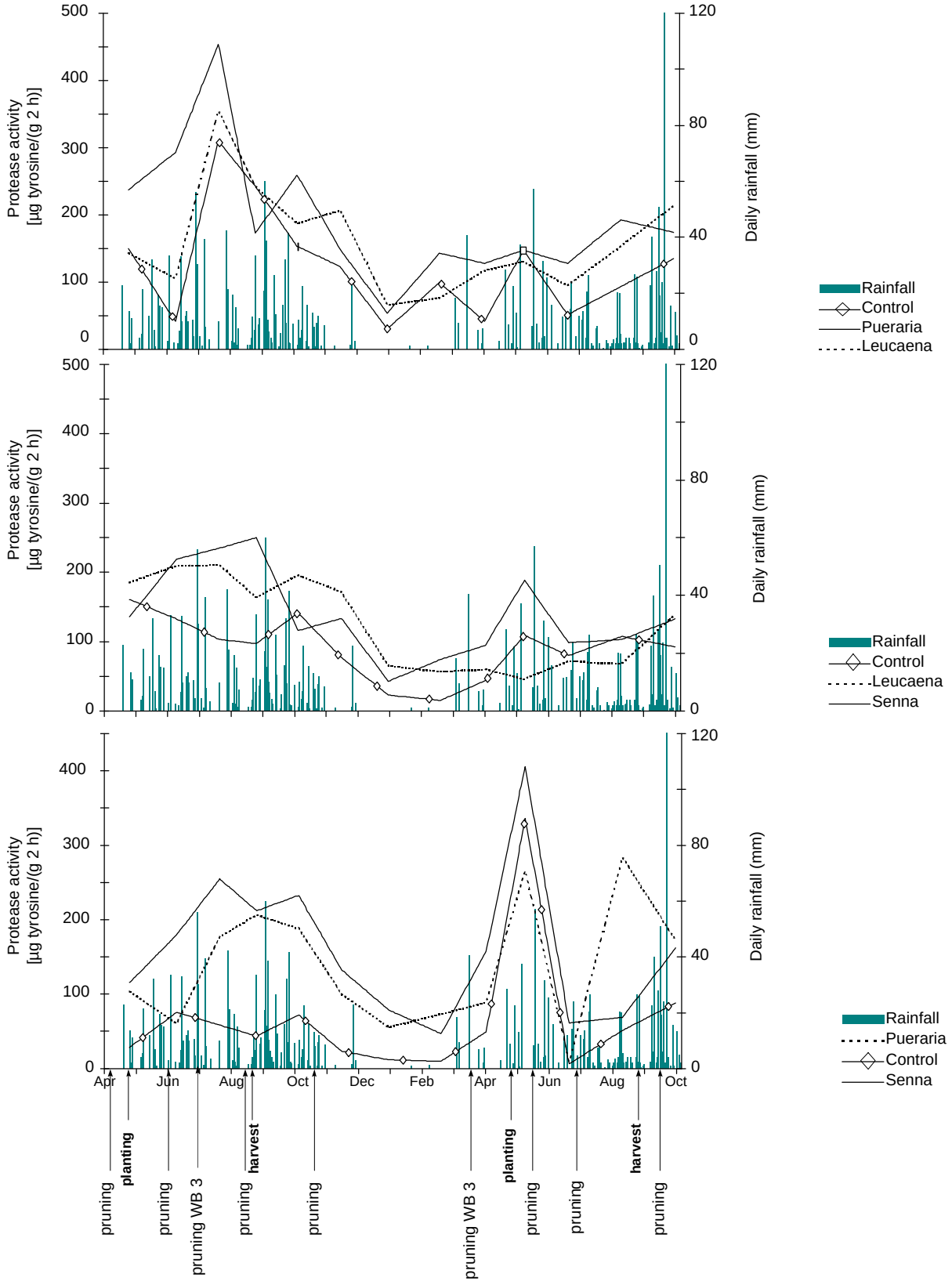


Fig. 16. Seasonal course of protease activity (µg tyrosine g^{-1} $2h^{-1}$) at Westbank 3 (top), D 2 (middle), and Westbank 1 (bottom) in the 0-5 cm layer ("pruning" applies only for leucaena at Westbank 3 and for senna and leucaena at D 2; "pruning WB 3" means that none was applied to D 2 at that time).

Lehmann et al. (1996) concluded also that polyphenols seemed to regulate mass loss and N- and Ca-release of mulch from alley cropped tree legumes in the subhumid savanna of central Togo.

4.2.9 .Summary

At the least degraded Westbank 3 soils under pueraria and leucaena management were not different from continuous cropping in terms of maize productivity, soil physical conditions, pH, exchangeable basic cations, and available inorganic and organic phosphorus contents. Organic carbon and total nitrogen contents of the soils were significantly higher under pueraria, while leucaena soils only had significantly higher total N but not total C-contents. Microbial biomass, alkaline phosphatase activity, ß-glucosidase, and protease activity were highest under pueraria. Acid phosphatase activity was only significantly higher than in continuous cropping during the 2nd season at 0-5 cm depth and during the 1st season at 5-10 cm depth. Leucaena alley cropping only improved ß-glucosidase during the dry and the 2nd season at 0-5 cm depth, whereas acid phosphatase activity was significantly higher only during the 2nd season at 0-5 cm depth. Microbial biomass, alkaline phosphatase activity and protease under leucaena were not different from continuous cropping but microbial biomass during the 2nd season at 5-10 cm depth. Thus, leucaena is considered less effective in improving soil conditions at WB 3 as compared to pueraria since only total N of the soil chemical properties and both ß-glucosidase and acid phosphatase of the microbiological properties were maintained at a higher level as compared to continuous cropping.

At D 2, leucaena alley cropping generally was not different in both crop productivity and soil chemical properties as compared to the control. Moreover, inorganic phosphorus content was reduced. With respect to soil microbiological properties, protease activity was only significantly higher during the 1st season at 0-5 cm depth, whereas ß-glucosidase was significantly higher during the 1st and the dry season in comparison to the control. The microbial biomass content was not different from continuous cropping. Senna performed slightly better compared to leucaena. Organic carbon, microbial biomass, alkaline phosphatase, and protease during the 1st season, and ß-glucosidase activity during the 1st (both depths) and 2nd (0-5 cm) season were improved. Crop productivity was not different from sole cropping, although Bray-I inorganic phosphorus was significantly lower compared to the control treatments.

At the most degraded Westbank 1 site, the postulated advantage of planted fallow species to biologically restoring a degraded Alfisol was not always confirmed. Of the different

fallow species investigated pueraria and natural regrowth performed poorest and only improved total C and N (and pH under natural regrowth) when compared to continuous cropping. Protease activity was only significantly improved during the 1st season at 0-5 cm depth. Leucaena fallowing for 4 years significantly enhanced maize yield at P = 10 %, total C, N, pH, and available cations. Microbial biomass, alkaline phosphatase, and ß-glucosidase activity were significantly increased in the top 5 cm, whereas protease activity was only increased during the 1st season at 0-5 cm depth. Most successful for improving soil productivity and fertility was the introduction of the senna fallow. Maize grain, pH, total C and N, available cations, Bray-I phosphorus (1st season in the top 5 cm), NaOH-extractable organic phosphorus as well as microbial biomass (0-5 cm), alkaline phosphatase, ß-glucosidase, and protease (1st season) were improved significantly over the continuous cropping controls.

4.3 Analysis of soil processes

4.3.1 Uptake of nutrients and soil nutrient status

Decreasing productivity of soils under long-term cultivation is often ascribed to declining nutrient availability in the soil. Thus, quantities of nutrients in the soil surface layer were compared to the uptake of nutrients by maize plants at harvest 1994. Comparison of nutrients in the 0-10 cm surface layer with nutrient uptake was reported to be sensitive indicator since about 80 % of the maize root mass at IITA, Nigeria was found in the surface layer under zero-tillage conditions (IITA, 1976 as cited by Mueller-Harvey et al., 1985).

Uptake of N, P, K, Ca and Mg (Table 5+20) of maize plants at harvest in 1994 was not correlated with total N (Table 7+22), inorganic P (Table 9, 10, 24, 25) and available cations (Table 3 of the Appendix and Table 23) in soil. Both dry matter production of maize (grain and stalks) and inorganic phosphorus (Bray-I and $NaHCO_3$-extractable) were higher at D 2 than at WB 3 but P-uptake at WB 3 (30.5 kg/ha) was superior to D 2 (13.3 kg/ha) although not significantly so. N-uptake of maize plants at D 2 (53 kg/ha) tended to be higher than at WB 3 (37.3 kg/ha) whereas total N in soils was significantly higher at the least degraded Westbank 3 site than at D 2. These findings contradict the results obtained by Kang and Osiname (1979). These authors postulated a positive correlation of Bray-I phosphorus and maize yield on the Egbeda soils at IITA, that were cleared from bush fallow, cropped to 5 high yielding maize crops and supplemented with N, P, K, Zn-fertilizer. However, results reported by Jonsson et al. (1996) and Jones and Stockinger (1976) support our data for N and cations in 1994. A positive impact of leucaena mulch on maize biomass production and N-uptake in Tanzania was not reflected in the total soil N-status as it did not represent the very small fraction of N available to plants (Jonsson et al., 1996). Similar results for the amounts of cations in soil and those taken up by cotton-sorghum-groundnuts cropped in rotation at Samaru, northern Nigeria are reported by Jones and Stockinger (1976). Correlation coefficients suggested that index-leaf contents of Ca and Mg were unrelated to the absolute amounts of exchangeable cations present, but rather to the proportions of those cations relative to exchangeable potassium. Jones and Stockinger (1976) concluded that the relative activities of cations in the soil solutions were controlled mainly by the ratios of the cations on the exchange complex.

The uptake of phosphorus by maize plants at harvest in 1994 was slightly negatively correlated with $NaHCO_3$-P_{org} ($r = -0.52$, $P \leq 0.001$) and NaOH-P_{org} ($r = -0.47$, $r \leq 0.005$) at

both depths, indicating that the soil organic phosphorus pools contributed to the P-nutrition of maize plants.

4.3.2 Relationship of crop and soil productivity

Data on soil chemical (kg ha^{-1}) and microbiological properties (µg g^{-1}) that were used for correlation are the mean of 5 sampling dates of both the 1st and 2nd cropping period (April-October) in 1993 and 1994.

In 1993 a weak positive correlation (r = 0.43, P = 0.035) between maize yield and pH at 0-5 cm depth was obtained. The 5-10 cm layer pH (r = 0.48, P = 0.016), clay (r = -0.42, P = 0.043), moisture (r = - 0.44, P = 0.032), microbial biomass content (r = 0.43, P = 0.034), and acid phosphatase activity (r = -0.44, P = 0.03) were weakly correlated with maize yield. In 1994, a significant correlation was only found between pH value of soil (r = 0.51, P = 0.012) and maize yield at both depths. The minor interrelationship of yield with chemical and microbiological properties under the prevailing conditions indicated that maize productivity was primarily controlled by other factors. Several authors, however, reported strong positive correlations between crop yield and acid phosphatase activity, whereas results obtained for microbial biomass content and crop productivity are discussed controversially in the literature. For instance, acid phosphatase activity was found to be significantly and positively correlated with herbage yield of both fertilized and unfertilized ryegrass and clover pastures in New Zealand (Speir and Cowling, 1991). Similar results were reported by Dick et al. (1988) for long-term (55 years) residue and fertilizer management trials in north-western USA, confirming a significant relation with crop grain yield (averaged over 6 years).

Insam et al. (1991) reported significant positive correlations between soybean yields from long-term experimental sites in Alabama, USA that were obtained one year prior to sampling and both microbial biomass carbon (substrate-induced-respiration; r = 0.77, P < 0.01) and the C_{mic}/C_{org} ratio (r = 0.71; P < 0.01) of the current year. The authors suggested that higher crop yields increased the C-input to the soil followed by subsequent higher soil microbial biomass and increased C_{mic}/C_{org} ratios (Insam et al., 1991). In the present study, however, significant yield differences under continuous cropping controls in the order D 2 > WB 3 > WB 1 (Table 4) were not followed by the microbial biomass content, declining in the order WB 3 > D 2 = WB 1 (Table 11). Moreover, no significant differences in the C_{mic}/C_{org} ratio (Table 12) was found despite significant yield differences. This suggests that

under the prevailing conditions at IITA, Nigeria factors other than crop yield appeared to contribute to the microbial biomass content and the relationship between microbial biomass and organic carbon.

Srivastava and Lal (1994) reported a positive correlation of rice and lentil yield, and total above and below-ground biomass with soil microbial biomass content at r = 0.83*, 0.88** and 0.76*, respectively, under tropical dryland farming in India. Hence, the authors concluded that the microbial biomass may contribute to grain production by providing N and P to the crops. Investigations by McGill et al. (1986) on long-term (50 years) management trials with wheat fallow or wheat-oats-barley-forage-forage rotations under temperate conditions in Canada revealed that only microbial biomass carbon content of soils (determined in 1982) and total crop yield (averaged over 1977-1981) were highly significant correlated ($r = 0.8$, $P \geq 0.01$). When biomass-C was correlated with the crop yield of the last year only, the correlation was non-significant ($r = 0.28$).

No correlation of C, N, Ca, Mg, K-contents, inorganic and organic soil phosphorus, alkaline phosphatase, ß-glucosidase, and protease activities with crop productivity was found. These findings are supported by several authors. Both the P-status and the size and distribution of the soil organic P-pools in alley cropped trials at CATIE, Costa Rica were not correlated with maize yields (Paniagua et al., 1995). Roder et al. (1995 a) found that soil fertility parameters such as available Bray-II-P, extractable K, pH, and CEC did not show any relationship with crop yield under slash-and-burn systems in Laos. Omotoso (1971) reported that available inorganic P was not significantly related to the yields of cacao plants in southern Nigeria. Although high yields are generally associated with high organic matter content under low external input management (Babalola and Opara-Nadi, 1993), our data showed that maize yield was not related to organic carbon. Changes in total soil carbon content are not necessarily correlated to changes in soil productivity. This was attributed to the importance of distinct fractions of organic carbon in the maintenance of soil fertility and productivity (Palm et al., 1996) rather than the total soil organic carbon content per se. The lack of correlation of alkaline phosphatase and ß-glucosidase with crop productivity (averaged over 6 years) was also reported by Dick et al. (1988) for long-term residue management trials in north-western USA.

4.3.3 Soil microbiological and soil chemical properties

The relation of microbial biomass with soil chemical and enzymatic properties is presented in Table 32.

Table 32. Correlation coefficients of microbial biomass with selected soil chemical and physical parameters, and enzyme activities in 1993 and 1994 at 0-5 cm and 5-10 cm depth; (n = 24).

	Microbial biomass(1)			
	1993		**1994**	
parameters(1)	***0-5 cm***	***5-10 cm***	***0-5 cm***	***5-10 cm***
C_{org}	0.81***	0.68***	0.85***	0.58***
N_{tot}	0.78***	0.78***	0.84***	0.69***
acid phosphatase	-0.14	-0.15	0.22	0.04
alkaline phosphatase	0.87***	0.81***	0.93***	0.66***
ß-glucosidase	0.76***	0.49*	0.85***	0.65***
protease	0.78***	0.85***	0.33	0.14
Bray-I P	-0.01	-0.32	-0.25	-0.25
$NaHCO_3$-P_i	n.d.	n.d.	-0.20	-0.32
$NaHCO_3$-P_{org}	n.d.	n.d.	-0.39	-0.48*
NaOH-P_i	n.d.	n.d.	-0.41*	-0.45*
NaOH-P_{org}	n.d.	n.d.	-0.38	-0.44*
Ca	0.66***	0.78***	0.75***	0.73***
Mg	0.37	0.52**	0.41*	0.42*
K	0.25	-0.02	0.16	-0.17
pH	0.72***	0.7***	0.83***	0.73***
clay	-0.11	-0.21	-0.02	-0.28
moisture	0.30	-0.07	0.79***	0.11

(1) = dimensions used were: microbial biomass (µg g^{-1}), soil enzymes (µg g^{-1}), soil chemical parameters (kg ha^{-1}), soil physical parameters (%);
significance level was: *** at $P \leq 0.001$; ** at $P \leq 0.01$;
* at $P \leq 0.05$;
n.d. = not determined.

Total soil organic carbon and nitrogen, pH, Ca, alkaline phosphatase, and ß-glucosidase constitute soil parameters which are mainly involved in the SOM-dynamics, and were significantly related to microbial biomass during both cropping seasons in the 0-5 cm and 5-10 cm layer. Protease at both depths was only significantly related to microbial biomass in 1993. No correlations were obtained between microbial biomass and inorganic phosphorus, K, clay and acid phosphatase activity. A very weak correlation was found with organic phosphorus ($NaHCO_3$ and NaOH-extractable) and Mg. The relation of microbial biomass with the gravimetric soil moisture content was already discussed in Chapter 4.1.5.1 and 4.2.5.1.

A strong relation between microbial biomass and soil organic carbon might be expected since both are part of the SOM-pool. Many soil microbial activities are dependent upon carbon as a substrate as most microbial populations are heterotrophic. Similar results were reported by Goyal et al. (1993), who showed that under long-term residue management trials at Hisar, India, soil microbial biomass was positively correlated with soil organic carbon ($r = 0.89$, $P < 0.01$). The authors concluded therefore, that organic carbon is an important factor in the development of soil microbial biomass-C (Goyal et al., 1993). Mazzarino et al. (1993) reported a lack of the correlation between water soluble- C and microbial biomass under alley cropping systems in Costa Rica, due probably to the diverse class of compounds that contribute to water soluble-C, not all of them being readily utilized by microbial biomass.

Similar to our results no correlation of microbial biomass from 3 long-term management trials in Alabama, USA (2 sorghum-soybean rotations and 1 cotton-maize-rye-soybean-rye rotation) with inorganic P (Mehlich-1-procedure) and exchangeable K was found (Insam et al., 1991). Since organic carbon is usually the limiting factor for the microbial biomass in agricultural soils, the impact of mineral fertilization and nutrient availability other than organic carbon was considered to be indirect (Insam et al., 1991).

The relationships of acid phosphatase with major soil chemical parameters and microbial biomass are listed in Table 33.

The correlation of total soil organic carbon, total nitrogen, and microbial biomass with acid phosphatase was non-significant, implying that the enzyme was not associated with total SOM-pools and microbial biomass. The findings for total C and N contradict the results reported by several authors (Lopez-Hernandez et al., 1989; Sparling et al., 1986; Dick et al., 1988; Deng and Tabatabai, 1997).

Table 33. Correlation coefficients of acid phosphatase with selected soil chemical and physical parameters, and microbial biomass in 1993 and 1994 at 0-5 cm and 5-10 cm depth;
(n = 24).

	Acid phosphatase[(1)]			
	1993		**1994**	
parameters[(1)]	***0-5 cm***	***5-10 cm***	***0-5 cm***	***5-10 cm***
C_{org}	-0.24	0.15	0.06	0.19
N_{tot}	-0.22	0.09	0.05	0.26
microbial biomass	-0.14	-0.15	0.22	0.04
Bray-I P	0.20	-0.08	0.00	-0.28
$NaHCO_3$-P_i	n.d.	n.d.	-0.06	-0.13
$NaHCO_3$-P_{org}	n.d.	n.d.	0.12	0.07
NaOH-P_i	n.d.	n.d.	0.09	0.06
NaOH-P_{org}	n.d.	n.d.	0.02	0.20
pH	-0.69***	-0.46*	-0.16	-0.15
clay	0.24	0.49*	0.27	0.65***
moisture	0.09	0.68***	0.03	0.41*

(1) = dimensions used were: microbial biomass (μg g^{-1}), soil enzymes (μg g^{-1}), soil chemical parameters (kg ha^{-1}), and soil physical parameters (%);
significance level was: *** at $P \leq 0.001$; ** at $P \leq 0.01$;
* at $P \leq 0.05$;
n.d. = not determined.

The relation of acid phosphatase activity and microbial biomass is discussed controversially in the literature. Thus, the activity of acid phosphatases was found by Skujins (1976) to be independent of microbial counts in the soil, whereas Sparling et al. (1986) reported that phosphatase activity of moist soil was significantly correlated with SIR-biomass (substrate-induced-respiration method) but not with ATP-biomass (ATP method). Chhonkar and Tarafdar (1984), Häussling and Marschner (1989), and Rastin et al. (1988), on the other hand, found significant positive correlations between microbial biomass and acid phosphatase activity under various conditions.

No correlation between the phosphorus status of the sites and acid phosphatase activity was found (see also Chapter 4.1.6.1). The lacking relation between inorganic and organic phosphorus pools and acid phosphatase activity is supported by results of Adams (1992) for eucalyptus forest soils in Australia and Speir and Cowling (1991) for both fertilized and unfertilized ryegrass and clover pastures in New Zealand. According to Barrett-Lennard et al. (1993), labile forms of organic phosphorus (monoesters) exist only in minute amounts in the soil so that phosphomonoesterases are of minor importance in improving plant utilization by decomposing more complex forms of organic phosphorus. In a P-enriched allophanic soil in Chile, Bishop et al. (1994) found that about 93 % of the organic P-fractions were in the inositol form with the esters being associated with iron and humic acid to form high molecular weight complexes. Using ^{31}P-NMR- (nuclear magnetic resonance) spectra of the soil extracts incubated with phosphomonoesterases and phytases, they could demonstrate that the predominant enzyme involved in the hydrolytic conversion of these complex associations were phytases.

The pH-value as well as clay and moisture contents showed no consistent relation to acid phosphatase activity. The pH was only significantly negatively correlated with acid phosphatase activity in 1993, similar to results obtained by Juma and Tabatabai (1978) and Dick et al. (1988). The absence of a relation ($r = 0.2$) between acid phosphatase and pH was reported by Deng and Tabatabai (1997) for different tillage and residue management trials in the USA. Margesin and Schinner (1994) stated that soil pH was not correlated with the optimum pH for phosphomonoesterases under temperate conditions in Austria. The lack of a correlation between acid phosphatase and soil pH was attributed to an adaptation of the enzyme to the prevailing soil conditions. The optimal pH-range of acid phosphatase activity was found to vary considerably between soils. Thus, the pH-optimum in acid, organic soils in Spain was about 5 (Trasar-Cepeda and Gil-Sotres, 1987) whereas under eucalyptus forests in Australia little variation in activity of acid phosphatase activity was observed over a range from pH 4 to 8 (Adams, 1992).

Table 34 presents the relation of alkaline phosphatase activity with major soil chemical parameters and microbial biomass during the cropping seasons of 1993 and 1994 at 0-5 cm and 5-10 cm depth.

A strong positive correlation of alkaline phosphatase activity with total soil organic carbon, total nitrogen, pH, Ca and microbial biomass carbon was found in 1993 and 1994. Since alkaline phosphatase is only produced by soil microbial biomass and soil fauna which are

involved in the organic matter dynamics in soils, a strong relation of the enzyme with C-related parameters might be expected.

Table 34. Correlation coefficients of alkaline phosphatase with selected soil chemical and physical parameters, and microbial biomass in 1993 and 1994 at 0-5 cm and 5-10 cm depth;
(n = 24).

	Alkaline phosphatase(1)			
	1993		**1994**	
parameters(1)	***0-5 cm***	***5-10 cm***	***0-5 cm***	***5-10 cm***
C_{org}	0.94***	0.62***	0.83***	0.57**
N_{tot}	0.93***	0.74***	0.83***	0.73***
microbial biomass	0.87***	0.81***	0.93***	0.66***
Bray-I P	-0.17	-0.42*	-0.26	-0.5**
$NaHCO_3$-P_i	n.d.	n.d.	-0.14	-0.42*
$NaHCO_3$-P_{org}	n.d.	n.d.	-0.46*	-0.58**
NaOH-P_i	n.d.	n.d.	-0.32	-0.39
NaOH-P_{org}	n.d.	n.d.	-0.31	-0.20
Ca	0.75***	0.87***	0.77***	0.87***
pH	0.72***	0.7***	0.83***	0.73***
clay	0.01	-0.04	0.06	0.27
moisture	0.31	-0.15	0.68***	-0.21

(1) = dimensions used were: microbial biomass (μg g^{-1}), soil enzymes
(μg g^{-1}), soil chemical parameters (kg ha^{-1}), and soil physical parameters (%);
significance level was: *** at $P \leq 0.001$; ** at $P \leq 0.01$;
* at $P \leq 0.05$;
n.d. = not determined.

The significant relationship with organic carbon also highlights the importance of microbial biomass in contributing to the soil phosphatase pool as most of the biomass is heterotrophic. Similar results with respect to the relation between alkaline phosphatase and total soil organic carbon and nitrogen were confirmed by several authors (Harrison, 1983; Dick et al., 1988; Deng and Tabatabai, 1997). A strong correlation of alkaline phosphatase

with microbial biomass is reported in the literature (Chhonkar and Tarafdar, 1984; Dick et al., 1988; Mulongoy and Bedoret, 1989).

A relation of alkaline phosphatase activity with NaOH-extractable organic phosphorus pool was non-existent. A weak negative correlation was found with inorganic Bray-I P and $NaHCO_3$-P_i at 5-10 cm depth. Labile organic phosphorus ($NaHCO_3$-extractable) was also weakly negative correlated with alkaline phosphatase in 1994, suggesting that alkaline phosphatase may be involved in labile organic and inorganic phosphorus turnover. In pot experiments strong correlations between both soluble extracellular phosphatase and alkaline phosphatase with $NaHCO_3$-P_{org} could be demonstrated (Asmar et al., 1995; Joner et al., 1995). However, similar to acid phosphatase a lack of a relation with inorganic and organic phosphorus pools under field conditions was reported for alkaline phosphatase by Adams (1992) and Speir and Cowling (1991).

The positive relation between alkaline phosphatase and Ca and pH was consistent with the correlations obtained for microbial biomass (Table 32), implying that synthesis and release of the enzyme by soil microorganisms is pH-dependent. Similar results were reported by Dick et al. (1988) and Deng and Tabatabai (1997).

No major effect of clay and gravimetric soil moisture content on alkaline phosphatase activity was found. This is discussed for soil moisture in more detail in Chapter 4.1.6.2 and 4.2.6.2.

Correlation coefficients of ß-glucosidase activity with selected soil chemical properties and microbial biomass are shown in Table 35.

ß-Glucosidase activity was significantly and positively correlated with organic carbon and microbial biomass, due probably to the involvement of the enzyme in the mineralization and cycling of carbohydrates in soils. However, the correlation with total soil organic carbon was not consistently high, due probably to the involvement of ß-glucosidase in the hydrolytic conversion of cellulose as one fraction of SOM rather than of total organic carbon. The importance of ß-glucosidase-organic carbon interrelations was emphasized by several authors (Dick et al., 1988; Eivazi and Tabatabai, 1990; Miller and Dick, 1995; Deng and Tabatabai, 1996). Positive significant correlations of ß-glucosidase with microbial biomass are reported in the literature (Rastin et al., 1988; Mulongoy and Bedoret, 1989).

No consistent correlation of ß-glucosidase with total nitrogen and pH-values were found. ß-Glucosidase is not directly involved in the N-cycle and is primarily produced by fungi

which, in turn, can tolerate acid soil conditions better than bacteria and actinomycetes (Roper and Gupta, 1995). Both Rastin et al. (1988) and Dick et al. (1988) obtained similar results, while Eivazi and Tabatabai (1990) reported significantly negative correlations of ß-glucosidase with pH. No correlation was found between clay content and soil moisture (except 1994 at 0-5 cm depth) with ß-glucosidase activity.

Table 35. Correlation coefficients of ß-glucosidase with microbial biomass and related soil chemical properties in 1993 and 1994 at 0-5 cm and 5-10 cm depth; (n = 24).

	ß-glucosidase(1)			
	1993		**1994**	
parameters(1)	***0-5 cm***	***5-10 cm***	***0-5 cm***	***5-10 cm***
C_{org}	0.51**	0.6***	0.76***	0.48*
N_{tot}	0.48*	0.48*	0.73***	0.55**
microbial biomass	0.76***	0.49*	0.85***	0.65***
pH	0.34	0.29	0.58**	0.33
clay	0.05	0.05	-0.11	0.26
moisture	0.37	0.25	0.64**	0.36

(1) = dimensions used were: microbial biomass (µg g^{-1}), soil enzymes (µg g^{-1}), soil chemical parameters (kg ha^{-1}), and soil physical parameters (%);
significance level was: *** at $P \leq 0.001$; ** at $P \leq 0.01$;
* at $P \leq 0.05$;
n.d. = not determined.

Table 36 summarizes the relation of protease activity with soil chemical conditions and microbial biomass in 1993 and 1994 at 0-5 cm and 5-10 cm depth.

No consistent relation of protease with microbial biomass and related soil chemical properties was obtained for both cropping periods. Organic carbon, total nitrogen, microbial biomass, and pH were significantly correlated with protease activity only during the 1st cropping season at 0-5 cm and 5-10 cm depth, whereas no correlation was obtained in 1994. Clay content, was positively correlated with protease activity in 1994 but not in 1993, while only a weak correlation was found between gravimetric soil moisture content and protease activity during the 2nd cropping season at 0-5 cm depth. The inconsistent relationship between total N and protease activity may be attributed to the complex nature of soil nitrogen with the different fractions being mineralized by discrete proteases.

Proteases constitute a heterogeneous mixture of enzymes with different substrate specificities (Ward, 1983), whereby the contribution of various proteases from microbial biomass are numerous and not yet fully understood (Law, 1980). Bonmati et al. (1991), for instance, reported a weak correlation coefficient of r = 0.49 (P < 0.01) between protease and total soil N in soils from a 5 year old grass-legume pasture in Italy, after air-drying and storing the soil samples at room temperature for 1 year prior to analysis. Enzyme activities observed after this prolonged storing period were considered to be mainly due to protected and stabilized enzymes by clay minerals and humic molecules (Bonmati et al., 1991).

Table 36. Correlation coefficients of protease with microbial biomass and selected soil chemical and physical properties in 1993 and 1994 at 0-5 cm and 5-10 cm depth; (n = 24).

	Protease[(1)]			
	1993		**1994**	
parameters[(1)]	***0-5 cm***	***5-10 cm***	***0-5 cm***	***5-10 cm***
C_{org}	0.8***	0.67***	0.25	0.19
N_{tot}	0.74***	0.74***	0.31	0.36
microbial biomass	0.78***	0.85***	0.33	0.14
pH	0.64**	0.77***	0.19	0.14
clay	0.00	-0.25	0.66***	0.73***
moisture	0.27	-0.14	0.40*	0.38

(1) = dimensions used were: microbial biomass (µg g^{-1}), soil enzymes (µg g^{-1}), soil chemical parameters (kg ha^{-1}), and soil physical parameters (%);
significance level was: *** at P ≤ 0.001; ** at P ≤ 0.01;
* at P ≤ 0.05;
n.d. = not determined.

Several authors, however, found a strong correlation of soil organic matter and total nitrogen with proteases (Loll and Bollag, 1983; Fraser et al., 1994). The correlation of protease activity with soil microbial biomass is discussed controversially in the literature. While Asmar et al. (1992) and Badalucco et al. (1996) revealed positive correlations between microbial biomass and protease activity, Sarathchandra et al. (1984) did not find a significant relation of protease with both, biomass-C and -phosphorus.

In 1994, protease activity was more affected by the clay content than by any other soil chemical and microbiological parameter. This was reflected in the non-significant correlation coefficients of the latter parameters. The significant positive correlation of protease with clay in 1994 may be attributed to the presence of cofactors of protease activity such as divalent metal ions that are part of bacterial extracellular proteases. These enzymes require Zn^{2+} in order to function or Ca^{2+} for stability (Law, 1980). Accordingly, proteases may be adsorbed on negatively charged clay minerals by cation exchange.

4.4 Synopsis

So far, soil biochemical and microbiological parameters were analyzed either independently or by linear correlation of two variables. Some parameters showed high variations within the sites and treatments, while others did not vary significantly between treatments. Thus, monocausal evaluations of parameters and treatments were often dissatisfying to assess a causal context of the variables and treatments within the data set, and to identify those parameters that play the most significant role in the explanation of the variance. The analysis of the principal components (PCA) is often performed to eliminate multicolinearity and to reduce the number of variables in a data set to make the data analysis more efficient (Momen et al., 1996).

By applying the PCA-method of factor analysis to the chemical and microbiological characteristics of the plots, a set of highly intercorrelated variables was replaced with a set of uncorrelated principal components or factors. Seventeen soil chemical, physical and microbiological parameters of the 12 long-term management treatments (each plot replicated twice) at the three sites differing in land use and degree of degradation, and 2 undisturbed secondary forest plots were included in the PCA in order to identify those variables that play a significant role in explaining the variance of the data. The data represented the average values of the 2^{nd} cropping season (April-October) in 1994. Maize grain yield was not considered in the analysis as it was not significantly correlated ($\geq | 0.5 |$) with either principal component or factor (data not shown). This does not mean that grain yield is not important to evaluate the productivity of long-term management trials, but in the multivariate context with other parameters grain yield did not contribute to reasonably group plots.

By analysis of principal component method 3 principal components (PCs) were extracted from 17 original soil chemical, physical, and microbiological parameters. As is illustrated

in Table 37 they explained 81.3 % of the total variance, thus confirming that further analysis can be made on 3 PCs without loosing too much information.

A 4th principal component was extracted with an Eigenvalue slightly above 1 (1.12) but explaining only 6.5 % of the total variance. The principal component did not improve grouping the plots and was excluded from the PCA.

Table 37. Eigenvalues and percentage of the total variance (%) explained by Varimax-rotated principal components.

	Eigenvalue	Variance %	cumulative
PC 1	8.5	47.3	47.3
PC 2	3.2	20.0	67.3
PC 3	2.1	14.0	81.3

As depicted in Table 38, the high loadings of the 1st principal component (47.3 % of total variance) included variables that characterize the microbiological activity of soils as related to the C-cycle (microbial biomass, alkaline phosphatase, ß-glucosidase) and variables indicative of the SOM-related nutrient supply (total N, organic carbon, Ca, Mg, K, pH). Therefore, the 1st PC was interpreted and named “SOM-related nutrient dynamics” (SOM-ND).

The highest loadings of the 1st PC were provided by microbial biomass (C_{mic}), alkaline phosphatase, total N, ß-glucosidase, and organic C, but also Ca, Mg, and pH had fairly high correlations with the principal component. This implies that these parameters were the major contributors for explaining most of the variance of the data or resource base. Alkaline phosphatase and ß-glucosidase were also strongly correlated with microbial biomass, thus showing the potential of these enzymes as indicators of metabolic activity of microbial biomass in the long-term management trials at IITA, Nigeria. Acid phosphatase, K, and protease were not strongly correlated with the 1st PC and are considered less important to explaining this principal component. Moreover, protease but also Mg were not clearly associated with the 1st PC but were correlated with the 3rd principal component.

The 2nd principal component (20 % of total variance) was described by inorganic and organic phosphorus pools with $NaHCO_3$-P_i and NaOH-P_{org} having highest loadings on the PC. The collective term ascribed to the 2nd principal component was “phosphorus

dynamics". The 3rd PC (14 % of total variance) was characterized by clay, protease and Mg and was summarized as "clay component". As already discussed earlier in Chapter 4.3.3 a strong correlation between clay and protease was obtained in 1994 possibly due to binding of protease to clay by cation exchange.

Since the PCs are not correlated but linearly independent of each other per definition, an increase of SOM-related properties thus does not implicitly increase phosphorus dynamics and vice versa.

Table 38. Principal components (PC) and component loadings extracted from 17 original soil chemical, physical, and microbiological parameters during the 2nd cropping season in 1994 at 0-5 cm depth.

	Principal component		
Variables	**1**	**2**	**3**
C_{mic}	0.981	-0.009	0.024
alk. phosphatase	0.971	-0.001	0.060
total N	0.936	-0.048	-0.014
ß-glucosidase	0.931	0.277	-0.046
C_{org}	0.931	0.146	-0.075
Ca	0.877	0.042	0.343
Mg	0.733	0.181	0.582
pH	0.733	-0.331	-0.071
acid phosphatase	0.676	0.346	0.221
K	0.617	0.454	0.444
protease	0.565	0.050	0.717
$NaHCO_3$-P_i	-0.015	0.816	-0.143
NaOH-P_{org}	-0.038	0.816	0.447
Bray-I P	0.302	0.786	-0.451
NaOH-P_i	-0.469	0.679	0.200
$NaHCO_3$-P_{org}	0.441	0.645	0.017
clay	-0.130	-0.074	0.820

Similar to our results Sarathchandra et al. (1984) could demonstrate that 2 PCs were sufficient to summarize the relationship among 13 microbiological and biochemical characteristics of 21 pasture topsoils in New Zealand. The 1st PC was represented by biomass-C and -P, organic C, phosphatase, total N, N-mineralization, and CO_2-production, whereas the 2nd PC was made up of arylsulfatase, mineral N-flush, urease, and nitrification index. Protease and pH was not strongly associated with either principal component.

The XY-ordination of the first two principal components (67 % of the total variance) is displayed in Figure 17. The 3rd principal component was not considered, as the characteristic feature was mainly given by the clay content. Thus, the 3rd PC did only contribute to group the plots according to their clay content (for more detail see Chapter 4.1.3 and 4.2.3).

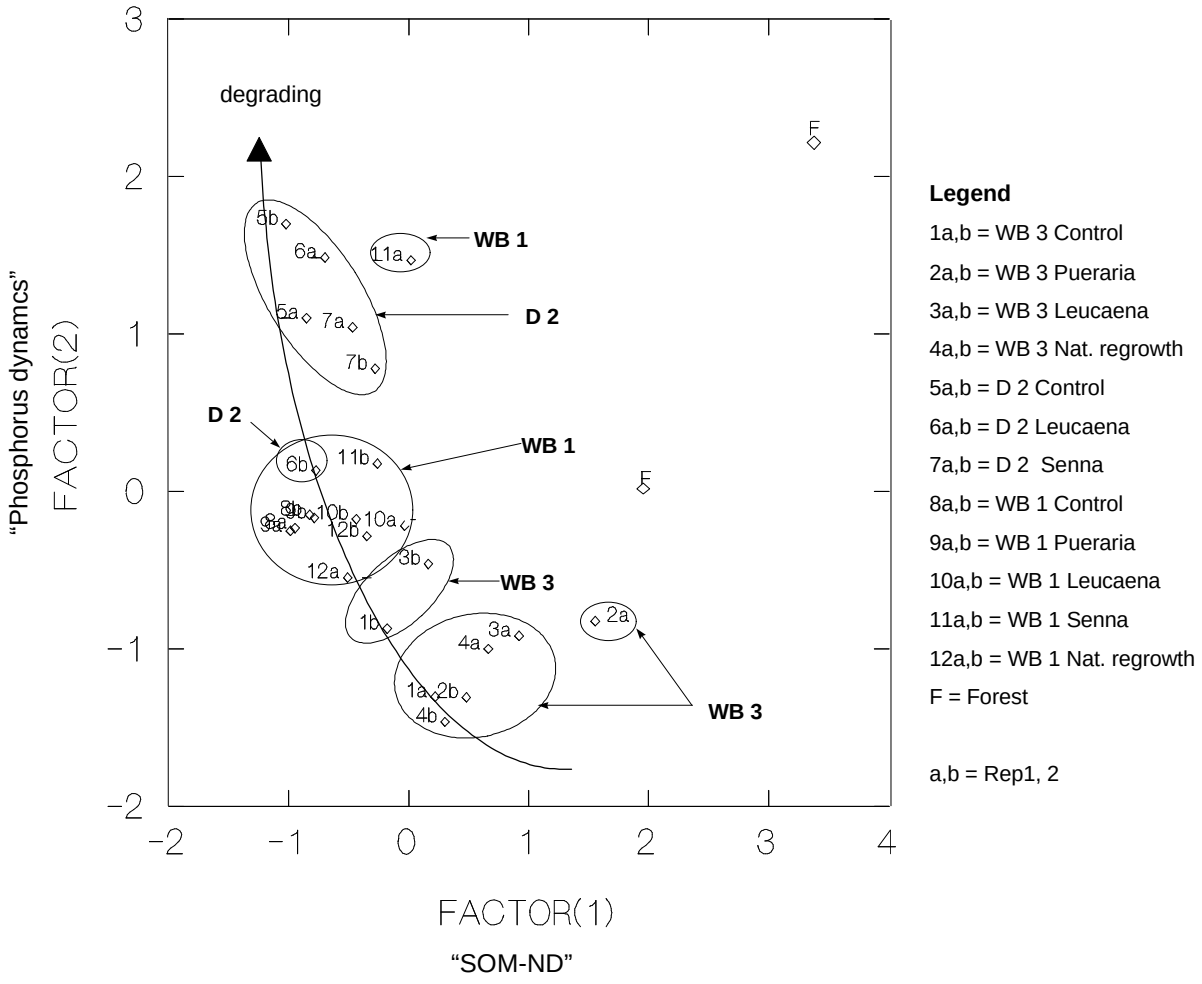


Figure 17. Factor scores of the plots and their assignment to the 1st and 2nd principal components at 0-5 cm depth.

As a result of the PCA-method of factor analysis the plots were grouped in entities that were consistent with the land use and degree of degradation (Figure 17). The factor scores more clearly reflected the differences between the plots than any of the individual variables.

Figure 17 shows that in terms of degradation (SOM-ND) WB 1 and D 2 are similar. However, due to fertilization the P-factor is better at D 2. The least degraded Westbank 3 site was characterized by above average (positive values) soil microbiological activities as indicated by "SOM-related nutrient dynamics" scores. The "phosphorus-dynamics" scores of the site were below average (negative values). The plots within WB 3 spread along both principal component axis, thus indicating cropping system dependent soil productivity at this site. Plots 1a,b (control) and 3b (leucaena) showed lowest "SOM-ND" scores, whereas 2a (pueraria) had the highest factor scores with respect to the 1st PC. The leucaena treatment (3b) at WB 3 approached the conditions found at the more degraded WB 1 site.

Westbank 1, in comparison, was very homogeneous except for plot 11a (senna), indicating no major variability in soil fertility due to cropping system at the most degraded site. The 1st PC was below average (negative values), the P-dynamics at the site (2nd PC) ranged from average to below average factor scores. Plot 11a (senna, 1st replication) as an exception was characterized by positive scores on the "phosphorus dynamics" PC and average scores on the "SOM-ND" principal component, and was next to the D 2 site. Apparently, senna seems to favorably restoring P and SOM-related nutrient dynamics in a degraded Alfisol.

The plots at D 2 were homogeneously distributed with respect to the "SOM-ND" principal component and fairly scattered along the "phosphorus-dynamics" PC. The site could be described by positive phosphorus dynamic scores (above average) but similar to WB 1 in below average "SOM-ND" scores (negative values). An exception was plot 6b (leucaena, 2nd replication) with negative "P -dynamics" and "SOM-ND" scores. This plot was closer associated with WB 1 group than with D 2, indicating that leucaena treatment at a degraded Alfisol may not sustain P and SOM related nutrient dynamics.

For the 5-10 cm depth, 3 principal components were extracted from 17 original soil chemical, physical, and microbiological parameters. As is illustrated in Table 39 the 3 PCs explained 87.5 % of the total variance.

As compared to 0-5 cm depth (Table 37) the 2nd PC gained importance in contributing to the total variance of the data set by explaining 29 % rather than 20 %.

The composition of the 1st PC and the component loadings are depicted in Table 40. The highest component loading was provided by alkaline phosphatase. Calcium and Mg were more closely correlated with the 1st PC whereas ß-glucosidase was less correlated than for the 0-5 cm depth. Potassium was not assigned to the 1st PC but to the 2nd, whereas $NaHCO_3$-P_{org} was included in the 1st and 2nd PC, and was slightly negatively correlated with the 1st principal component. However, similar to the top 5 cm the 1st PC was described by variables that characterize the microbiological activity of soils (alkaline phosphatase, C_{mic}, ß-glucosidase) and parameters indicative of the SOM-related nutrient supply (Ca, N, Mg, C_{org}, pH). The interpretative term of the 1st PC was again "SOM-ND", and the most dominant parameters to explaining the total variance of the data were consistent with those for the top 5 cm.

Table 39. Eigenvalues and percentage of total variance (%) explained by Varimax-rotated principal components.

	Eigenvalue	**Variance %**	**cumulative**
PC 1	9.2	45.3	45.3
PC 2	3.7	29.1	74.4
PC 3	2.0	13.1	87.5

Acid phosphatase, protease, and $NaHCO_3$-P_{org} showed only a modest correlation with the 1st PC. Both protease and $NaHCO_3$-P_{org} were closely associated with the 3rd and 2nd PC, respectively. The negative correlation of $NaHCO_3$-P_{org} implied that an increase of "SOM-ND" is followed by a decrease in the labile organic phosphorus pool.

The 2nd PC was described by inorganic and organic phosphorus pools and was consistent with that for the 0-5 cm layer. Highest component loadings were provided by inorganic and organic NaOH-extractable phosphorus. The 2nd PC was named again "phosphorus-dynamics". Organic carbon and potassium were also contributions to the 2nd PC, however, with poor component loadings, and were not considered to contribute much to this principal component. Unlike the situation with the 0-5 cm depth, the 3rd PC was only characterized by clay and protease, magnesium was not included. Clay gained importance as compared to the top 5 cm and was closely correlated with the 3rd PC.

Table 40. Principal components (PC) and component loadings extracted from 17 original soil chemical, physical, and microbiological parameters during the 2nd cropping season in 1994 at 5-10 cm depth.

	Principal component		
Variables	**1**	**2**	**3**
alk. phosphatase	0.948	0.125	0.209
Ca	0.938	0.021	0.065
C_{mic}	0.933	0.128	-0.174
total N	0.870	0.410	0.072
Mg	0.863	0.304	0.331
ß-glucosidase	0.831	0.319	0.209
C_{org}	0.819	0.501	0.040
pH	0.779	-0.400	-0.257
acid phosphatase	0.651	0.474	0.417
protease	0.582	-0.023	0.712
$NaHCO_3$-P_{org}	-0.530	0.734	-0.021
NaOH-P_i	0.213	0.947	-0.001
NaOH-P_{org}	0.034	0.882	0.216
Bray-I P	0.309	0.844	-0.308
$NaHCO_3$-P_i	0.476	0.827	-0.078
K	0.396	0.550	0.443
clay	-0.112	-0.077	0.945

The XY-plot of the first two principal components (74.4 % of the total variance) is displayed in Figure 18.

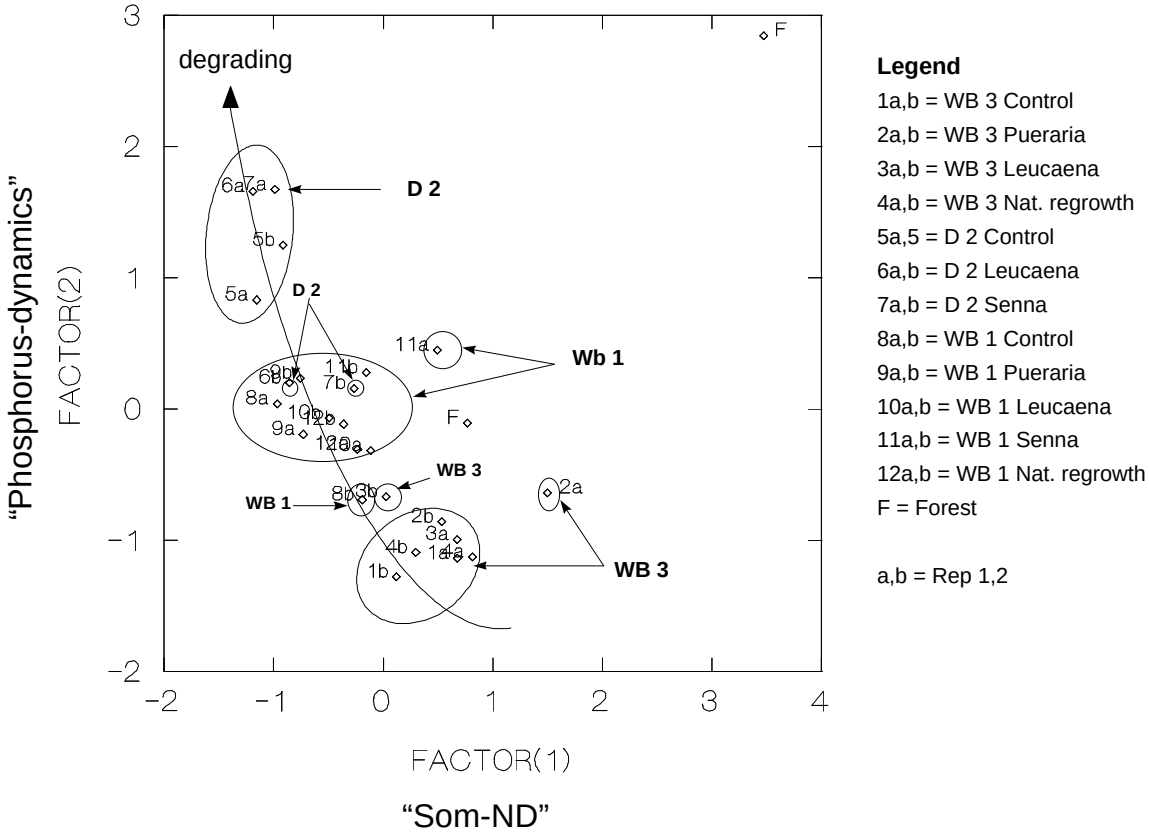


Figure 18. Factor scores of the plots and their assignment to the 1st and 2nd principal components at 5-10 cm depth.

Contrary to the 0-5 cm depth, the sites were more homogeneously distributed along the 1st and 2nd PC, and were more clearly separated from each other. Westbank 3 could be described by positive microbiological activities and "SOM-ND" (above average) and negative (below average) "phosphorus-dynamic" scores. Similar to the top 5 cm plot 2a (pueraria) had highest factor scores with respect to SOM-related activities ("SOM-ND"). Plot 1b (control) and 3b (leucaena) had the poorest SOM-ND scores. Westbank 1 and D 2 were characterized by negative "SOM-ND". The "phosphorus-dynamic" PC was above average reflecting years of P-fertilization. Exceptions were 8b (control) and 11a (senna) of WB 1. The former plot had negative scores on "SOM-ND" and "P-dynamics" PC and was closely associated with plot 3b (leucaena, Westbank 3). The senna (11a) plot was characterized by positive scores for "SOM-ND" and "P-dynamics" principal components (above average) and was similar to the top 5 cm. D 2 with positive factor scores with respect to "P-dynamic" PC and negatively "SOM-ND" PC (below average) had two

exceptional plots: 6b (leucaena) and 7b (senna). The “P-dynamic” scores at these plots were only slightly above average, and were strongly associated with the Westbank 1 site.

5 Conclusions

Soil quality or soil health has emerged as the central concept for examining and integrating relationships and functions among various biological, chemical, and physical parameters of soils which are important in the context of sustainable land use and management (Doran and Parkin, 1994; Karlen et al., 1997). Identifying appropriate quantitative criteria and methods for assessing soil quality is a primary requirement to advance the concept, as was discussed recently in the Soil Science Society of America (SSSA) Ad Hoc Committee on Soil Quality (Karlen et al., 1997). Varying perceptions of soil quality in relation to agricultural production are existent. As a result, soil quality or soil health have been related to crop productivity, to the quality of feed and food produced or to species diversity of a habitat (Karlen et al., 1997). Indicators appropriate to assessing soil quality should (1) reflect major processes or controlling factors which would affect sustainability at the sites, (2) be measurable against some definable standard, (3) be sensitive enough to detect differences in time and space, and (4) reflect cause-effect relations (Karlen et al., 1997; Smyth and Dumanski, 1995). A minimum data set was already proposed and basic soil chemical and physical properties determined (Larson and Pierce, 1991; Doran and Parkin, 1994). However, only a few biological aspects of soil quality were included so far, making the identification of biological indicators of soil quality as critically important (Doran and Parkin, 1994; Brown et al., 1994; Elliott et al., 1996).

Therefore, the main emphasis of our research was focused on identifying soil microbiological parameters as candidate indicators for quality of soils at various stages of degradation and under contrasting resource management systems. Of the soil microbiological parameters analyzed, microbial biomass, alkaline phosphatase, and ß-glucosidase activity were the most sensitive and consistent indicators to (1) reflect major soil degradation processes, (2) reflect cause-effect relationships, and therefore (3) to discriminate between contrasting resource management systems.

By means of PCA it could be demonstrated that SOM-related nutrient dynamics was the major contributor to explaining the total variance (> 80 %) of the resource base under the prevailing experimental conditions. Microbial biomass, ß-glucosidase, and alkaline phosphatase activities are parameters that are strongly associated with SOM and its turnover in soil. Highest loadings with the major PC were provided by microbial biomass and alkaline phosphatase, but also ß-glucosidase had loadings above 0.8.

Contrasting soil and crop management systems (alley cropping, live mulch, planted fallow, controls in long-term experiments) at three sites differing in degree of soil degradation

could be assessed adequately by these indicators. Of the soil enzymes measured, ß-glucosidase activity was a sensitive indicator of the effect of improved fallow managements (alley cropping, live mulch, planted fallow) on site degradation. The enzyme was more sensitive in indicating changes as compared to total organic carbon. Alkaline phosphatase was more sensitive than microbial biomass in characterizing the sites and their degree of degradation as well as the effects of improved fallow managements on site degradation. The temporal fluctuations in the activity were much less pronounced than for microbial biomass, which fluctuated highly. Since both enzymes had strong correlations with microbial biomass, they indicate the metabolic activity of microbial biomass under different long-term management systems. Moreover, the activity of both enzymes was comparatively easy to measure.

Acid phosphatase and protease activity showed inconsistent responses across a range of soil management practices and had only poor associations with major ecological soil processes. This was more so for acid phosphatase than for protease. Thus, both acid phosphatase and protease were not considered sensitive indicators for soil quality evaluations under the prevailing conditions of long-term management trials at IITA, Nigeria.

Time and depth of soil sampling for microbial biomass content should be restricted to the cropping period and the 0-5 cm depth, as the most pronounced differences occurred in the top layer due to more favorable environmental conditions (substrate availability, moisture regime). In fact, most of the treatments were centered on the management of soil surface conditions. Both, alkaline phosphatase and ß-glucosidase measurements are not necessarily restricted to any particular season as the activity remained rather stable throughout the year. Samples should be collected from the top 5 cm, as soil microbiological activities were concentrated in the topsoil due to SOM-return and no-tillage managements. However, before application of these parameters to other soil surface studies, short-range variability has to be checked for this location in order to develop an appropriate sampling strategy.

As pointed out by Karlen et al. (1997) appropriate indicators should be measurable against some definable local standard. Difficulties related to the establishment of threshold values were already discussed by Syers et al. (1995) and the International Working Group for conceptualizing the Framework for Evaluation of Sustainable Land Management (Smyth and Dumanski, 1995). It simply would be expecting too much for a single threshold value to represent the boundary or cut-off between sustainable and unsustainable, which is more gradual than clear-cut. Therefore, they proposed a range of threshold values and trends for

particular indicators rather than single threshold values. For the long-term management sites at IITA, Nigeria, varying in the degree of degradation and time of land use, the lowest limit or baseline for the microbiological indicators proposed could be derived from continuous cropping control treatments of these experiments. They are bottom standards and already non-sustainable. As a matter of fact, definable standards or a range of thresholds need to include upper-range standards as well. Comparison of agricultural land management practices with undisturbed secondary forests as single upper-range standard is not considered suitable, as crop management systems can not have the closed nutrient cycles of undisturbed forests. Hence, appropriate upper-range standards for non-degraded sites could be derived from pueraria *in situ* live mulch at WB 3 site, and for degraded sites from senna at WB 1. Pueraria, thus, worked on WB 3, the non degraded site but not on WB 1, the severely degraded site, suggesting that pueraria is a maintenance crop. In contrast, senna worked on the degraded sites and more so on WB 1 than on D 2. Senna alley cropping at D 2 performed fairly well compared to leucaena and sole cropping. Parameters related to SOM-dynamics, including soil microbiological activity, were sustained, but not crop productivity and fertility. At WB 1, however, senna was most successful for improving soil productivity and fertility. Soil microbiological activity as well as crop productivity and chemical fertility was increased most over continuous cropping. Apparently, senna may work as a restoration crop.

6 Summary

Soil quality or soil health has emerged as the central concept for examining and integrating relationships and functions among various biological, chemical and physical parameters of soils which are important in the context of sustainable land use and management. Identifying appropriate quantitative criteria and methods for assessing soil quality is a primary requirement to advance the concept. A minimum data set was already proposed and basic soil chemical and physical properties determined. However, only a few biological aspects of soil quality were included so far, making the identification of biological indicators of soil quality as critically important.

The present study was undertaken to link soil microbiological and soil biochemical parameters with soil quality conditions and crop productivity and to identify those parameters or processes that were affected most by long-term management. Degradation was defined by land-use history and was reflected in the soil quality status and the productive potential. A degradation index was used to discriminate between three selected sites varying in time and intensity of land use based on the continuously cropped controls of long-term experiments. Various improved fallow management systems were evaluated for their potential as low-input continuous crop production systems by comparing them to sole cropping.

The experimental sites were located at the research farm of the International Institute of Tropical Agriculture (IITA) in south-western Nigeria. Three sites varying in degree of degradation and land use history were examined. The non-degraded Westbank 3 site (1) was established in 1989 and cleared from secondary forest. Three fallow management systems with maize/cassava intercropping - natural regrowth of the spontaneous vegetation, alley cropping with leucaena [*Leucaena leucocephala* (Lam.) de Wit], and pueraria *in situ* (“live”) mulch (*Pueraria phaseoloides*) were introduced. The degraded D 2 site (2) was used by breeders between 1980 and 1985, and since 1986 cropped to two alley cropping managements with maize/cowpea sequential cropping - leucaena and senna [*Senna siamea* (Lam.) Irwin&Barneby]. The most severely degraded Westbank 1 site (3) was established in 1979 and was used under intensive mechanized cropping for a period of 10 years. Between 1989 and 1993 woody and herbaceous fallow species were planted to biologically restoring a severely degraded Alfisol. In 1993 one third of the plots were cleared and cropped to maize/cassava intercropping. The fallow species investigated

comprised pueraria, leucaena, senna and natural regrowth of the spontaneous vegetation. Continuous cropping at all sites was used as control.

Between April 1993 and October 1994 composite soil samples were taken at random every 6 weeks from the 0-5 cm and 5-10 cm depth. In the leucaena and senna alley cropping treatments sampling was done along the hedgerows and in the interrow space. They were analyzed for bulk density, particle size distribution, gravimetric soil moisture content, pH, exchangeable basic cations, inorganic and organic phosphorus pools, total organic carbon and total nitrogen, microbial biomass carbon, acid and alkaline phosphatase, ß-glucosidase, and protease activity.

The characterization of the study sites and their degree of degradation was assessed by analyzing continuous cropping controls. It showed for (1) WB 3: medium maize productivity, high levels of soil organic matter related properties, low phosphorus status and acid phosphatase activity, high microbial biomass content, alkaline phosphatase and protease activity; (2) D 2 was characterized by high maize productivity, low levels of soil organic matter related properties, high phosphorus status, low microbial biomass content as well as low alkaline phosphatase and protease activity. Characteristic for (3) Westbank 1 was low maize productivity, low levels of soil organic matter related properties, low inorganic phosphorus status and high organic phosphorus content at 0-5 cm depth, high acid phosphatase activity, low microbial biomass content and alkaline phosphatase activity as well as low protease activity.

Differences between the degraded D 2 and Westbank 1 sites as reflected in maize productivity were largely due to inorganic Bray-I phosphorus at both depths and organic phosphorus at 5-10 cm depth. Differences in relation to soil microbiological properties were largely due to alkaline phosphatase activity.

The effects of improved fallow management systems on site degradation were as follows: (1) at Westbank 3 leucaena was considered less effective in improving soil conditions than pueraria, as only total N of the soil chemical properties and both ß-glucosidase and acid phosphatase (1994 in the top layer) activities of the microbiological properties were maintained at a higher level as compared to continuous cropping. Pueraria maintained consistently and significantly highest values of the soil chemical and microbiological properties, except for maize productivity, pH, exchangeable basic cations, and inorganic phosphorus; (2) at D 2 leucaena alley cropping generally was not different in crop productivity, soil chemical as well as soil microbiological properties over sole cropping. Senna performed slightly better compared to leucaena. Organic carbon and microbial

biomass content, alkaline phosphatase and protease during the 1st season, and ß-glucosidase activity during the 1st (both depths) and 2nd (0-5 cm) season were improved, crop productivity was not different from sole cropping; (3) at the most degraded Westbank 1 site, pueraria and natural regrowth performed poorest and only improved total C and N (and pH under natural regrowth) when compared to continuous cropping. Leucaena fallowing for 4 years significantly enhanced maize yield at P = 10 %, total C, N, pH, and exchangeable basic cations. Microbial biomass content, alkaline phosphatase, and ß-glucosidase activity were significantly increased in the top 5 cm, whereas protease activity was only increased during the 1st season at 0-5 cm depth. Most successful for improving soil productivity and fertility was the introduction of the senna fallow. Maize grain, pH, total C and N, exchangeable basic cations, Bray-I phosphorus (1st season), NaOH-extractable organic phosphorus as well as microbial biomass content (0-5 cm), alkaline phosphatase, ß-glucosidase, and protease activity (1st season and dry season at 5-10 cm depth) were improved significantly over the continuous cropping controls.

Indicators appropriate to assessing soil quality should (1) reflect major processes or controlling factors which would affect sustainability at the sites, (2) be measurable against some definable standard, (3) be sensitive enough to detect differences in time and space, and (4) reflect cause-effect relations. Of the soil microbiological parameters analyzed, microbial biomass content, alkaline phosphatase, and ß-glucosidase activity were the most sensitive and consistent indicators to meet these requirements. By means of PCA it could be demonstrated that SOM-related nutrient dynamics was the major contributor to explaining the total variance (> 80 %) of the resource base under the prevailing experimental conditions. Microbial biomass, ß-glucosidase and alkaline phosphatase activities are parameters that are strongly associated with SOM and its turnover in soil. Highest loadings with the major PC were provided by microbial biomass and alkaline phosphatase, but also ß-glucosidase had loadings above 0.8. The 2nd PC could be interpreted as “phosphorus dynamics”. By plotting the factor scores against both PCs, the differentiation of the sites and treatment effects could be improved.

Contrasting soil and crop management systems (alley cropping, live mulch, planted fallow, controls in long-term experiments) at three sites differing in degree of soil degradation could be assessed adequately by these indicators. Of the soil enzymes measured, ß-glucosidase activity was a sensitive indicator of the effect of improved fallow managements (alley cropping, live mulch, planted fallow) on site degradation. The bioassay of this enzyme was more sensitive in indicating changes as compared to total

organic carbon. Alkaline phosphatase was more sensitive than microbial biomass in characterizing the sites and their degree of degradation as well as the effects of improved fallow managements on site degradation. The temporal fluctuations in the activity were much less pronounced than for microbial biomass, which fluctuated highly. Since both enzymes had strong correlations with microbial biomass, they indicate the metabolic activity of microbial biomass under different long-term management systems. Moreover, the activity of both enzymes was comparatively easy to measure.

Acid phosphatase and protease activity showed inconsistent responses across a range of soil management practices and had only poor associations with major ecological soil processes. This was more so for acid phosphatase than for protease. Thus, both acid phosphatase and protease were not considered sensitive indicators for soil quality evaluations under the prevailing conditions of long-term management trials at IITA, Nigeria.

Depth of soil sampling for microbial biomass content as well as for alkaline phosphatase and ß-glucosidase activity should be restricted to 0-5 cm depth, as the most pronounced differences occurred in the top layer due to more favorable environmental conditions (substrate availability, moisture regime) under these no-tillage managements. Time of sampling for microbial biomass should be restricted to the wet season, whereas either enzyme is not necessarily restricted to any particular season.

Appropriate indicators should be measurable against some definable local standard. Therefore, a range of threshold values was proposed as the boundary or cut-off between sustainable and unsustainable is more gradual than clear-cut. The lowest limit or baseline for the proposed microbiological indicators could be derived from continuous cropping control treatments of these long-term experiments. Comparison of agricultural land management practices with undisturbed secondary forests as single upper-range standard is not considered suitable, as crop management systems can not have the closed nutrient cycles of undisturbed forests. Hence, appropriate upper-range standards for non-degraded sites could be derived from pueraria *in situ* live mulch at WB 3 site, and for degraded sites from senna at WB 1. Pueraria, thus, worked on WB 3, the non degraded site but not on WB 1, the severely degraded site, suggesting that pueraria is a maintenance crop. In contrast, senna worked on the degraded sites and more so on WB 1 than on D 2. Apparently, senna may work as a restoration crop.

7 Zusammenfassung

Der Begriff Bodenqualität ist zu einem zentralen Konzept erhoben worden, welches die Untersuchung und Integrierung der Wechselbeziehungen und Funktionen von biologischen und physikalischen Bodeneigenschaften im Rahmen des nachhaltigen Landbaus bzw. -managements umfaßt. Zur Umsetzung dieses Konzeptes müssen geeignete quantitative Kriterien und Methoden zur Abschätzung der Qualität eines Bodens entwickelt und eingeführt werden. Ein sogenanntes „Minimum Data Set“ wurde bereits aufgestellt und grundlegende bodenchemische und physikalische Parameter aufgenommen. Jedoch sind bisher nur wenige biologische Aspekte der Bodenqualität in dieses Konzept integriert worden, so daß die Identifikation der noch unbekannten biologischen Indikatoren von größter Bedeutung ist.

Ziel der vorliegenden Arbeit war es, mikrobiologische und biochemische Bodenparameter auf deren Eignung als Indikatoren für Bodenqualität und -produktivität zu prüfen. Weiterhin sollten solche Bioparameter identifiziert werden, die durch langjähriges Management beeinflußt wurden. Die Degradation eines Bodens wurde anhand der Nutzungsgeschichte und deren Auswirkung auf die Bodenqualität und -fruchtbarkeit definiert. Ein mittels Kontrollen von langjährigen Experimenten aufgestellter Degradationsindex wurde eingesetzt, um drei selektierte Standorte, die sich hinsichtlich der Dauer und Intensität des Landbaus unterscheiden, zu evaluieren. Verbesserte Brachemanagementsysteme wurden auf ihr Potential als „low-input“-Anbausysteme im Vergleich zu Flächen ohne Brachemanagement untersucht.

Die Versuchsflächen befanden sich auf der Versuchsfarm des „International Institute of Tropical Agriculture“ (IITA) in Südwestnigeria. Wie schon erwähnt wurden drei Standorte untersucht, die sich hinsichtlich ihrer Bodendegradierung und Landnutzungsgeschichte unterschieden. Die nicht degradierte Westbank 3-Fläche (1) wurde 1989 nach Abholzung von Sekundärwald in Kultur genommen. Drei simultane Brachemanagementsysteme mit Mais/Maniok-Mischanbau wurden berücksichtigt - natürlicher Aufwuchs der Sekundärvegetation, „Alley cropping“ mit *Leucaena* [*Leucaena leucocephala* (Lam.) de Wit] und Pueraria als Bodenbedecker (*Pueraria phaseoloides*). Der degradierte D 2-Standort (2) wurde von 1980 bis 1985 für Züchtungsversuche benutzt und ist seit 1986 unter Nutzung zweier „Alley cropping“-Systeme — Leucaena und Senna [*Senna siamea* (Lam). Irwin&Barneby] mit Mais/Vigna (*Vigna unguiculata* ssp. unguiculata) in Rotation.

Der am stärksten degradierte Westbank 1-Standort (3) wurde 1979 in Kultur genommen und war für 10 Jahre unter intensiver und maschineller Nutzung. Von 1989 bis 1993 wurden Baum- und Krautbrachesysteme eingeführt, um ihre Fähigkeit zur biologischen Verbesserung von degradierten Alfisolen zu untersuchen. Im Jahr 1993 wurde ein Drittel der Flächen gerodet und mit Mais/Maniok-Mischanbau kultiviert. Die untersuchten Brachesysteme waren Pueraria, Leucaena, Senna und natürlicher Aufwuchs der spontanen Vegetation. Der permanente Anbau ohne verbessertes Brachemanagement wurde auf allen Flächen als Kontrollvariante verwendet.
Von April 1993 bis Oktober 1994 wurden alle 6 Wochen randomisierte Bodenproben der Tiefen 0-5 cm und 5-10 cm gezogen. Die Beprobung der „Alley cropping"-Flächen mit Leucaena und Senna auf D 2 und WB 1 erfolgte entlang der Heckenreihen und in der Mitte zwischen zwei Heckenreihen („interrow"). Die Bodenproben wurden auf Trockenraumdichte, Textur, gravimetrische Feuchte, pH, austauschbare basische Kationen, verschiedene anorganische und organische Phosphorfraktionen, Gesamtkohlenstoff- und stickstoff, mikrobielle Biomasse, saure und alkalische Phosphatase-, ß-Glucosidase- und Proteaseaktivität untersucht.

Die Charakterisierung der Standorte und ihre Degradationseinstufung wurde anhand der Kontrollvariante (permanenter Anbau) vorgenommen. Es zeigte sich für (1) WB 3: moderater Maisertrag, hoher Gehalt an bodenorganischer Substanz, geringer Boden-P-Status und niedrige Aktivität der sauren Phosphatase, hoher Gehalt an mikrobieller Biomasse als auch hohe alkalische Phosphatase- und Proteaseaktivität; (2) D 2 war charakterisiert durch hohen Maisertrag, geringen Gehalt an bodenorganischer Substanz, hohen Phosphorgehalt, geringe mikrobielle Biomasse und niedrige alkalische Phosphatase- und Proteaseaktivität. Charakteristisch für (3) WB 1 war der geringe Maisertrag, geringer Gehalt an bodenorganischer Substanz, geringer anorganischer Phosphorgehalt, hoher organischer Phosphorgehalt in 0-5 cm Tiefe, hohe saure Phosphataseaktivität, geringe mikrobielle Biomasse und niedrige alkalische Phosphatase- und Proteaseaktivität. Die Unterschiede im Maisertrag zwischen den beiden degradierten Standorten D2 und WB 1 wurden hauptsächlich durch den anorganischen Phosphorgehalt (Bray-I) in beiden untersuchten Bodentiefen und den organischen Phosphorgehalt in 5-10 cm Tiefe verursacht. Unterschiede bezüglich der mikrobiologischen Bodeneigenschaften wurden vor allem durch die Aktivität der alkalischen Phosphatase hervorgerufen.

Der Einfluß der unterschiedlichen Landnutzungssysteme mit verbessertem Brachemanagement auf die Bodendegradierung der jeweiligen drei Standorte war wie folgt: (1) auf WB 3 war Leucaena für die Verbesserung der Bodenbedingungen weniger effektiv als Pueraria. Von den chemischen Bodeneigenschaften wurde nur der Gehalt an Gesamtstickstoff und von den mikrobiologischen Eigenschaften die Aktivität der ß-Glucosidase und saure Phosphatase (1994 in den obersten 5 cm) im Vergleich zum permanenten Mischanbau von Mais und Maniok nachhaltig verbessert. Außer bei den Parametern Maisertrag, pH, austauschbare basische Kationen und anorganischer Phosphor wirkte sich Pueraria am nachhaltigsten bei den restlichen gemessenen chemischen und mikrobiologischen Bodenparameter aus; (2) Leucaena- „Alley cropping“ am Standort D 2 unterschied sich nicht bezüglich des Maisertrages und der chemischen und mikrobiologischen Bodeneigenschaften von der permanenten Rotation mit Mais und Vigna. Senna war vergleichsweise effizienter als Leucaena, da der Gesamtkohlenstoff, die mikrobielle Biomasse, die alkalische Phosphatase- und Proteaseaktivität während der ersten Anbausaison und die ß-Glucosidaseaktivität sowohl während der ersten (in beiden Bodentiefen) als auch während der zweiten Anbausaison (oberste 5 cm) erhöht wurden, wohingegen sich der Maisertrag nicht von der Kontrolle unterschied; (3) auf dem am stärksten degradierten Westbank 1-Standort brachten Pueraria und der natürliche Aufwuchs der Sekundärvegetation keine Verbesserung gegenüber der Kontrolle. Von den gemessenen Parametern erhöhten sie gegenüber der Kontrolle lediglich den Gesamtkohlenstoff- und stickstoffgehalt, ebenfalls den pH unter dem natürlichen Aufwuchs. Die für 4 Jahre mit Leucaena bepflanzte Behandlung wies hingegen eine signifikante Erhöhung des Maisertrages (P = 10 %), des Gesamtgehaltes an C und N, des pH-Wertes und des Gehaltes an austauschbaren basischen Kationen auf. Die mikrobielle Biomasse sowie die alkalische Phosphatase- bzw. ß-Glucosidaseaktivität wurden in den obersten 5 cm erhöht, während die Proteaseaktivität nur während der ersten Anbausaison in 0-5 cm Tiefe gesteigert worden ist. Der größte Erfolg hinsichtlich der Verbesserung der Bodenproduktivität- und fruchtbarkeit wurde durch die gepflanzte Sennabrache erzielt. Hierbei wurden die Parameter Maisertrag, pH, Gesamtkohlenstoff- und stickstoff, austauschbare basische Kationen, anorganischer Phosphor (Bray-I, erste Anbausaison), organischer Phosphor (NaOH-extrahierbar), mikrobielle Biomasse (0-5 cm) und alkalische Phosphatase-, ß-Glucosidase- und Proteaseaktivität (erste Anbausaison und Trockenzeit in 5-10 cm Tiefe) im Vergleich zur Kontrolle signifikant erhöht.

Geeignete Bodenqualitätsindikatoren sollten: 1.) auf dem jeweiligen Standort die vorrangigen Einflußgrößen einer nachhaltigen Bewirtschaftung widerspiegeln, 2.) meßbar gegenüber einer definierbaren Bezugsgröße sein, 3.) zwischen zeitlichen und räumlichen Unterschieden differenzieren können und 4.) die Ursache/Wirkungs-Wechselbeziehungen reflektieren. Diese Voraussetzungen für Bodenqualitätsindikatoren erfüllten von den untersuchten mikrobiologischen Parametern sowohl die mikrobielle Biomasse als auch die alkalische Phosphatase- und ß-Glucosidaseaktivität, die sich als besonders sensitiv bzw. geeignet erwiesen. Anhand einer Hauptkomponentenanalyse konnte gezeigt werden, daß unter den gegebenen Bedingungen hauptsächlich (1. Faktor) die von der organischen Substanz im Boden abhängige Nährstoffdynamik über 80 % der Gesamtvarianz innerhalb des Datensatzes erklären konnte. Die Parameter mikrobielle Biomasse, ß-Glucosidase- und alkalische Phosphataseaktivität sind mit der Dynamik der organischen Substanz im Boden eng verbunden. Weiterhin waren die mikrobielle Biomasse und die alkalische Phosphataseaktivität am stärksten mit dem ersten Hauptfaktor korreliert; aber auch die ß-Glucosidaseaktivität hatte eine Faktorladung über 0.8. Der zweite Faktor wurde als die Phosphor-Dynamik interpretiert. Durch Auftragen von sogenannten Faktorwerten gegen beide Hauptkomponenten in einem Koordinatensystem wurde die Differenzierung zwischen den Flächen und Behandlungen erleichtert. Die verschiedenen Landnutzungssysteme („Alley cropping“, Pueraria als Bodenbedecker, bepflanzte Brache und permanenter Anbau [Kontrolle] aus Langzeitversuchen), der drei Standorten mit unterschiedlichem Degradierungsgrad konnten durch diese Indikatoren differenziert bzw. beurteilt werden. Von den untersuchten Bodenenzymen war die ß-Glucosidaseaktivität ein sensibler Indikator, um den Einfluß verbesserter Brachesysteme („Alley cropping“, Pueraria als Bodenbedecker und bepflanzte Brache auf die Degradierung einer Fläche abzuschätzen. Darüber hinaus war die Bestimmung der ß-Glucosidaseaktivität sensibler als die Bestimmung vom Gesamtkohlenstoff, um Unterschiede zwischen den Behandlungen aufzuzeigen. Die Aktivitätsbestimmung der alkalischen Phosphatase war hingegen sensibler als die Messung der mikrobiellen Biomasse, um sowohl die Standorte zu charakterisieren und ihren Degradierungsgrad zu bestimmen als auch den Einfluß verbesserter Brachesysteme auf die Degradierung eines Bodens zu beurteilen. Die Schwankungen in der Aktivität über die Zeit waren nicht so ausgeprägt wie die stark variierende mikrobielle Biomasse. Da beide Enzyme mit der mikrobiellen Biomasse eng korrelierten, spiegeln sie die metabolische Aktivität der mikrobiellen Biomasse in

unterschiedlichen Langzeitsystemen wider. Darüber hinaus war die Aktivität der Enzyme vergleichsweise einfach zu bestimmen.
Sowohl die saure Phosphatase- als auch die Proteaseaktivität zeigten keinen eindeutigen Verlauf in den verschiedenen Landnutzungssystemen und waren auch nur schwach mit den Nährstoffkreisläufen des Bodens korreliert. Dies zeigte sich stärker für die saure Phosphatase als für die Protease. Folglich wurden beide Enzyme unter den gegebenen Bedingungen am IITA, Nigeria als weniger geeignete und sensible Indikatoren betrachtet, um die Qualität eines Bodens abzuschätzen.
Die Tiefe der Probenahme für die Bestimmung der mikrobiellen Biomasse und der alkalischen Phosphatase- und ß-Glucosidaseaktivität sollte auf die obersten 5 cm beschränkt werden, da durch die günstigeren Bedingungen (Substratverfügbarkeit, Feuchtegehalt des Bodens) in den Behandlungen mit Minimalbodenbearbeitung die stärksten Unterschiede in der obersten Bodenschicht auftreten. Der Zeitpunkt der Probenahme für die mikrobielle Biomasse sollte während der Regenzeit erfolgen, wohingegen die Probenahme für beide Enzyme zeitlich nicht begrenzt ist.

Geeignete Indikatoren sollten hinsichtlich lokal definierbarer Meßgrößen oder Standards bestimmbar sein. Demzufolge wurden obere und untere Grenzwerte vorgeschlagen, da der Übergang von nachhaltig zu nicht nachhaltig graduell und nicht abrupt verläuft.
Der untere Grenzwert („baseline“) für die vorgeschlagenen mikrobiellen Indikatoren kann von den Kontrollflächen (permanenter Anbau) der Langzeitversuche abgeleitet werden. Ein Vergleich von landwirtschaftlich genutzten Flächen mit ungestörtem Sekundärwald als oberer Richtwert ist nicht geeignet, da ackerbauliche Nutzungssysteme nicht so geschlossene Nährstoffkreisläufe aufweisen, wie sie in ungestörten Sekundärwäldern vorkommen. Deshalb können obere Richt- oder Grenzwerte für nicht degradierte Flächen von der Pueraria-Behandlung (Bodenbedecker) der Westbank 3-Fläche abgeleitet werden, wohingegen als oberer Richtwert für degradierte Flächen die Senna-Brache auf Westbank 1 geeignet ist. Da Pueraria sich positiv auf dem nicht degradierten Westbank 3-Standort aber nicht auf dem stark degradierten Westbank 1-Standort auswirkte, kann als Schlußfolgerung gesagt werden, daß Pueraria eine Nachhaltigkeitskultur („maintenance crop“) ist. Demgegenüber steht Senna, die auf den degradierten Standorten zur Verbesserung beitrug, wobei die Auswirkungen stärker auf WB 1 als auf D 2 waren. Demzufolge ist Senna eine Restaurationskultur („restoration crop“).

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9 Appendix

Table 1. Nutrient uptake (kg ha^{-1}) of N in total dry matter(1) of maize plants at harvest 1994 as affected by cropping sites and fallow management systems - single values for stover and grain in rep 1 and 2.

	Nitrogen			
	stover		grain	
Management system	**rep 1**	**rep 2**	**rep 1**	**rep 2**
Westbank 3				
Ctrl	16.6	20.3	20.1	17.7
Leucaena	17.5	16.7	21.8	8.9
Pueraria	17.2	14.8	23.8	15.6
D 2				
Ctrl	31.6	0.3	50.3	23.6
Leucaena	6.7	11.4	20.1	26.3
Senna	12.1	19.4	22.0	n.a.
Westbank 1				
Ctrl	1.0	2.5	1.5	3.4
Leucaena	2.9	9.4	5.9	11.2
Senna	n.a.	5.1	24.6	29.4
Pueraria	2.6	10.8	6.6	4.8
Nat. regrowth	7.4	17.0	16.6	10.0

n.a. = not available;
(1) = total dry matter production of the aboveground plant material including stalks and grain;
data for WB3 and WB 1 were received from RCMD, IITA and for D 2 from Vanlauwe (personal communication).

Table 2. Nutrient uptake (kg ha^{-1}) of P in total dry matter(1) of maize plants at harvest 1994 as affected by cropping sites and fallow management systems - single values for stover and grain in rep 1 and 2.

	Phosphorus			
	stover		grain	
Management system	**rep 1**	**rep 2**	**rep 1**	**rep 2**
Westbank 3				
Ctrl	0.4	0.8	12.0	47.8
Leucaena	0.5	0.6	20.5	7.8
Pueraria	0.6	0.7	22.8	12.3
D 2				
Ctrl	6.1	5.3	13.4	6.7
Leucaena	n.a.	3.6	4.5	6.1
Senna	3.3	4.1	4.5	n.a.
Westbank 1				
Ctrl	0.2	0.2	0.4	0.8
Leucaena	0.3	0.5	1.1	2.6
Senna	n.a.	0.3	8.9	8.6
Pueraria	0.2	1.1	1.7	1.1
Nat. regrowth	0.7	1.9	4.5	2.1

n.a. = not available;
(1) = total dry matter production of the aboveground plant material including stalks and grain;
data for WB3 and WB 1 were received from RCMD, IITA and for D 2 from Vanlauwe (personal communication).

Table 3. Average soil nutrient status (kg ha^{-1}) of the control treatments at 0-5 cm and 5-10 cm depth in October 1993.

	Ca	Mg	K	Mn
Site/depth		**kg ha^{-1}**		
0-5 cm				
sec. Forest	1385	159	188	0.000
Westbank 3	677	45	47	0.000
D 2	193	32	50	0.008
Westbank 1	124	22	32	0.007
5-10 cm				
sec. Forest	725	100	117	0.000
Westbank 3	426	31	27	0.000
D 2	97	14	68	0.059
Westbank 1	130	18	19	0.004

Table 4. Average soil organic carbon (t ha^{-1}), total nitrogen (kg ha^{-1}), and pH ($CaCl_2$) characteristics under improved fallow management systems at 5-10 cm depth in 1993 and 1994.

	C_{org} (t ha^{-1})			total N (kg ha^{-1})			pH ($CaCl_2$)		
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
5-10 cm									
sec. Forest	13.5	11.9	11.8	1319	907	1178	6.5	6.7	6.7
Westbank 3									
Ctrl	5.2	5.1	5.2	511	513	484	6.7	6.8	6.8
Leucaena	4.7	5.9	6.4	438	560	609	6.5	6.8	6.7
Pueraria	6.9	7.8	7.9	647	717	717	6.8	6.9	6.9
Nat. regrowth	5.1	6.4	fallow	537	522	fallow	6.7	7.0	fallow
D 2									
Ctrl	4.0	4.5	4.9	394	446	438	5.6	5.4	5.5
Leucaena	4.1	4.5	4.9	421	452	481	5.9	5.5	5.3
Senna	5.1	4.1	4.9	411	429	431	5.9	6.0	5.9
Westbank 1									
Ctrl	3.9	4.0	4.6	411	378	446	5.2	5.3	5.3
Leucaena	5.2	3.9	5.2	505	461	492	5.9	5.7	5.8
Senna	7.6	6.5	7.3	598	623	613	6.1	6.3	6.3
Pueraria	4.6	3.9	5.4	443	403	485	5.2	5.1	5.4
Nat. regrowth	4.6	4.1	6.0	458	415	564	5.3	5.0	5.6
LSD	1.3	1.2	2.0	117	122	169	0.3	0.5	0.5

LSD (excluding forest) at $\alpha = 0.05$

Table 5. Average soil nutrient status ($cmol^+ kg^{-1}$ soil and $kg\ ha^{-1}$) under improved fallow management systems at 5-10 cm depth in 1993.

Management	Ca	Mg	K	Mn	Ca	Mg	K
	$cmol^+ kg^{-1}$				$kg\ ha^{-1}$		
0-5 cm							
sec. Forest	6.36	1.46	0.53	0.000	725	100	117
Westbank 3							
Ctrl	3.74	0.46	0.12	0.000	426	31	27
Leucaena	2.76	0.55	0.23	0.000	314	37	52
Pueraria	4.24	0.60	0.19	0.000	484	41	41
Nat. regrowth	2.89	0.52	0.21	0.000	330	36	47
D 2							
Ctrl	0.88	0.21	0.32	0.059	97	14	68
Leucaena	1.04	0.27	0.23	0.020	114	18	50
Senna	1.34	0.23	0.28	0.004	148	15	59
Westbank 1							
Ctrl	1.37	0.32	0.1	0.004	130	18	19
Leucaena	2.36	0.73	0.43	0.000	224	42	79
Senna	4.34	0.91	0.64	0.000	413	52	118
Pueraria	1.03	0.34	0.12	0.01	98	19	22
Nat. regrowth	1.67	0.59	0.31	0.000	159	33	58
LSD	2.06	0.27	0.206	ns			

Table 6. Available Bray-I phosphorus (μg g^{-1} and kg ha^{-1}) under improved fallow management systems at 5-10 cm depth.

	Bray-I P (μg g^{-1})			Bray-I P (kg ha^{-1})		
site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
5-10 cm						
sec. Forest	27.3	22.1	26.1	17	12.6	14.8
Westbank 3						
Ctrl	2.9	2.2	4.2	1.7	1.3	2.4
Leucaena	3.3	2.8	5.3	2.1	1.5	3.0
Pueraria	3.5	3.1	4.6	2.2	1.7	2.6
Nat. regrowth	3.4	1.9	fallow	2.1	1.1	fallow
D 2						
Ctrl	16.3	17.7	14.8	9.0	9.8	8.4
Leucaena	6.6	14.1	16.9	3.3	7.8	9.3
Senna	12.7	12.6	20.1	6.6	6.9	11.6
Westbank 1						
Ctrl	4.4	2.9	4.6	2.0	1.4	2.3
Leucaena	2.0	1.2	3.1	1.0	0.6	1.3
Senna	5.7	2.6	4.5	2.3	1.2	2.2
Pueraria	3.5	3.3	4.7	1.7	1.6	2.2
Nat. regrowth	3.1	2.4	4.4	1.3	1.2	2.1
LSD	1.8	6.2	4.7	0.96	2.4	2.6

LSD (excluding forest) at $\alpha = 0.05$

Table 7. Inorganic and organic $NaHCO_3$ and NaOH-extractable phosphorus pools (μg g^{-1} and kg ha^{-1}) under improved fallow management systems at 5-10 cm depth.

site/depth	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}	$NaHCO_3$-P_i	NaOH-P_i	$NaHCO_3$-P_{org}	NaOH-P_{org}
	μg g^{-1}				kg ha^{-1}			
5-10 cm								
sec. Forest	33.9	49.6	9.2	77.9	19.3	28.3	5.3	44.4
Westbank 3								
Ctrl	3.7	9.2	6.1	45.8	2.1	5.2	3.5	23.8
Leucaena	6.1	10.2	8.0	51.0	3.1	5.3	4.3	28.4
Pueraria	6.6	14.5	8.3	45.6	3.7	7.6	4.7	26.0
Nat. regrowth	7.1	10.9	7.4	41.7	3.5	5.8	4.2	23.5
D 2								
Ctrl	17.6	37.3	11.7	71.5	9.7	20.6	6.5	39.5
Leucaena	10.6	39.4	11.1	74.0	5.9	21.8	6.1	41.0
Senna	18.7	44.4	12.3	64.5	9.5	24.5	6.6	35.5
Westbank 1								
Ctrl	7.9	21.2	10.0	50.0	3.5	10.3	4.6	24.3
Leucaena	6.5	18.4	9.0	61.3	3.1	8.8	4.3	29.2
Senna	10.1	30.4	8.8	83.2	4.8	15.9	4.4	39.6
Pueraria	7.9	20.8	10.1	63.1	3.7	9.8	4.8	30.0
Nat. regrowth	6.3	18.2	9.1	50.1	2.7	8.9	4.2	25.1
LSD	5.5	12.3	3.1	24.1	2.9	6.6	1.6	12.9

LSD (excluding forest) at $\alpha = 0.05$

Table 8. Average soil microbial biomass carbon (kg há^{1}) under improved fallow management systems at 0-5 cm and 5-10 cm depth in 1993 and 1994.

	Microbial biomass (kg ha^{-1})					
Site/depth	**1st season**	**dry season**	**2nd season**	**1st season**	**dry season**	**2nd season**
		0-5 cm			***5-10 cm***	
sec. Forest	165	133	205	80	69	106
Westbank 3						
Ctrl	82	65	83	45	49	42
Leucaena	90	88	109	44	42	
Pueraria	125		135	71	68	80
Nat. regrowth	87	96	100	58	49	48
D 2						
Ctrl	51	44	33	25	39	18
Leucaena	75	59	45	37	40	18
Senna	93	56	71	41	56	36
Westbank 1						
Ctrl	34	27	27	24	25	19
Leucaena	65	53	58	36	44	23
Senna	93	56	71	41	56	36
Pueraria	48	30	39	27	39	24
Nat. regrowth	48	34	49	27	25	22

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