POTENTIAL OF *Tephrosia vogelii* Hook F. AND *Tithonia diversifolia* (Hemsley) A. Gray SHORT DURATION FALLOWS FOR IMPROVING THE PRODUCTIVITY OF MAIZE IN WESTERN KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university

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Potential of *Tephrosia vogelii* Hook F. and *Tithonia diversifolia* (Hemsley) A. Gray short duration fallows for improving the productivity of maize in Western Kenya

GENERAL ABSTRACT

Earlier studies showed beneficial effect of 1 to 3 years-improved fallows on maize production compared to the natural fallow. This period however is still too long for small-scale farmers who must use the land to produce food at least once a year. In fallow systems the rotational effect and the effect of above ground biomass on maize yield have not yet been studied separately. The objective of this study was to evaluate the potential of *Tephrosia vogelii* and *Tithonia diversifolia* short duration fallows in improving soil fertility and maize yield when compared to the natural fallow and continuous maize crop with or without fertilisers. Two cycles of *Tephrosia*, *Tithonia* and natural vegetation six-month fallows alternating with two consecutive maize crops were grown at Maseno, in Western Kenya on well-drained deep clay soils low in available nitrogen (N) and phosphorus (P). At the fallow cutting time, the biomass produced and nutrient accumulated were quantified and decomposition patterns determined. The fallow biomass were applied to the maize crop as fertiliser input and each plot was then split into two for 0 and 20 kg inorganic P addition. Soil samples were taken at the beginning and the end of each fallow and crop season.

Both, *Tephrosia* and *Tithonia* produced more biomass than the natural fallow vegetation. Roots obtained from 0 to 45 cm soil depth were a significant component and contributed 18, 36 and 65 % of total biomass and 15, 8 and 21% of total biomass N for *Tephrosia*, *Tithonia* and natural fallow, respectively. *Tithonia* produced more litterfall than the other two fallows. *Tephrosia* material and *Tithonia* litter and above ground biomass had higher N content, compared to the natural fallow biomass. The proton consumption capacity of *Tithonia* leaves was high, about 50 cmol(+)/kg of biomass while that of *Tephrosia* materials, natural fallow leaves and maize stover was medium, about 20 cmol(+)/kg. Natural fallow roots mainly comprising of *Digitaria sclarum* rhizomes had the least proton consumption capacity. *Tithonia* leaves decomposed very fast while *Tephrosia* stems, *Tithonia* and natural fallow roots were the slow to decay. More than 80 % of nutrients accumulated in the mixture of *Tithonia* leaves plus stems were released during the first month after biomass incorporation into the soil whereas *Tephrosia* and natural vegetation biomass required two to three months to get the same percent nutrient release. Grain yield of the maize following the shrub fallow was about 2.5 to 3 Mg ha^{-1} compared to continuous maize crop which produced 1.3 Mg ha^{-1}. Inorganic P added to these systems increased the yield by about 40%. Plots where the biomass was removed produced less maize, compared to the fallow or biomass incorporated systems. The yield of maize subsequent to the natural fallow was lower compared to that of the maize following the shrub fallow, but higher than that of the continuous cropping system. The effect of organic and inorganic P inputs on the second and third maize crop decreased progressively over time. No significant changes in soil bulk density and chemical properties were found at the fallow cutting or at the maize harvesting periods. However, mineral N was leached down the soil profile during the first maize-growing season.

The various organic inputs obtained from the three fallow species were all low in P and showed different nutrient release patterns. When these inputs were applied to the crop at the same time, the pattern release of nutrients was not always properly matching with the maize nutrient requirement stages. Three observations, namely: an N deficiency in plots where large amount of *Tithonia* biomass was applied, a lack of effect of fallows or single biomass application on soil properties and a decrease over seasons of the effect of biomass on maize performance indicated that sustained crop production can not be obtained with one short duration fallow. In highly depleted soils, ‘fallow-maize-fallow’ rotation may be more sustainable than ‘fallow-maize-maize-fallow’ or ‘fallow-maize-maize-maize-fallow’ rotations. In a no-fallow system, application of biomass once or twice a year will be more beneficial than a single application every 3 or 4 cropping seasons

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CHAPTER 1: GENERAL INTRODUCTION

1.1. BACKGROUND

Many African countries are faced with food shortage. This is mainly due to rapid population growth, climatic hazards, inappropriate agricultural techniques and soil fertility degradation through erosion and insufficient use of fertilisers. The latter aspect could be related to the low income and the inadequacy of farmers' education for maximising the use of the locally available resources. In the bimodal highlands of Kenya, only a few farmers (less than 40%) apply fertilisers to food crops (Minae and Akyeampong, 1988). Moreover, most of these 40% do not apply the fertilisers at the recommended rate. An alternative that can be used is low-input agroforestry technologies. Among these, alley cropping and fallow are used for restoring soil fertility in nutrient depleted fields.

Alley cropping is a production system in which trees/shrubs are established in hedgerows on arable crop land with food crops planted in the alleys between the hedgerows (Kang *et al.*, 1981). Fallow consists of leaving land to lie idle, either tilled or untilled, during the growing season (Huxley and van Houten, 1997). Inclusion of tree/shrub component in cropping system could generate beneficial interactions, which include recycling of soil nutrients from deep layer by deep roots (Nair *et al.*, 1994), addition of organic matter and nutrients from litterfall and tree prunings (Jama, 1993; Schroeder, 1995), N_2-fixation by N_2-fixing legumes (Peoples and Craswell, 1992), mobilisation of some unavailable soil nutrients (i.e. phosphorus) into organic forms through the scavenging nutrient uptake by some trees/shrubs and improvement of soil physical and soil water status (Lal, 1989). Appropriate trees can increase the efficiency and the products of fallow (Raintree and Warner, 1986) and cropping systems.

The major advantage of alley cropping over the fallow system is that the cropping and fallow phases can take place concurrently on the same land, allowing the farmer to crop the land for an extended period. The constraint with alley cropping is the competition between trees/shrubs and crops for light, nutrients and water (Kang, 1995) while the area under and the duration of fallow depend on land and labour availability during the peak periods in planting, weeding and harvesting.

No-tillage has been found to increase the concentration of carbon (C) and nitrogen (N) in the 7.5 cm surface depth of soil (Doran, 1980; Ismail *et al.*, 1994). High C, N and soil water content results in great soil microbial biomass activity which increases short term immobilisation and long term mineralisation of organic nitrogen (Brown *et al.*, 1993). Thus, fallow trees/shrubs and cover crops that are efficient in soil fertility restoration need to be identified. This justifies a study on soil biological and chemical effect of the short duration enriched fallows. The fallow effect may be improved by applying levels of inorganic fertiliser such as phosphorus that is generally low in many Ultisols and Oxisols of tropics (Sanchez, 1976). The preliminary results from a nutrient flow experiment in Siaya and Vihiga Districts, Western Kenya, showed the importance of P inputs in increasing crop yield (Braun, 1995) and this needs to be better understood.

1.2. JUSTIFICATION OF THE STUDY

The highlands of Central and Eastern Africa (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda) have a high population density (Wang'ati, 1994). The farms have become relatively small and are often under continuous cultivation that could increase the rates of organic matter decomposition leading to enhanced C and N mineralisation (Wadsworth *et al.*, 1990; Ismail *et al.*, 1994). This was observed in western Kenya (Heinman *et al.*, 1990). Income from such farms is far below the subsistence requirements (Minae and Akyeampong, 1988) while level of organic (e.g., legumes, green manure, crop residues, animal manure) and inorganic fertiliser application is insufficient for good crop production. The amount of farmyard manure for improving soil chemical and physical properties (IBSRAM, 1989; Tandon, 1992; Eghball *et al.*, 1995) is limited and the use of inorganic fertilisers is constrained by availability of capital and the uncertainty of ideal weather conditions for crop production (Jama *et al.*, 1997). Crop residues are removed from the fields and used as fodder, firewood or are burnt in the field leading to a great loss of nutrients by volatilisation, erosion and leaching and physical mining. Thus, the farmers experience a gradual decline in soil fertility especially in crop fields, leading to a decline in crop yields. Sanchez and van Houten (1994) pointed out that high crop yields can be obtained using integrated nutrient management approaches which include conservation tillage, crop rotation and judicious use (e.g., small dosages and frequent applications) of inorganic fertilisers, lime and organic inputs.

A survey carried out in western Kenya by Swinkels *et al.* (1997) showed that 50% of the farmers periodically let 10-50 % of the land lie natural fallow for at least a short period of six months, mainly for soil fertility restoration. These fallows that are a component of a rotation system with continuous maize cropping have a vegetation whose quality in terms of C:N ratio, lignin content etc. and productivity are generally low. The short fallow period combined with the low quality and quantity of natural fallow biomass make this technology ineffective in restoring soil fertility. The use of such a bush fallow normally requires a period of many (2-20) years for soil fertility restoration to be achieved (Kang and Wilson, 1987; van Reuler and Prins, 1993). Long-term addition of organic material to the soil increases soil organic matter, crop productivity and soil biological activity (Collins *et al.*, 1992; Chander *et al.*, 1998).

Since the long period fallows are not applicable to the farmers who are confronted with land shortage, short biologically enriched fallow may be a useful alternative to natural fallows (Kang and Wilson, 1987). Such an improved fallow is defined as "a targeted use of carefully selected plant species in an ordinary fallow land in order to achieve one or more of the benefits of natural fallow within a short time or on a small area of land" (Prink, 1986). For example, ICRAF (1995) found that one and two year-old fallows of *Sesbania sesban* grown in N-depleted soils in Zambia had a potential to increase the grain yield of subsequent maize crops even without fertilisers. The average yield from three crops following two year-old fallow was 3.5 Mg/season and higher than 1.7 Mg/ha obtained after one year old fallow, which was in turn higher than 1.2 Mg/ha obtained with the unfertilised continuous maize crops.

Different experiments on shrub fallow species and leaf biomass application as green manure have been conducted in Western Kenya where soils are N or N and P (phosphorus) depleted (Jaetzold and Schmidt, 1982). *Tephrosia vogelii* and *Tithonia diversifolia* species seem to be adapted to Western Kenya (Amadalo *et al*, 1995). These species were tested as fallows planted for a period of more than one year to improve soil fertility. The on-going trials at Maseno (Amadalo *et al.*, 1995) are neither adequately addressing the importance of litterfall and roots as source of soil organic inputs and plant nutrients, nor the soil depletion through the removal of above ground biomass. Roots are expected to enrich soil with organic matter, reduce nutrient leaching, recycle nutrients from the subsoil below the crop rooting zone, contribute N_2-fixation and improve soil physical properties (Lundgren, 1979). Soil fertility improvement depends on above ground biomass and root biomass and abundance at various depths and different distance away from the plant/shrub. According to ICRAF (1989), the short term fertility effects of tree are associated with decomposition of leaf litter, while long term effects are related to root decomposition and improvement in soil physical properties. Thus, monitoring root system is an important aspect of agroforestry research (Govindarajan, 1996).

Another knowledge gap for the current fallow experiments at Maseno is insufficient studies on biomass decomposition patterns. Organic inputs are converted into available nutrients and soil organic matter through the process of decomposition and mineralisation (Sanchez and van Houten, 1994). Leaves and roots rapidly rot after trees / shrubs are cut or remain undecomposed for a long-time. Since the chemical composition of organic inputs affects the rates of decomposition and nutrient release (Swift *et al.*, 1979), the quality biomass parameters which include % N, C:N ratio, polyphenol:N ratio, lignin:N ratio (Melillo *et al.*, 1982; Palm and Sanchez, 1991; McDonagh *et al.*, 1995) need to be determined for roots and above ground biomass. The rates of *Tephrosia vogelii* and *Tithonia diversifolia* decomposition and the fate of released nutrients are not known (Fungameza, 1991).

Legume rotations have often been recognised as an effective way of maintaining soil fertility in N-limited soils (Sanchez, 1976; Petrickova, 1992). The current question was whether organic inputs produced by the six month-old *Tephrosia vogelii* and *Tithonia diversifolia* fallows and used as green manure could supply adequate amount of nutrient as well as sustain crop production in N or N and P-depleted soils of Western Kenya. Preliminary data obtained from 12 month-old fallows showed that N balance between N exported through the wood and that held in the leaves of *Tephrosia vogelii* and *Tithonia diversifolia* was positive while P balance was negative (Niang *et al*, 1996). Due to this information, the importance of supplying mineral phosphorus to the shrub biomass incorporated into the soil for improving crop yields needs to be assessed.

1.3. OBJECTIVES

The broad objective of the study was to assess the potential of the six month-old fallow to improve soil fertility and sustain maize yields. This would be achieved through the following specific objectives:

1.3.1. Specific objectives

1. To evaluate biomass production and nutrient accumulation of three different fallows as compared to maize crop;

2. To determine the decomposition patterns of below and above-ground biomass obtained from the six month shrub and natural fallows;

3. To evaluate the effects of fallows and continuous maize system on soil nutrient content and maize crop performance; and

4. To assess the importance of supplementing the above cropping systems with mineral phosphorus on maize yield.

1.3.2. Research Hypotheses

1. *Tephrosia vogelii* and *Tithonia diversifolia* grow faster than natural fallow vegetation, produce large amount of biomass that accumulate high amount of N, P and other nutrients than natural fallow.

2. *Tephrosia* and *Tithonia* biomass release plant nutrients quickly when they are incorporated into the soil.

3. Biomass inputs from the six-month-old fallow of *Tephrosia vogelii and Tithonia diversifolia* improve bulk density and pH, organic carbon, nitrogen and base content in nutrient depleted soils.

4. Incorporation of shrub biomass supplemented with mineral P fertiliser increases maize yields and provides significant residual effect.

1.3.3. Organisation of the study

Activities and research findings are presented in chapters as follows: Chapter one introduces the subject and the objectives of the study. Chapter two reviews the knowledge and the gaps in existing literature. Chapter three describes the characteristics of the experimental site and the general methodology followed during the fieldwork and data analyses. Chapters four, five, six and seven present the detailed materials and methods, results, discussion and conclusion in relation to various experiments while chapters eight and nine give the overall discussion and conclusion derived from the study, respectively.

CHAPTER 2: LITERATURE REVIEW

2.1. CROPPING SYSTEMS

Land can be used for woodlots, forests, pasture, crops and others (Buigutt, 1987). This variation in the land-use is due to the variation in biophysical and socio-economic factors in a given area (Minae and Akyeampong, 1988; Rai, 1995). Thus, many land-use systems including various cropping systems are identifiable in Western Kenya. Crops may be grown as monocrops where one species is planted or as intercrops where two species or more are simultaneously grown on one piece of land (Steiner, 1982; Wortman and Allen, 1994). Intercropped species may be planted at the same time or relay planted in the season. In the two systems, the same species may be planted continuously or rotated with other species over time. The practice of intercropping crop (s) and woody perennial species are called agroforestry systems (Kang *et al.*, 1981). Lundgren (1987) defined agroforestry systems as "all land-use systems or practices in which woody perennials are deliberately grown on the same land management units as crops and/or animals with an aim of optimizing the economic and ecological interactions between the components".

Many Western Kenya food-cropping systems are maize-based (Wortman and Allen, 1994) and need fertiliser inputs to give high yields (Furp, 1994). Green manure can be provided to the cropping system through improved fallow that is grown and plowed under the same field in rotation with the crop to be benefited. Alternatively intercropped green manure plants generally legumes are also grown and plowed under the same field with the crop and sometimes green biomass are cut and brought from elsewhere to the field for application (biomass transfer) (Yost and Evans, 1988).

Agricultural practices in the food crop-based-system of Western Kenya are at subsistence level and have evolved over the years from trial-and-error by the farmers to meet the daily demands of food, fodder and wood (Buigutt, 1987). A forest or a bushland can be cut and replaced by a food crop system, while an exhausted food crop field can be left into fallow (van Reuler and Prins, 1993). In the later case, because of no-tillage, soil generally accumulates higher levels of organic matter in the surface soil, microbial biomass and potential mineralisable N as compared with conventional tillage (Doran and Smith, 1987). Generally, crop rotations that include legumes or manure amendments maintain or even increase total C and N contents in the topsoil compared to continuous monoculture with little or no organic inputs (Dick, 1992; Varvel, 1994; Carsky *et al.*, 1997).

Any cropping system is characterised by its proper ecological (soils, climate, landscape), social (population needs and priorities), economic (labour, farm income, marketing) and managerial (field size, spatial arrangement, other main components) conditions (IBSRAM, 1987). A sustainable development can only be achieved if cropping systems developed are economically viable in the short run and maintain the natural resource productivity in the long run (Norman and Douglas, 1994). For a cropping system, it is important to identify the potential for development and the limiting factors to alleviate in order to limit its degradation and raise the productivity. More sustainable cropping systems may result from changing the ways in which the soil is managed for improving physical, chemical, and biological properties. Some cropping systems are not sustainable because soil and plant management systems have been separated rather than integrated (Norman and Douglas, 1994). For example, maize is the most soil nutrient exhausting crop that requires the highest nutrients per unit area. However, it is continuously planted on depleted soils in Western Kenya (Jaetzold and Schmidt, 1982) resulting in low crop yield (Jama *et al.*, 1997) and worsening soil fertility depletion.

Agroforestry systems consisting of cereals, legumes and perennial plants such as trees can increase soil productivity through tapping nutrients and water from deep soil depths (Young, 1997) and through N_2-fixation (Sprent, 1987). Cropping system sustainability means a long-term equilibrium between the exploitation of natural resources and their potential and has to be restored as an absolute condition for safeguarding the environment (Geerling and de Bie, 1986). According to Hart and Sands (1991), sustainable cropping systems focus on the following principles:

- Achieving short-term economic viability,
- Using inputs, which preserve the natural resources against degradation,
- Using natural resources while at the same time regenerating their productive potential,
- Maintaining the productivity of the system at a level not exceeding the productivity of its resources (e.g., soil fertility restoration with rotational systems involving fallows is more efficient and more appropriate when and where zero grazing system is adopted at the same time (personal observation)).

The impact of improved fallow on crop production has been found beneficial in Zambia (Kwesiga and Coe, 1994), Tanzania (Fungameza, 1991) and elsewhere (Lee, 1989;

Pommer, 1994). The "sustainable farmers" in the United States of America primarily utilise traditional methods such as animal and green manures, crop rotations, cover crops and a more diversified crop mixture, in place of inorganic fertilisers and chemical pesticides (Hanson *et al.*, 1995). However, it should be remembered that replacement of lost plant nutrients with fertilisers and practices which optimise the efficient use of applied fertilisers constitute an equally valid and often more economic nutrient management strategy (Woomer and Swift, 1994).

Soils in subhumid tropics (e.g., Western Kenya) are predominantly of low-activity clay (Sanchez, 1976) and therefore, have inherent low cation exchange capacity (C.E.C.). An integrated soil fertility management system, combining the use of chemical amendments, biological and organic nutrient sources appears the most appropriate system to ensure sustainable soil fertility and productivity (Kang and Wilson, 1987). High biological activity in warm and humid climates reduces the effectiveness of green manure and other organic materials to increase soil organic matter levels in cultivated soil (Giddens, 1957).

2.2. ORGANIC MATTER

Living animals, micro-organisms, above and below ground plant parts and their debris form organic matter (Brady and Weil, 1999). The below ground biomass is commonly called soil organic matter and is an important regulator of numerous soil characteristics influencing crop productivity (Woomer and Swift, 1994).

2.2.1. Above-ground biomass

Above ground biomass or aerial biomass includes live leaves of plants, twigs, branches, stems, aerial roots, some animal, litter and plant residues, compost and brown manure. This organic matter is easily quantifiable for different processes (growth rates and conditions, biomass production) and uses (nutrient supply, fodder). When there is little or no above ground biomass returned to the soil especially in tropical cropping systems, the decline in soil organic matter which follows frequently results in low plant yields (Lal, 1986; Woomer and Ingram, 1990).

2.2.2. Below-ground biomass

This is organic matter present or incorporated into the soil and includes live and non-living organic matter that constantly interact. Living biomass present as roots, micro-organisms and fauna rarely exceeds 4% of the total soil organic matter (Doran and Smith, 1987; Theng *et al.*, 1989). Below ground biomass can be separated into different fractions and is an important pool for soil fertility (e.g., release, availability and storage of nutrients, improvement of soil structure, soil porosity and water retention) (Lal, 1986)) and plant productivity (Woomer and Ingram, 1990). Tree/shrub below ground biomass includes fine roots (diameter < 2mm) and woody roots (diameter > 2mm).

Live and dead roots and debris play a major role in improving long term soil fertility status (ICRAF, 1989). Roots are expected to enrich soil with organic matter and nutrients and improve soil physical properties (Lundgren, 1979). Roots plus debris may contribute an important source of nutrients for crops (Barrios, 1995) while root growth and decay may play an important role in nutrient cycling where the nutrient cycles are closely tied to organic matter as in highly weathered soils (Sanchez *et al.*, 1989).

All aspects on root systems are not entirely known. This is due to the high labour and time required for evaluating root quantity and quality, variability in root locations and activity and to lack of easy techniques for the study of rooting systems (Caldwell and Virginia, 1991). The difficulties are often exacerbated for very fine roots and deep root systems. It is also difficult to find techniques for observing the root system at one point in time (morphology) and for studying root function and root growth. The extent of root proliferation in a soil is expressed in various ways, e.g., root length density (cm cm^{-3}), root biomass (g cm^{-3}), root surface area (cm^2 cm^{-3}), root spread (number of the root tips <2mm in diameter) in a unit area and root structure (vertical/horizontal arrangement of woody roots) (Van Noordwijk and Brouwer, 1992). Different methods are used for root studies, each method having some advantages and disadvantages (Taylor *et al.*, 1992). The most common are:

1. Excavation method (Rao *et al.*, 1993) that requires a lot of labour and time and involves loss of fine roots;
2. Monolith method (Nelson and Allmaras, 1969), which is expensive and time consuming;
3. Root observation through minirhizotron (Klepper and Kaspar, 1994) that requires expensive equipment and is not applicable to statistical randomisation;

4. Coring method (Anderson and Ingram, 1993) that is less expensive in money and time. Bohm (1979) and van Noordwijk *et al.* (1995) proposed the use of soil coring or monolith method to get the best quantitative information on root system biomass and root length per volume of soil.

In fallows, the tree species with a developed rooting system are probably preferable. In tree-crop associations, trees/shrubs with less lateral root extension and root length density in the topsoil are more adequate for reducing competition for water and nutrients. In the latter system, high root biomass with rapid turnover rates in the topsoil is needed for increasing carbon inputs while deep root system with high root length density in the subsoil is required for improving nutrient recycling (Schroth, 1995). A deep-rooted fallow vegetation can recover nutrients leached from the topsoil during the cropping period.

The importance of below ground competition depends on the tree species and the site conditions. For example, with wet and nutrient-rich sites, there are more competitive effects on above ground than on below ground plant parts (Putz and Canham, 1992). In order to favour deep-rooted tree fallow, a close spacing of trees can be adopted. Such a spacing leads to early intraspecific root competition and root-intensive understorey vegetation that dries out the topsoil and forces the tree roots into subsoil (Commerford *et al.*, 1984).

According to Fogel (1985), tree root biomass comprises of 15-25 % of the total biomass; for the grassland, below ground biomass can reach 75-85 % of the plant biomass. In humid tropics N uptake efficiency is related to the amount of rainfall in excess of evapotranspiration and rooting depth whereas N leaching rate increases in old tree root channels (van Noordwijk, 1989; van Noordwijk *et al.*, 1991). Crop roots can develop in these channels coated with some decayed organic matter that helps to detoxify aluminium (Tan, 1993). However, roots in channels are not very efficient for nutrient and water uptake because of their incomplete contact with the surrounding soils. In acid soils where shallow crop root systems develop due to subsoil toxicity, the rate of N leaching tends to be high.

For common tree crops, the horizontal roots spread within 20 m from the trees, the vertical spread in 1-2 m depth and most roots are concentrated in 0-50 cm depth (Atkison, 1980). For trees in general, structural roots constitute the essential component of the root biomass (weight/cm3) but account for little of the total root length (cm/cm3). Fine roots (diameter < 2mm) account for most of the length but very little for biomass. Root growth depends on the hereditary characteristics of species, soil properties such as texture, structure, temperature, water, aeration, nutrients and light (Herman R.K., Report of Department of Forest Science, Oregon State University).

The most important characteristic of a root system for water absorption and nutrient uptake is root density (cm/cm3) since the sharing of soil water and nutrients by competing plants is proportional to the effective root length (Sands and Nambier, 1984). This is illustrated by competition from weeds against crops. The ability of plant species to acquire nutrients from soil depends on root morphology (Barley, 1970), mycorrhizal or/and other biological associations, root exudation products and level of contact between soil and roots. Veen *et al.* (1992) found that in soils having pore volume of 44%, 51% and 60%, the average rate of root soil contact was 87%, 72% and 60%, respectively. The same author reported that root distribution was affected by soil compaction so water absorption and N uptake were generally high in medium porous soils and slightly low in the very porous soils. Per root length unit, water and nutrient uptake decreased from the compact to loose soil. When the porosity increases, the ratio fresh shoot/root weight increases but the ratio shoot/root length decreases. A very loose or well-aggregated soil can negatively affect crop growth. The effect of variation in soil bulk density on crop development follows the Gauss's curve and reflects the fact that root penetration is easier, oxygen supply better, water and nutrient uptake per root length unit restricted, in loose than in compact soils.

2.2.3. Phytomass production

Plant organic matter is mainly produced in forests and savannah, natural regrowth, agroforestry and cropping systems. The type and development of natural vegetation depend on soil properties and climatic conditions, particularly rainfall and temperature. Total biomass production in the equatorial preforest, secondary and primary forests of Zaïre varies between 19 and 32 Mg ha^{-1} yr^{-1} whose above-ground biomass ranges from 14 to 29 Mg ha^{-1} yr^{-1} and roots between 5 and 3 Mg ha^{-1} yr^{-1} (Bartholomew *et al.*, 1953; Mosango, 1991). Biomass production becomes lower in savannah areas.

The amount of biomass produced in relay and rotational natural fallows depends on the fallow species and duration. The duration of fallow is often determined by land availability. Fallow may last for 0.5 to 1 year where the land is scarce as in Western Kenya (Ohlson and Swinkels, 1993) and for 4 to 9 years where the land is still available as in Zaïre (FAO, 1998). Biomass production and nutrient recycling efficiency in fallow systems also depends on the management and the inherent fertility of the soil (Buresh, 1993; Sanchez and van

Houten, 1994). Regular burning and overgrazing decrease the rate of biomass production and reduce the species high in nitrogen and sulphur content (FAO, 1998). Fallows growing on infertile soils are less productive and recycle less amounts of nutrients than do fallows on relatively fertile soils (Schroeder, 1995). Soils low in nutrients can particularly reduce the biomass yield of legume species.

One of the objectives of agroforestry is to identify the techniques of producing high biomass in a short time and the best way of using it to achieve sustainable productivity in different land-use systems (Nair *et al.*, 1994). The fast-growing and preferably N_2-fixing shrubs and trees are suited to soil fertility improvement and better substitute for natural fallows (Prink, 1986). Some *compositae* species such as *Tithonia diversifolia* that produces an efficient green manure in the Philippines are desirable spontaneous species for fallows (Pandosem, 1986; Garrity and Amosoro, 1997). In Western Kenya, the most common species are *Sesbania* sp., *Calliandra calothyrsus*, *Leucaena* sp. *Tephrosia* sp., *Crotalaria* sp. and *Tithonia diversifolia* (ICRAF, 1996). Large amount of above ground biomass has been obtained with these species after a growth period of 1 to 2 years. Cereal crops leave residues to the soil after harvesting grains. These residues, weeds and other manure are important sources of organic inputs.

2.2.4. Biomass decomposition

When plant biomass are incorporated into the soil, some are converted into soil organic matter (Nye and Greenland, 1960) while others are mineralised into CO_2 and other inorganic and organic components (Brady and Weil, 1999). This transformation of biomass is done through the decomposition process, which is controlled by climatic and soil conditions (mineralogy, texture, moisture, aeration), biomass quality and nature of decomposer micro-organisms (Jannsen, 1984; Sanchez and van Houten, 1994; McDonagh *et al.*, 1995). In general, the rate of decomposition decreases with increasing C:N ratio (McDonagh *et al.*, 1995), lignin:N ratio (Melillo *et al.*, 1982) and polyphenol content (Palm and Sanchez, 1991). Biomass decomposition depends also on the plant age that increases lignification, exposed surface per gram of biomass and biomass (rates, application techniques and timing) management (Swift *et al.*, 1979; Theng *et al.*, 1989; Buchanan and King, 1993; Lugo and Brown, 1993; Nair *et al*, 1999).

The dead biomass (plant, animal, microbial debris and soil humus) is normally at various stages of decomposition, ranging from labile compounds that mineralise rapidly during the first stage of decomposition to more recalcitrant residues that accumulate (Woomer and Swift, 1994). The roots may provide high amount of organic material entering the decomposition. However, root biomass generally decomposes slowly compared to shoot material because of their high content of lignin (Woomer and Swift, 1994).

Litterbag technique is among the most common methods used in biomass decomposition studies (Anderson and Ingram, 1993). However, the decomposition patterns of biomass retained in litterbags may greatly differ with those of biomass incorporated in the cultivated soils since decomposition products are stabilised in the soil through complexation with mineral cations or clays (Woomer and Swift, 1994). Hendricksen and Robinson (1984) and Woomer and Swift (1994) reported that the phases of decomposition comprising of initial rapid decomposition of fresh biomass and labile fraction of soil organic matter and slow decomposition of rebuilt microbial products, cellulose and lignin are still comparable. When describing short-term (e.g. first year) mass loss where all the recognisable plant materials had not yet disappeared and comparing decomposition patterns of various biomass types, simple exponential model ($Y_{(t)}= Y_{(o)}\ e^{-kt}$) and exponential model with asymptote $Y_{(t)}= Y_a + (Y_o - Y_a)e^{-kt}$[1] fit well (Paustian *et al.*, 1997). These two models cannot be used for a deeper exploration of the mechanisms governing decomposition processes. Such study requires more complex models (Paustian *et al.*, 1997).

2.2.5. Organic matter as fertiliser and amendment

Nutrients needed for crop growth performance may be obtained from biomass tissues. For example, fresh litter from forests in Zaire contain an average of 15 g N, 0.7 g P, 9 g K (potassium), 14 g Ca (calcium) and 2.9 g Mg (magnesium) per kg of dry matter (Mosango, 1991). These nutrients when released to the soil through the decay processes improve soil nutrient status, hence soil suitability for crop growth performance.

Agroforestry technologies can improve soil fertility by increasing the level of organic matter in the soil through addition of leaf litter and other plant parts, efficient nutrient cycling within the system, through biological N_2-fixation and by improving soil physical properties and erosion control (Nair, 1984). According to the same author, agroforestry is not an approach to replace other profitable and stable production systems, nor is it a means to do

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[1] t: time of decomposition; Y_t: biomass remaining at given t; Y_0: biomass at t zero; Y_a: asymptote biomass; k: decomposition rate constant

away with nutritional input to soil through manure and fertilisers if sustained productivity at high level is to be achieved. In the absence of fertilisers or sufficient animal manure, agroforestry may be another practical means of replenishing N and other nutrients in exhausted soils (Giller and Wilson, 1991).

Incorporation of *Gliricidia sepium* and *Senna spectabilis* biomass in the Philippines hastened the maturity of maize crop by approximately 1 week and significantly increased the yields (Maclean *et al*, 1992). Kwesiga and Coe (1994) observed a beneficial effect of short fallow rotations with *Sesbania sesban* on subsequent maize crop in N-depleted soils in Zambia. In Kigoma (Tanzania), compared to the natural fallow, application of *Tephrosia vogelii* (TV) or *Crotaralia* sp. (CG) biomass and fertilisers significantly increased the yield of maize (Fungameza, 1991); high maize yields were obtained with application of high biomass quantity or when both TV or CG and fertilisers were applied together. Sprent (1987) reported that the use of legume plants to improve soil N status provided an alternative to chemical fertiliser in many parts of the tropics. Lory *et al.* (1995) showed that the maize crop following the *Medicago sativa* fallow needed little additional N to produce the maximum dry matter, compared to continuous maize crop. Other workers (Sanchez, 1976; Petrickova, 1992; Ladda *et al.*, 1996) have reported the positive effect of N_2-fixing legumes in maintenance of soil fertility in N-limited soils. The short term effects of tree/shrub on soil fertility are associated with the decomposition of leaf litter, while long term effects are related to the slow decomposition of roots and improvement in soil physical properties (ICRAF, 1989).

Increasing the organic matter status in the soil can result in an increased activity of favourable micro-organisms, better plant growth and high content in fulvic and humic acids which have high affinity for aluminium (Al), iron (Fe), calcium (Ca), Copper (Cu) and zinc (Zn) cations (Tan, 1993). By complexing these cations, organic matter contribute the capacity of soil Al detoxifying (Hue *et al.*, 1986; Hue and Amien, 1989), reduce the capacity of the soil to irreversibly adsorb P and hence, improve P and micronutrient availability (Harrison, 1987; Tan, 1993). In cropping systems of the tropics, organic matter is a major source of nutrients and an important reservoir for nutrients that would otherwise leach from the soil (Jordan, 1985). Crop responses to brown manure or compost may be explained in terms of chemical composition of the organic materials, particularly N, P, K and labile organic fraction content, their quantity and the timing of the application that ensures enough available nutrients just when needed by the crop. Compared to other nutrients, P is low in most organic inputs (Mosango, 1991; Maclean *et al.*, 1992; Palm, 1995), while N is high in N_2-fixing plants (Sprent, 1987). Nitrogen fixed by legumes becomes available from below ground plant parts (roots, nodules and mycorrhizal hyphae) and above ground parts (litterfall, plant residues) (Giller, 1992). In simultaneous and rotational systems (improved fallow), the potential to increase nutrient use efficiency arises through the capacity of tree/shrub roots and associated mycorrhizal/ symbiotic (Biu Kung'u, 1995) systems to take up nutrients from the soil or atmosphere.

Juo and Lal (1977) reported that returning large amount of high quality crop residues to an Alfisol might reduce the decline in soil organic matter due to cropping. However, the microbial biomass may restrict the nutrient availability to the plants because the micro-organisms seem to be competitively superior to use available soil N at least in a short run.

This is particularly true in zones with slight to moderate heat limitation, where an experiment with continuous straw addition to the soil showed N immobilisation and a negative effect of frequent straw baling on soil quality during the first few years (Nyborg *et al.*, 1995). Sanchez *et al.* (1983) reported that continuous cultivation of annual crops on humid tropical soils led to the decline in N availability and total soil N because of low quantity of organic inputs added to the soils. Such a decline reduces mineralisation of soil organic N and recovery of soil nutrients, leading to high nutrient losses by leaching. Thus, C, N, P, K, Ca, and Mg content in the soil are often used to investigate tree/shrub effect on degraded soil properties (Nyberg and Högberg, 1995; Young, 1997). To maintain yields in continuous cropping systems, supply of nutrients particularly N from fertilisers, manure and N_2-fixing plants is required (Doran and Smith, 1987).

2.3. SOIL NITROGEN

Soil N content can be maintained or restored through management practices such as adequate N fertilisation, green manuring and returning crop residue to the soil (Ismail *et al.*, 1994). Atmospheric N_2-fixation through legumes and rhizobium symbiosis is another alternative for improving soil N level. When low quality residues are used under humid climatic conditions, immobilisation of N fertiliser becomes a major factor that may result in low crop N recovery where no tillage is practised (Doran and Smith, 1987). Such residues may be supplemented with N fertiliser in order to improve the N use efficiency (Melillo *et al.*, 1995). The % of unaccounted-for N fertiliser in evaluating crop N recovery by crop is generally attributed to the loss of NH_3 from surface soil and plants (Francis *et al.*, 1993), denitrification losses (Tiedje *et al.*, 1984; Babbar and Zak, 1995) and NO_3-N leaching (Mekonnen *et al.*, 1997).

The effect of N fertiliser depends on its N rate, the methods and timing of application, source of N, tillage and cropping system, soil types and climatic conditions (Raun and Johnson, 1995). The best rates of N are those optimising the grain yield while minimising the potential for soil inorganic N accumulation (Westerman *et al.*, 1994). Nitrogen supply should not be in excess or imbalance to avoid some damage to the crop growth and production.

The type of N fertiliser has to be adequate to closely match several soil and crop N requirements. For acid soils for example urea that is less acidifying than other N fertilisers such as $(NH_4)_2$ SO_4 and $H_2NH_4PO_4$ is more adequate. However, application of urea produces H^+ through the following reaction: $NO_3(NH_2)_2CO + O_2 \rightarrow 2\ NO_3^- + 2\ H^+ + CO_2 + H_2O$) (Adams, 1984). The proton formed can only be neutralised by OH^- in the rhizosphere if the nitrate is completely recovered by plants and assimilated into organic N (Bolan, 1991). In this case, removing the excess of basic cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) over anions (Cl^-, SO_4^{2-}, $H_2PO_4^+$ and NO_3^-) through the crop harvest (van Reuler and Janssen, 1993) and NO_3-N leaching lead to permanent acidification. Since NO_3-N is highly soluble in water, it is very susceptible to leaching in tropical area, especially where annual rainfall is high (>1400 mm yr^{-1}) and average annual temperature cool (<18°C) (Rutunga, 1997). This reduces the plant production and N fertiliser-use efficiency and may cause contamination to the ground water. Reduction of nutrient leaching may be achieved through an addition of organic inputs that increase N immobilisation (Bunyasi, 1997). However, some N may be lost by denitrification as the available carbon from organic inputs in decomposition (McKenney *et al.*, 1993) and the microbial respiration increase O_2 consumption (Aulakh *et al.*, 1991), thereby increasing anaerobic microsite formation.

Application of urea especially on the soil surface produces NH_3-N (Gould *et al.*, 1986) that increases pH around fertiliser particles and dissolves some soil organic matter (Chien *et al.*, 1987). This improves soil P availability and efficiency by decreasing P fixation with Fe and Al compounds (Fan and MacKenzie, 1994). Increasing soil P availability improves crop P uptake.

2.4. SOIL PHOSPHORUS

There are three forms of soil phosphorus: P (organic and inorganic) in soil solution, insoluble inorganic P and P immobilised in organic matter (Tisdale *et al.*, 1990). The organic P concentration can exceed inorganic P in soil solution due to low sorption of organic P (Yuen and Pollard, 1951). Plants contain both inorganic and organic P, but in P deficient plants, organic P form is the most dominant (Barr and Ulrich, 1963). However organic materials are generally low in P (Palm, 1995).

P deficiency may be due to low soil P availability for plant uptake or due to lack of P in soils (Giller and Wilson, 1991). According to Mallarino (1996), soils are low in available P for the values below 8 to 15 mg P/kg (Bray-P 2 method). Phosphorus sorption is a major process controlling P availability in acic Oxisols and Ultisols (Sanchez and Uehara, 1980), the most dominant soils in Western Kenya. This P fixation increases with increasing clay and kaolinite content, Fe and Al sesquioxides, exchangeable Al and amorphous colloid content, but decreases with increasing organic matter level and flooding. Le Mare *et al.* (1987) reported that green manure increased the long-term efficiency of P fertilisation. Soil organic matter does not adsorb P unless it is associated with cations such as Fe^{+3}, Al^{+3}, and Ca^{+2} (White, 1981) but additional fresh organic inputs may block the cation adsorption sites and again decrease P sorption (Matar *et al.*, 1992; Iyamuremye and Dick, 1996). The net outcome of these competing processes varies. When a soil is P deficient, any build up of organic P requires addition of organic inputs and P. Chauhan *et al.* (1979) showed that addition of cellulose to the soil increased microbial activity that increased organic and inorganic P content and this was true only when P was added to the cellulose.

Use of P fertilisers improve crop growth and yields as observed with beans in P deficient neutral soils in Kenya (Ssali and Keya, 1983). Although the crops use inorganic and labile P (soluble in H_2CO_3), the decrease in soil P due to the crop exportation mainly affect organic and stable P that constitute the mineralisable pool. Some crop species (e.g., maize) and crop rotation enhance VAM infection that increases the efficiency of low P rate application in soils low in P (about 10 mg P/kg, Olsen method) (Chandrashekara *et al.*, 1995).

When dealing with P availability in soils, the rich countries can apply P in a very high rate as amendment while countries with limited resources can adopt the low input management strategy (Sanchez and Uehara, 1980). The latter approach is realised through improved placement methods, use of cheaper natural rock phosphates, lime application for decreasing P fixation and selection of plant species tolerant to P stress. The combined application of P, lime and organic matter had transformed some physically excellent acid Oxisols into highly productive soils (IBSRAM, 1989).

CHAPTER 3: MATERIALS AND METHODS

3.1. CHARACTERISTICS OF THE EXPERIMENTAL SITE

Experiments were conducted near the Kenya Forestry Research Institute (KEFRI), Maseno Agroforestry Research Centre at latitude 0°0' and longitude 34°35' E, on the boundary of Western and Nyanza Provinces in Kenya (appendix 3.1). The site is at an altitude of 1500 m above sea level with a slope of 4%. In general, the landscape is hilly and rolling. There are two growing seasons viz, the short- (September to January) and the long- (March to August) rainy seasons. The study was carried out from September 1996 to August 1999.

According to the agroclimatic zone map of Kenya (Sombroek *et al.*, 1980), the climate of the study area is classified as humid with a ratio of mean annual rainfall to average annual evaporation (r/Eo) of > 0.85. The rainfall distribution during the time the experiments were carried out (Figures 3.1 and 3.2) was variable. The average annual temperature varied from 20 to 23°C. The minimum and maximum temperatures were 6.5°C and 35.0°C respectively.

The primary natural vegetation namely the equatorial rain forest (Kokwaro, 1988) has been destroyed through intensive cultivation and replaced by wooded savannah (Philip, 1977) comprising of grass and shrubs such as *Tithonia diversifolia* and *Lantana camara* L.

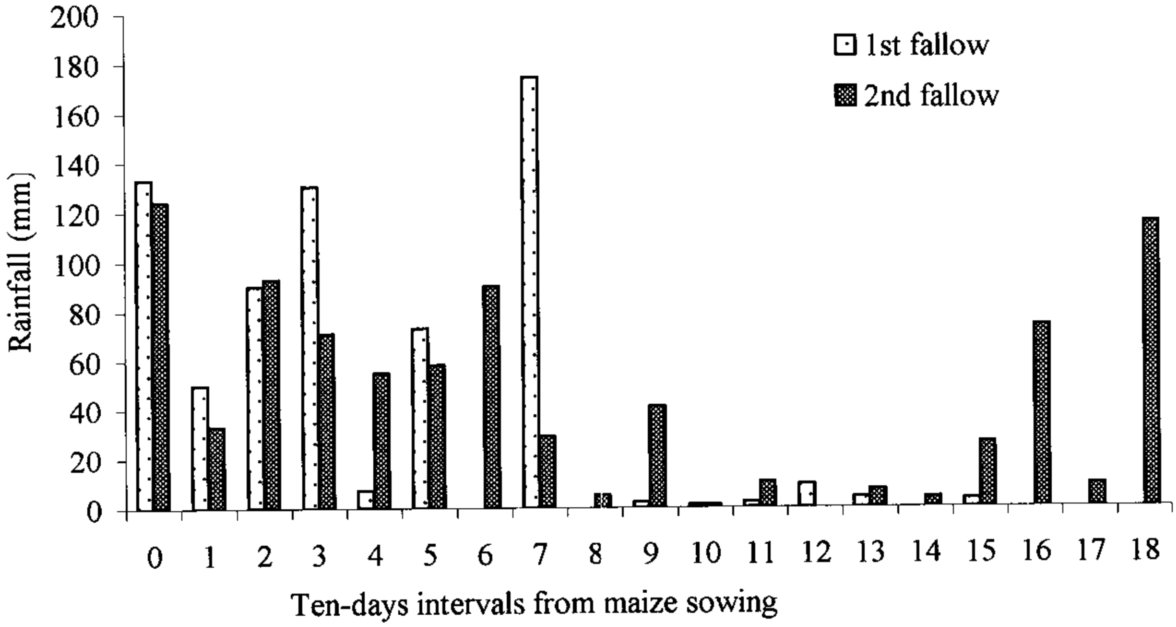

Figure 3.1a. Rainfall data during the fallow periods

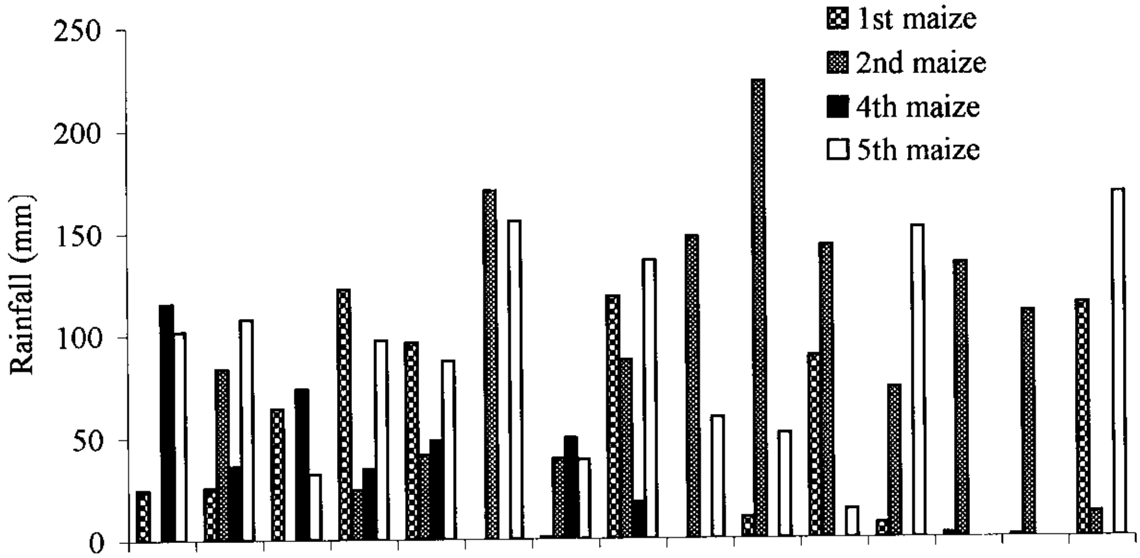

Figure 3.1b. Rainfall data during the maize cropping periods

At the study site, the most dominant species recorded in a three month-natural fallow were *Digitaria sp.* Haller (78%), *Senescio discifolius* L. (7%), *Crassocephalum vitellinum* Moench (6%), *Bidens pilosa* L. (3%), *Cynodon sp.* Rich. (2%), *Richardia brasiliensis* L. (1%) and *Leonotis mollissima* R.Br. (1%). In Western Kenya, the major land-use system is food crop-based system (Otieno *et al.* 1993). Maize (*Zea mays* L.) is the most common food crop followed by beans (David and Swinkels, 1994). *Striga hermonthica* Lour. and *Richardia brasiliensis* are the most important weeds (Frost, 1994; Hassan *et al.*, 1995).

The soils at the site are developed from basic igneous rocks. They are deep and well drained. A description of the soil profile is given in appendix 3.2. The texture is mainly clay (Table 3.1). The bulk density increases from 1.2 Mg/m^3 in the Ap horizon to 1.3 Mg/m^3 in the Bt horizons. Maseno soils are acid, low in available N, P and K particularly in the upper horizons. In one block, exchangeable Al content in the topsoil approached the critical level of toxicity (60 % of total cations) proposed by Sanchez (1976) for maize crop. The soils are classified as Humic Nitisols based on the FAO/UNESCO System (FAO-UNESCO, 1994), equivalent to kaolinitic, isohyperthermic Typic Kanhaplohumults in the USDA Soil Taxonomy system (Soil Survey Staff, 1996).

3.2. EXPERIMENTS

There were rotational field experiments comprising of fallow and maize crops (Table 3.2), a biomass decomposition study in field conditions and a laboratory study to analyse plant material and soils for nutrient content and physical properties. All this work was done from

Table 3.1. Physical and chemical properties of soils at the study site

Soil properties	Horizons and depth (cm)					
	Ap 0-20	AB 20-37	BA 37-55	Bt1 55-100	Bt2 100-135	Bt3 135-165
% sand (0.05-2mm)	26	22	18	21	22	18
% silt (2-50μm)	21	17	22	13	12	14
% clay (< 2μm)	53	61	60	66	66	68
pH (1:1, water)	4.1	4.7	4.5	5.0	5.2	5.4
pH (1:1, KCl)	3.4	3.7	3.6	4.0	4.4	4.8
C (g/kg)	18.0	11.0	7.0	3.0	4.0	3.0
Avail. Bray 2 P (mg/kg)	3.0	1.0	1.0	2.0	3.0	3.0
Total N (g/kg)	2.1	1.5	1.1	0.8	0.5	0.2
CEC (cmol(+)/kg)	19	16	16	10	14	13
Ca^{2+} (cmol(+)/kg)	0.3	1.0	1.0	1.3	1.5	1.7
Mg^{2+} (cmol(+)/kg)	0.7	0.9	0.9	0.9	1.2	1.2
K^{+} (cmol(+)/kg)	0.2	0.2	0.2	0.2	0.2	0.2
Al^{3+} (cmol(+)/kg)	0.6	0.5	0.4	0.03	tr*	tr

tr: trace

September 1996 to August 1999. The first experiment (Chapter four) was for assessing biomass production and nutrient accumulation by the six-month-fallow. The second experiment (Chapter five) was for evaluating the decomposition rate of and nutrient release by the biomass obtained from the first experiment. The third experiment (Chapter six) was for assessing the effect of biomass obtained from the first experiment and used as green manure on the maize yields. Chapter seven presents the changes in soil chemical and physical properties due to the fallow and biomass incorporation treatments. Materials and methods are more detailed in these subsequent four chapters.

Table 3.2. Treatments in the rotation system used in the study

Season	Sep. 96 to Mar. 97	Apr. to Aug. 97	Sep. 97 to Feb. 98	Mar. to Aug. 98	Sep. 98 to Feb. 99	Mar. to Aug. 99
Rotation system	1st fallow	1st maize crop*	2nd maize crop	2nd fallow/ 3rd crop**	4th maize crop*	5th maize crop
Treatments		Biomass incorporation			Biomass incorporation	
Tephrosia (Te) fallow (TeF)	Te	All plant material	Maize	Te	All plant material	Maize
(Te) biomass transfer (TeT)	Te	Litterfall and roots	Maize	Te	Litterfall and roots	Maize
Te biomass incorporation (TeR)	Maize	Maize stover and Te green biomass	Maize	Maize	Stover and Te green biomass	Maize
Tithonia (Ti) fallow (TiF)	Ti	All plant material	Maize	Ti	All plant material	Maize
Ti biomass transfer (TiT)	Ti	Litterfall and roots	Maize	Ti	Litterfall and roots	Maize
Ti biomass incorporation (TiR)	Maize	Maize stover and Ti green biomass	Maize	Maize	Maize stover and Ti green biomass	Maize
Continuous maize crop (CC)	Maize	Maize stover	Maize	Maize	Maize stover	Maize
Natural fallow (NF)	NF	All NF material	Maize	NF	All NF material	Maize

* Each plot was split with or without P fertiliser application; ** Third maize crop refers only to the treatments TeR , TiR and CC where the maize was planted.

CHAPTER 4: BIOMASS PRODUCTION AND NUTRIENT ACCUMULATION BY *Tephrosia vogelii* AND *Tithonia diversifolia* DURING THE SIX MONTH-GROWTH PERIOD

4.0. ABSTRACT

One year or more of improved fallows showed good potential for biomass production and nutrient accumulation but farmers in Western Kenya are faced with land shortage hence need a shorter fallow period. *Tephrosia vogelii*, *Tithonia diversifolia* and natural fallow were grown on N and P depleted soils for a period of six months and repeated after two consecutive maize crops. At cutting time, the amount of biomass for each fallow was determined and analysed for nutrient content and proton consumption capacity. Shrub fallows produced higher amounts of total biomass (> 9 Mg/ha) than the natural fallow. The amount of above ground biomass was the highest followed by litterfall and roots for each fallow. The roots were concentrated in 0 to 30-cm soil depth. The shrub accumulated more nutrients than the natural fallow biomass. Shrub leaves were high in N, K, Ca and Mg content, *Tephrosia* roots in N and K while *Tithonia* roots were low in N. All plant parts were low in P. Only *Tithonia* leaves had the highest proton consumption capacity. Removal of above ground biomass from field in the 1st fallow led to low biomass production and nutrient accumulation for the 2nd fallow.

4.1. INTRODUCTION

Western Kenya highland region has been under continuous cultivation since the late 1930's (Dickinson and Jensen, 1998) and this has led to the depletion of soil fertility. Many farmers in this region lack financial resources and are unable to use sufficient amounts of external nutrient input on the food crops (ICRAF, 1996; Sanchez *et al.*, 1997; Smaling *et al.*, 1997). Use of local inputs such as tree and shrub biomass, which are easily available in farms may be a potential solution to improve soil fertility.

Leucaena sp. Benth. and *Calliandra* sp. Benth. hedgerow prunings as source of green manure did ensure benefit to farmers although the technology had low adoption levels in the region (ICRAF, 1993). Improved fallow technology where legume shrubs such as *Sesbania sesban* (L.) Merr, *Tephrosia vogelii* and other plants such as *Tithonia diversifolia* were grown for a period of 12 to 24 months indicated a potential to improve crop yields (Kwesiga and Coe, 1994; ICRAF, 1995; 1996; Niang *et al.*, 1996). The period during which these shrubs/plants are grown do reduce land available for crop production and so, farmers are reluctant to let their land lie fallow for one to two years. The two-year period also results in large amount of woody materials, which accumulate some nutrients that are normally taken away from the field as fuel wood or rails materials (ICRAF, 1994; 1997). One strategy to overcome these problems may be to shorten the fallow period to no more than one season and to produce sufficient high quality biomass.

Species that are not useful for fodder or do not have other uses might be more appropriate as improved fallow species. *Tephrosia vogelii* and *Tithonia diversifolia*, which are not palatable to animals and are therefore not good fodder materials could be useful as green manure or improved fallow species.

The objectives of this study were: (1) to compare the production of biomass and the amount of nutrients accumulated by *Tephrosia* and *Tithonia* during a period of six months and that of the natural fallow, (2) to assess the effects of fallow and the removal of the above ground biomass of *Tephrosia* and *Tithonia* on the performance of the second fallow established after two maize crops and (3) to assess the residual effect of inorganic P applied to the first maize crop following the fallow on the performance of a second fallow season.

4.2. MATERIALS AND METHODS

4.2.1 Establishment of fallows

Two selected shrubs, namely *Tephrosia vogelii* provenance Yaoundé and *Tithonia diversifolia* provenance Maseno, and the natural fallow (NF) were assessed for biomass production and nutrient accumulation and compared to that of a continuous maize crop variety H 512. The fallows were a component in the crop rotation system namely "First fallow - first maize - second maize - second fallow" carried out on the same plots (Table 3.2). *Tephrosia, Tithonia* and the natural fallow had all bushy growth forms. The most dominant species recorded in a three-month natural fallow were given in Chapter 3.

4.2.1.1. The first fallow season (September 1996 to March 1997)

The four main treatments were: *Tephrosia vogelii* fallow[2], *Tithonia diversifolia* fallow[1], natural regrowth and continuous maize crop without fertiliser. These treatments were laid out in 7.5 m x 10.0-m plots in a randomised complete block design with three replicates. The blocking was done on a basis of a uniform crop of maize grown without fertiliser prior to the establishment of fallow. The plots were separated by a 2-m wide strip and trenched to 0.6 m.

Shrub seedlings were raised in the nursery according to agroforestry procedures as outlined by Kerkhof (1988) and Singh (1994). *Tephrosia vogelii* seedlings were inoculated with the

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[2] These treatments were in double so that the comparison between the effect of fallow and that of biomass transfer system could be done later

Bradyrhizobium spp. strain No.3384, provided by the Microbial Resources Centre (MIRCEN) of the University of Nairobi. The seedlings were inoculated twice, ten days after pricking out and at eight days before transplanting the seedlings in the field in order to improve the plant growth (Ding Ming-Mao *et al.*, 1994). Land preparation (digging and leveling) was done on 1st September, 1996. *Tephrosia* and *Tithonia* seedlings were transplanted at a spacing of 50 cm x 50 cm in early October, 1996. At this time, *Tephrosia* seedlings were well nodulated (more than ten nodules on each seedling) and had four leaves which had an average length of 15 cm. *Tithonia* seedlings had three leaves with an average length of 7 cm. Maize was planted on 15th September, 1996 at a spacing of 30 cm by 75 cm with two seeds per planting hole (Ministry of Agriculture, 1980). At two weeks after planting, the maize was thinned to one plant per hole. Weeding was done manually whenever the need arose in *Tephrosia, Tithonia* and maize plots. Natural fallow plots were only dug during land preparation and left undisturbed until the end of the fallow period. The fallow lasted for a period of six months (from September, 1996 to March, 1997) after which the fallow biomass was harvested. Maize stover and grains were harvested 4 months after planting.

4.2.1.2 The second fallow season (March 1998 to August 1998)

The second fallow was similar to the first fallow except for the following:

Before planting the first maize crop in April 1997, the above ground biomass obtained from the first fallow had either been returned to or removed from the plots (Table 3.2). The litterfall and root biomass had been returned into the soil. The main plots used in the first fallow had been split into two for assessing the effect of applying P (at 0 and 20 kg P/ha) from triple superphosphate on the crop performance. The stover obtained from the first and the second maize crops had been returned into the plots. *Tephrosia* seeds and non-split *Tithonia* cuttings (25 cm long) were used as planting material. Two seeds were placed in a hole at 2 to 5 cm deep, covered with soil, then thinned to one plant at 3 weeks after germination. There was no inoculation during the second fallow. Cuttings from mature *Tithonia* stems were planted in a slanting position with 2 nodes below ground and 2 above ground (Kendall and van Houten, 1977).

4.2.3. Data collection and statistical analysis

The growth rate of the fallows was assessed through height and percentage ground cover measurements. The height of sixteen randomly selected shrubs was measured at 15 days intervals in each plot from the date of planting to the time of harvesting. The plant (shrub and maize) height was measured from the ground to the stem tip or to the tassel. The percentage ground cover was recorded every month at about noon, using a square ruled 50 cm x 50 cm paper that was randomly laid down in the space between four plants. Shaded squares were counted and expressed in percentage of total number (100) of paper squares.

The production of biomass was assessed through litterfall, above ground biomass (leaves plus twigs plus stems) and root weight. Litterfall was collected at two-weeks intervals, using 1-m^2-quadrants. The first collection was done at 120 days after transplanting. The litter was oven-dried at 60°C for 48 hours, weighed and then bulked for a period of two months after which, a sample was ground and analysed for N, P, K, Ca and Mg. The fallows of the first and the second season were cut at six months after establishment. The above ground biomass was separated into the leaves/twigs and stems and weighed. A 50-g representative sample was taken for the moisture and nutrient determination. After this, the leaves plus twigs and the stems from each treatment were chopped and then mixed in weight ratio of leaves plus very soft twigs to stems of 2:1 for *Tephrosia* and 1.3 to 3.3:1.0 for *Tithonia*. These mixtures have been referred to as *Tephrosia* or *Tithonia* mixture in the text presented hereafter. For the natural fallow, all above ground biomass was mixed and called leaves. Representative samples of mixtures and NF leaves were taken following the same procedure as for leaves/twigs and stems biomass for the same chemical analyses. For maize, stover was separated from cores and grains, weighed and sampled for moisture determination and chemical analyses. All the samples were dried in the oven at 60°C for 72 hours then weighed for the dry matter content and ground for nutrient determination.

The below ground biomass was separated into small roots including fine (diameter <2mm) and coarse (diameter between 2 and 5 mm) roots and big roots consisting of primary taproots. Small roots were sampled from each treatment following the methods described by Van Noordwijk *et al.* (1985; 1995) and Anderson and Ingram (1993). The core sampling depths in this study were at 0 to 15 cm, 15 to 30 cm and 30 to 45 cm. For the 30 to 45 cm depths, mini-pits were dug for root sampling. Twelve sampling points were made in each plot. Small roots were separated from the soil by soaking and washing using water and a 0.5-mm sieve. Fine roots were manually separated from coarse roots using a 2-mm sieve. Small roots were dried in the oven at 60°C to constant weight to obtain the dry biomass. The primary taproots from 12 shrubby plants per plot were dug out to a depth of 45 cm for their fresh weight determination. After taking a sample for moisture determination, the remaining primary taproots were left in the field. The length of the lateral small roots was assessed at 75 days after planting by excavating some shrub plants.

Shoot and all root dry matter was ground for the determination of N, P, K, Ca and Mg content, following the procedures described by Anderson and Ingram (1993). Nutrients accumulated in the harvested biomass and litterfall collected over the period of 60 days were calculated by multiplying biomass nutrient concentration and biomass quantity. The proton consumption capacity of the plant part biomass, which is closely related to the level of basic cations and reflects the capacity of organic material to increase soil and soil solution pH and Al detoxification (Bessho and Bell, 1992; Bell and Bessho, 1993; Wong et al., 1995; Hairiah *et al.*, 1996a) was measured by titration of the organic material suspension (water/biomass weight ratio of 10:1) from its natural pH value down to pH 4.0, using 0.1 M HCl solution (Wong *et al.*, 1998).

To compare the above and below ground biomass production and nutrient accumulation in various treatments, the analysis of variance (ANOVA) following the Statistical Analysis System (SAS Institute, 1982) and Gomez and Gomez (1984) was used. Treatment means were compared, using the least significant difference (LSD) at the 0.05 level of p significance.

4.3. RESULTS

4.3.1. Fallow growth performance

4.3.1.1. The first fallow season

Generally the three fallows had poor growth performance (very dark green or yellowish stunted plants) in highly nutrient depleted plots. In relatively less depleted plots, the growth was better, but *Tithonia diversifolia* leaves turned yellowish at flowering stage. This would not be confused with the phenological yellowish colour that appears after the flowering stage for many species. At two months after transplanting, few nodules were found on the roots of *Tephrosia vogelii* up to 80-cm soil depth.

The average stem height was 138 cm for *Tephrosia* and 120 cm for *Tithonia* at six months after planting compared to 55 cm for natural fallow (Figure 4.1). The difference in average height growth between the two shrubs was about 2.8 cm/15 days and was about 1.9 cm/ 15 days between the shrubs and natural fallow. *Tephrosia* plants were not much affected by the low amount of rainfall received from December 1996 to March 1997 while the natural fallow and *Tithonia*'s leaves were wilting. Most of the shrubs had produced flowers by 165th day after transplanting. The maximum height attained by the maize and natural fallow was 113 and 55 cm respectively. During the first month, *Tephrosia* and natural fallow had the highest percentage ground cover, but *Tithonia* showed better performance than *Tephrosia vogelii* at later dates (Figure 4.2). Both *Tephrosia* and *Tithonia* produced significantly higher biomass than the natural fallow (Table 4.1). The amount of *Tephrosia* litterfall in six months was significantly less than that produced by *Tithonia*.

The roots of *Tithonia diversifolia* were healthy and their number was greater (about 9 roots per dm^2 in the top 30 cm of soil and at a distance of 8 cm from the base of the stem) than that of *Tephrosia vogelii,* which was about 6 roots per dm^2 in the same soil layer. The lateral roots for *Tephrosia* and *Tithonia* grew fast and were about 110 cm long at 75 days after planting. At this time, the taproot of *Tephrosia* attained 140 cm and that of *Tithonia* 120-cm depth. The taproot system of *Tephrosia* had reached a maximum length

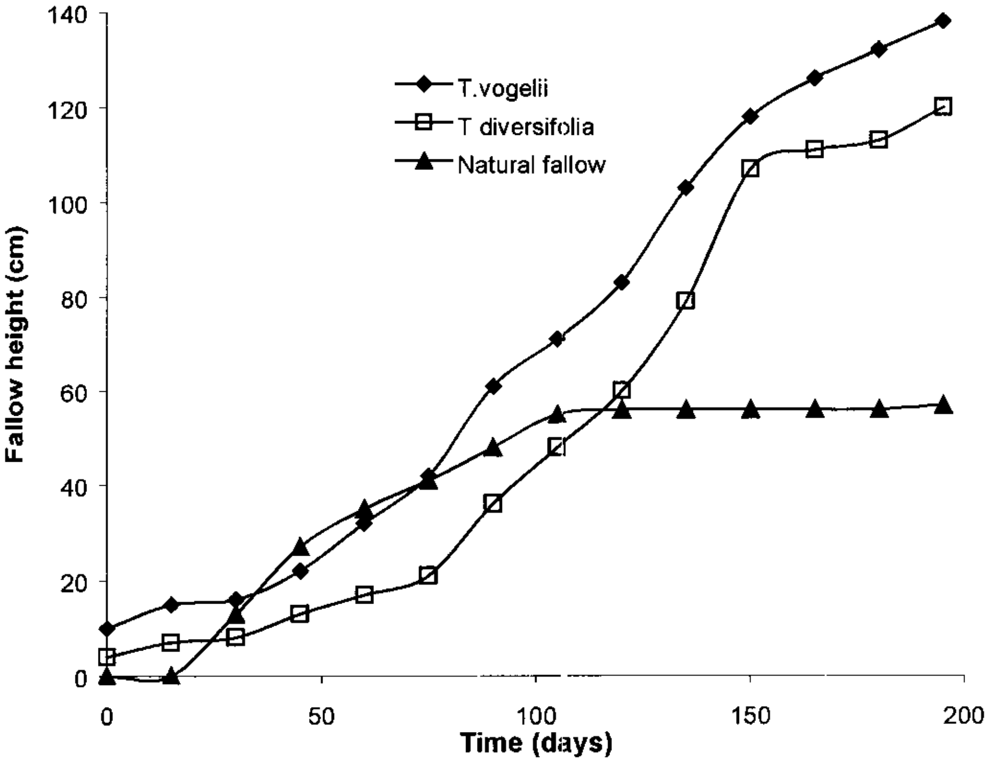


Fig 4.1. Cumulative height of the three fallow species during the growth period

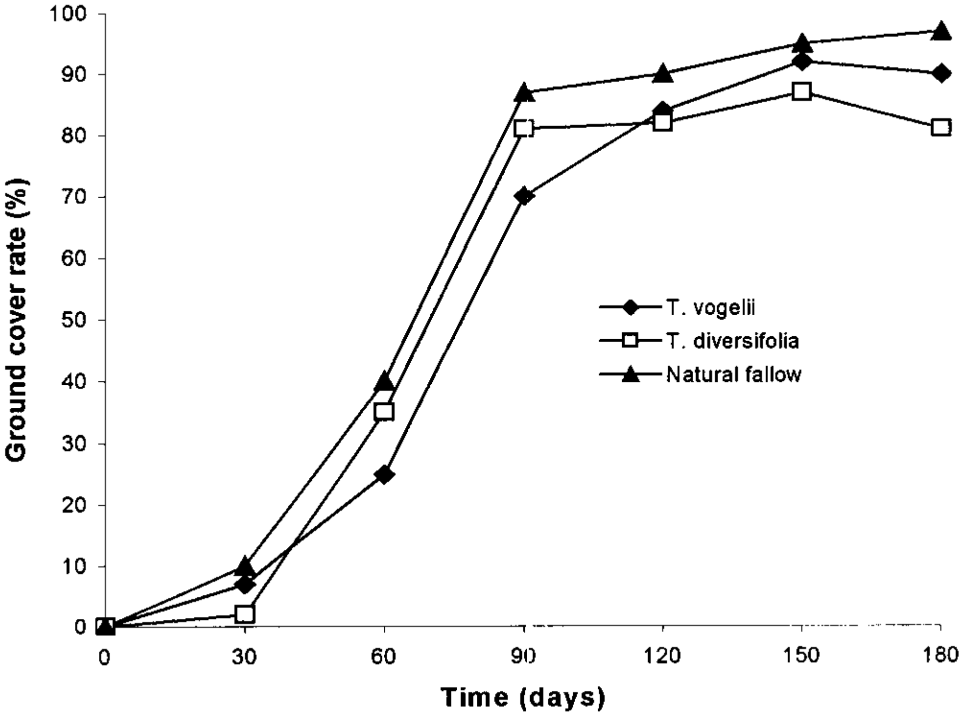


Figure 4.2. Cumulative percentage ground cover in the three fallows during the growth period

Table 4.1. Biomass produced (Mg/ha) by the first fallow during the six month-growth period

Fallows	Litter	Above ground biomass	Small root/stolon biomass in 0-45 cm soil depth	Primary taproots	Total biomass	Stem/ Leaves+ twigs ratio
Tephrosia	1.0	5.3	1.0	2.2	9.5	2:1
Tithonia	3.2	4.4	1.6	2.6	11.9	3.3:1.0
Maize	Nd*	2.2**	Nd	Nd	3.1***	Nd
Natural fallow	Nd	2.3	1.5	Nd	3.8	Nd
$LSD_{0.05}$	0.6	1.1	0.3	Nd	2.2	Nd

* Nd: not determined; ** Maize stover alone; *** Maize stover and cobs together.

of 225 cm at six months after planting. At the same time, the deep roots in natural fallow had reached 80-cm depth. A reduction in nodule number on *Tephrosia* roots was observed from the 60 day-old seedlings to the harvesting period. At this period, most small roots in the two shrubs and natural fallows were concentrated in the topsoil (0 to 15cm) and their amount decreased with soil depth (Table 4.2).

The amount of total biomass (root, litter and above ground biomass) was the highest for the two shrubs, followed by the natural fallow and then the maize. *Tithonia* produced more litter than *Tephrosia*. The ratio of litterfall to above ground biomass was about 1:2 for the two shrubs. The stem material in the shrub and natural fallows was not very woody and its weight ratio to leaves + soft twigs was still low (table 4.1), particularly for the natural fallow and *Tithonia* biomass.

Table 4.2. Average small root biomass (kg/ha) at various soil depths in the three fallows

Soil depth (cm)	*Tephrosia*	*Tithonia*	Natural fallow	Mean/depth	Maize*
0-15	523	902	777	734	193
15-30	359	448	526	444	69
30-45	132	236	97	150	29
Mean/species	336	528	466	466	97

$LSD_{0.05}$ for depth means : 133

$LSD_{0.05}$ for species means: 250

* Data from a poor maize crop grown in the same area (Mekonnen *et al.*, 1997), not used in the statistical analysis. Data obtained on maize crop during this study are given in appendix 4.1.

There were no significant differences in the amount of small root biomass among *Tephrosia vogelii*, *Tithonia diversifolia* and natural fallow and no significant interaction between species and soil depth. The root biomass of poor and medium maize crop (Mekonnen *et al*, 1997; appendix 4.1) was the lowest. The total small root biomass obtained from 0-45 cm depth in the three fallows was lower than the above ground biomass. The ratio of small root biomass to above ground biomass quantity for *Tephrosia*, *Tithonia* and natural fallow was 1:6, 1:5 and 1:1.5, respectively. The percentage of fine roots obtained from the small root biomass was 27-36 % for *Tephrosia*, 29-44 % for *Tithonia* and 5-18 % for the natural fallow.

4.3.1.2 The second fallow season

Direct seeding of *Tephrosia* delayed the plant growth in the beginning compared to the fast shooting of *Tithonia* cuttings, but these differences were no longer there at three months after planting. Flowering of *Tithonia* plants began at 70 days after planting and spread out during two months. Other growth characteristics were similar during the two fallow seasons. In general, the production of biomass was better in the second than in the first fallow. *Tithonia* (TiF) had the highest biomass production followed by *Tephrosia* (TeF) and the natural fallow (NF) (Table 4.3). At cutting time, *Tithonia* had more woody twigs in the first than in the second fallow. Plots where the biomass was removed had lower performance in term of biomass production than fallow plots (TeF>TeT; TiF>TiT). Phosphorus applied to the previous maize crop had no significant effect on fallow biomass production.

Table 4.3. Dry biomass produced (Mg/ha) during the second fallow in a six-month-growth period

Fallow treatments*	Litter biomass	Above ground biomass	Small root/stolon biomass in 0 to 45 cm horizons	Primary taproots	Total biomass	Stem/leaves + twigs ratio***
TeF	2.5	5.9	1.1	2.4	11.9	2.0:1.0
TeT	1.2	2.6	0.7	1.9	6.4	2.0:1.0
TiF	4.0	9.8	1.8	3.0	18.6	1.3:1.0
TiT	4.0	7.7	1.3	2.5	15.5	1.2:1.0
CC	Na**	(1.7)	Nd**	Nd	(1.7)	Na
NF	Na	7.6	1.6	Na	9.2	1.0:2.0
$LSD_{0.05}$	1.44	2.8	Nd	Nd	3.0	Na
No P	2.7	6.4	Nd	Nd	11.8	Na
Plus P	3.2	7.0	Nd	Nd	12.9	Na
$LSD_{0.05}$	0.5	1.1	Na	Na	1.2	-

*See the meaning of the treatments in Table 3.2; **Na: not applicable; Nd: not determined; ( ) Maize stover and cobs, not used in the statistical analysis; *** Leaves included a large amount of twigs.

4.3.2. Nutrient accumulation in the fallow biomass

The shrub biomass had high concentrations of N, K, and Ca but low P and Mg (Tables 4.4 and 4.5).

Table 4.4. Average nutrient concentration in the various plant parts of the fallow species at harvest.

Type of biomass	Nutrients (g/kg)				
	N	P	K	Ca	Mg
Tephrosia vogelii					
Tephrosia mixture*	19.0	0.6	12.3	9.0	2.2
Tephrosia leaves	30.5	1.2	15.7	13.0	4.7
Tephrosia litter	14.9	0.5	10.6	15.6	2.2
Tephrosia stems	10.0	0.8	7.8	14.8	2.8
Tephrosia small roots	24.3	1.4	20.5	3.3	2.0
Tephrosia primary taproots	6.4	0.3	1.8	4.0	0.5
Tithonia diversifolia					
Tithonia mixture	22.3	0.9	37.1	11.5	3.6
Tithonia leaves	30.0	1.8	46.0	19.1	3.7
Tithonia litter	14.3	0.5	28.8	7.9	5.5
Tithonia stems	16.6	0.6	16.8	4.8	3.5
Tithonia small roots	11.1	0.6	24.5	0.4	1.8
Tithonia primary taproots	8.4	0.5	5.7	1.4	0.8
LSD$_{0.05}$	3.0	0.5	1.8	4.9	2.0
CV%	11	29	6	26	30
Nat.fallow (NF)					
NF leaves	15.4	0.8	17.0	4.3	2.5
Nf roots/rhizomes	12.6	0.5	8.5	0.1	0.9
LSD$_{0.05}$	9.2	0.4	3.5	-	-
CV%	19	20	8	-	-
Maize					
Maize stover	10.8	0.6	10.3	3.7	3.3
Maize grains	13.7	1.1	18.4	trace	0.5
Cores	7.7	0.5	13.0	trace	0.5
LSD$_{0.05}$	3.0	0.4	1.3	-	1.0
CV%	12	20	4	-	32

*Mixture means above ground biomass including stems, soft twigs and leaves together.

Table 4.5. Average nutrient concentration in the various plant parts of the second fallow species at harvest.

Treatments#	Leaves*	Litter	Stems	$LSD_{0.05}$
			N (g/kg)	
TeF	25.9	13.6	12.2	2.6
TeT	24.6	12.3	10.8	2.6
TiF	24.5	14.3	4.8	2.6
TiT	25.0	13.9	4.8	2.6
NF	(11.9)**	Na***	Na	Na
Maize stover	(10.3)	Na	Na	Na
$LSD_{0.05}$	2.7	2.7	2.7	Na
			P (g/kg)	
TeF	0.92	0.82	0.92	0.14
TeT	0.88	0.65	0.78	0.14
TiF	1.75	1.66	0.93	0.14
TiT	0.94	1.38	1.50	0.14
NF	(1.0)	Na	Na	Na
Maize stover	(0.65)	Na	Na	Na
$LSD_{0.05}$	0.14	0.14	0.14	Na
			K (g/kg)	
TeF	16.5	9.5	8.1	1.7
TeT	16.0	9.6	6.8	1.7
TiF	30.0	28.7	17.8	1.7
TiT	25.5	25.3	15.7	1.7
NF	(14.6)	Na	Na	Na
Maize stover	(9.5)	Na	Na	Na
$LSD_{0.05}$	1.8	1.8	1.8	Na
			Ca (g/kg)	
TeF	11.4	6.2	15.1	1.3
TeT	10.8	5.1	13.6	1.3
TiF	20.1	8.7	5.3	1.3
TiT	17.8	7.4	5.1	1.3
NF	(3.1)	Na	Na	Na
Maize stover	(2.4)	Na	Na	Na
$LSD_{0.05}$	1.3	1.3	1.3	Na
			Mg (g/kg)	
TeF	3.2	1.7	2.5	0.5
TeT	2.9	2.0	1.1	0.5
TiF	3.1	6.0	3.3	0.5
TiT	2.9	5.0	2.8	0.5
NF	(2.2)	Na	Na	Na
Maize stover	(2.3)	Na	Na	Na
$LSD_{0.05}$	0.6	0.6	0.6	Na

The meaning of the treatments are shown in Table 3.2; *Leaves mean soft twigs and leaves together; ( ) means data not used for statistical analysis; *** Na: not applicable.

Tephrosia vogelii leaves and roots had more N, P and K concentrations than other plant parts of the same species. The effect of P applied to the first maize subsequent to the first fallow and the interaction between inorganic P and biomass fertiliser inputs on the concentration of nutrients in different plant parts of the second fallow species were not significant ($p=0.05$). For *Tithonia diversifolia*, the N, P, K and Ca levels were higher in leaves than in stems and roots. *Tithonia* leaves contained more P, K and Ca than *Tephrosia* leaves. Materials from plots where shrub biomass have been removed (biomass transfer) showed a trend of low nutrient concentration compared to that obtained from the fallow plots.

The biomass produced by *Tithonia* fallow in six months period accumulated more nutrient than the biomass from the natural vegetation fallow and maize stover plus cobs (Tables 4.6 and 4.7).

Table 4.6. Nutrient accumulation during the first six-month-fallow period

Treatments	Total biomass (Mg/ha)*	Nutrients (kg/ha)				
		N	P	K	Ca	Mg
Tephrosia	9.5	154	5.7	100	75	17
Tithonia	11.8	191	8.1	271	70	32
Natural fallow	3.8	54	2.6	52	10	7
Maize stover + cobs	3.1	34	2.1	37	8	8
$LSD_{0.05}$	2.2	43	1.9	52	14	6
CV%	16	18	19	23	16	17

* Total biomass= above ground, litter and root biomass.

Table 4.7. Nutrient accumulation during the second six month-fallow period

Fallow treatments*	Total biomass (Mg/ha)**	Nutrients (kg/ha)				
		N	P	K	Ca	Mg
TeF	11.9	176	9.7	115	110	24
TeT	6.4	86	4.5	56	45	9
TiF	18.6	234	21.9	404	155	61
TiT	15.6	201	17.2	305	119	47
CC	(1.7***)	(17)	(1.1)	(16)	(4)	(4)
NF	9.2	110	8.4	124	24	18
$LSD_{0.05}$	3.0	48	3.1	53	40	8
No P	11.8	158	11.6	288	85	30
Plus P	12.9	170	13.0	214	97	34
$LSD_{0.05}$	1.2	18	1.6	26	13	4

* See the meaning of the treatments in table 3.2; ** Total biomass= above ground, litterfall and root biomass. *** For maize, roots were not included and ( ) means that the data was not used for the statistical analysis.

This high amount of nutrients accumulated was also observed with *Tephrosia vogelii* fallow for N and Ca. The low amount of biomass produced in the cut-and-carry system particularly from *Tephrosia* and the low nutrient concentration at some extend led to low nutrient accumulation. For all the three fallows, the most important plant part that greatly contributed to the biomass and nutrient quantity was the above ground material. This was due to the high biomass production and to some extent to the high nutrient content in leaves including soft twigs.

The proton consumption capacity (pcc) of *Tithonia* leaves was high, about 50 cmol(+)/kg of biomass while that of the natural fallow leaves, maize stover and all *Tephrosia* material was medium, about 20 cmol(+)/kg (Figure 4.3).

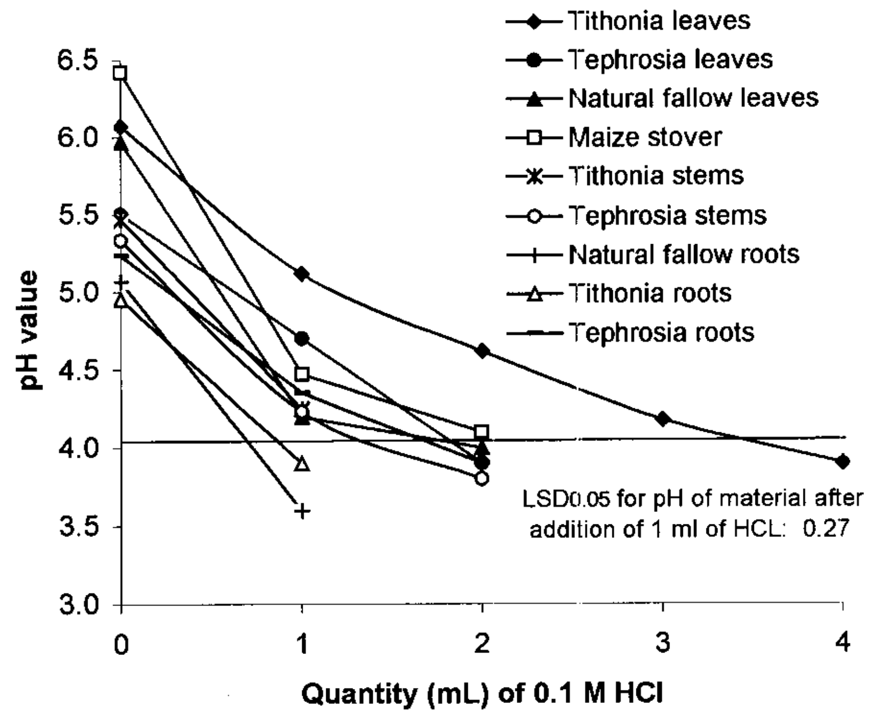


Figure 4.3. Titration curves of various plant part materials

The pcc of *Tithonia* roots and stems was about 14 cmol(+)/kg. The natural fallow roots comprising mainly of *Digitaria* sp. (couch grass) rhizomes had the lowest pcc (5 cmol(+)/kg).

4.4. DISCUSSION

The amount of above ground biomass produced by *Tephrosia vogelii* and *Tithonia diversifolia* during the first six month-fallow season was lower than that reported by Amadalo *et al.*(1995) who obtained 10 and 13 Mg/ha of above ground biomass from *Tephrosia vogelii* and *Tithonia* respectively on more fertile soils in the same area after a six month-fallow period. The low biomass produced may have been due to low soil fertility (Table 3.1) and inadequate rainfall (Figure 3.1a). The better yields obtained in the second fallow season were due to the residual effect of organic material and inorganic P applied to the previous maize crop with more rainfall. According to Fungameza (1991), Drechsel *et al.*(1996) and Waddington *et al.* (1998), the amount of biomass produced by *Tephrosia vogelii* and *Tithonia diversifolia* is influenced by the fertility status of the soil and the amount of rainfall. Schroeder (1995) and Sanchez *et al.* (1997) stated that a soil with some (at least medium) fertility is necessary for the growth of organic material, be they green manure or plant biomass for transfer. Removing fallow biomass from plots resulted in low biomass production of the second fallow season (Table 4.3) indicating increased soil fertility depletion.

The ratio of leaves (including soft twigs) to woody material (stems) for *Tephrosia* and *Tithonia* at harvesting was about 1:2 and 1.0:1.3 to 3.3, respectively. This means that the amount of leaves which are rich in nutrients were high at the harvesting time. Such an observation is in agreement with Nagarajah and Nizar (1982) who have suggested harvesting the green material from the *Tithonia* plant at flowering stage. Higher amount of woody twigs recorded in the second fallow than in the first fallow season was due to the earlier flowering and senescence of shoots from cuttings.

The small roots were a significant component of biomass in the three fallows, although at a lower level compared to litterfall and above ground biomass. However, their contribution to the biomass input may be reduced when some small roots/rhizomes such as those of

Tithonia and *Digitaria* that shoot when left fresh in the soil are removed from the soil. The primary taproots of the shrubs were woody and low in N content (Table 4.4) in that they were not completely decayed six months after cutting the fallow. The deep roots of the two shrubs as well as the high amount of small roots in the 0-45 cm depth for the three fallows are likely to improve the recycling of nutrients from the subsoil (Kang and Wilson, 1987). However, the efficiency of recycling process may be limited where the subsoil is poor (Buresh, 1993) as is the case for Maseno soils with low P content. Since the small root length density was not determined, the high percentage of fine root biomass for the shrubs was of a limited use. No firm comparison between the efficiency of the shrubs and that of the natural fallow or maize for soil nutrient uptake could be done. Root characteristics of maize with good performance were improved compared to those of poor crop (Appendix 4.1).

Legume tissues usually have higher nitrogen content than those of non-fixing shrubs (Sprent and Sprent, 1990). This N is taken up from both soil mineral N and N_2 fixed through symbiotic relationships. *Tephrosia vogelii* though a legume was highly infested with nematodes, which might have caused the poor nodulation observed on the roots. Other reasons for this poor nodulation might be the high soil acidity, low levels of soil phosphorus and the low nodulating capacity of *Tephrosia*. Giller and Wilson (1991) reported that phosphorus depletion could have a serious negative effect on N_2-fixation by legumes. Furthermore, a good nodulation with naturally occurring rhizobium was observed on *Tephrosia candida* DC. at the same site. More research on *Tephrosia vogelii* nodulation is needed since N_2-fixation is one of the important characteristics for agroforestry studies

(Nair, 1984) and for nutrient-depleted-soils such as in Maseno, external inputs from outside are needed to improve their fertility status (Sanchez *et al.*, 1997).

The below and above ground biomass of the two shrubs accumulated higher amount of N, K, Ca and Mg than the natural fallow and the maize. The below ground biomass N of each of the three fallows was about 20 % of total biomass N while *Tephrosia vogelii* and *Tithonia diversifolia* small root N was about 15 and 8%, respectively (Appendix 4.2). The high N content in *Tephrosia* leaves and litter recorded in this study had also been reported by Kwesiga and Coe (1994) and Drechsel *et al.* (1996). For *Tithonia*, Nagarajah and Nizar (1982) found that dried leaf and soft stem mixture contained about 20.0 g N/kg, 1.6 g P/kg and 33.2 g K/kg, which is in agreement with the current study. The P concentration in *Tithonia* leaves although higher than that in the *Tephrosia* and natural fallow materials, was lower than the value of 2.7-3.8 g/kg recorded by Gachengo (1996). Such a difference may be due to the low P content in soils obtained from study site. The nutrient content of the leaf materials from the two shrubs agrees with the range of 25-40 g N/kg, 1-3 g P/kg, 10-25 g K/kg and 15-20 g Ca/kg reported by Young (1997) for fast growing N_2-fixing trees. Since *Tephrosia* was not well nodulated and *Tithonia* is not a legume, the mechanisms used by the two shrubs to extract more nutrients from the soil than do the natural vegetation and the maize need to be assessed.

The second fallow was successfully established by direct seeding for *Tephrosia* and cuttings for *Tithonia*. This is an appropriate method when this technology is introduced under farmer's conditions. Once the fallow biomass is harvested and incorporated into the soil, the subsequent crops could benefit from the nutrients released through decomposition and mineralisation. The 5.3 Mg/ha of dry *Tephrosia* mixture or 4.6 Mg/ha of *Tithonia* mixture could provide about 100 kg N/ha and only 3 to 4 kg P/ha. Compared to the current recommended rate of about 25 kg P/ha for maize in Kenya (Furp, 1994), this amount of N would be sufficient, while phosphorus would be insufficient. Palm (1995) and Palm *et al.* (1997) reported that organic inputs are very low suppliers of P because of their low P concentrations. In this case, there is a need for supplementing P from external sources for better crop growth as stated by Buresh and Tian (1998). Another condition for increasing crop performance with the use of biomass is an appropriate or favourable rate of decay, which ensures the release of nutrients just when needed by the crop.

If there was more available land, a twelve month-duration fallow would be more appropriate since it will have more time for roots to recycle nutrients from deeper soil horizons and for increasing organic matter in topsoil through litter and root biomass. However, the woody material may develop (Drechsel *et al.*, 1996) and this is true particularly for *Tephrosia.* Thus the biomass harvested may be a mixed quality material that decompose slowly and release nutrients during a relatively long period.

The high proton consumption capacity of *Tithonia* leaves may be in relation to their high content of K and Ca and indicates that such material is more efficient in reducing soil acidity than the other plant parts and other species materials studied when used as green manure. This is in agreement with the findings by Nziguheba *et al.* (1998) that *Tithonia* leaves have a potential to reduce the P fixation capacity of the soil. However, a greenhouse experiments showed that the effect of organic material on soil acidity reduction is temporary, lasting not longer than three months (Hoyt and Turner, 1975).

4.5. CONCLUSION

Tephrosia vogelii and *Tithonia diversifolia* are fast growing shrubs that can accumulate substantial amounts of biomass and nutrients during a six-month fallow. This is particularly true where the rainfall is adequate and well distributed and where soil fertility is high or improved with fertiliser (biomass, inorganic P) inputs. The above ground biomass and litterfall from these shrubs have high concentration of N and K but contain low phosphorus levels. However, *Tithonia* leaves had higher P concentration than *Tephrosia* and natural fallow leaves. According to the results obtained in this study, a period of six months is appropriate for the production of high quality biomass (green manure) from the two shrubs. Their ability to accumulate high levels of N and K makes them suitable substitutes for the natural fallow. Although they do have high nutrient accumulation than the natural fallow they require more labour and some investment for planting material. More research on how they accumulate the nutrient (symbiosis, soil nutrient mining) and how these nutrients are released through biomass decomposition, hence their availability to crops, is also required. Furthermore, alternative sources of P for high crop yield need to be addressed. Finally it was observed that the removal of the above ground biomass from plots decreased the performance of the subsequent fallow.

CHAPTER 5: DECOMPOSITION RATES OF BIOMASS FROM *Tephrosia vogelii*, *Tithonia diversifolia* AND NATURAL FALLOW

5.0. ABSTRACT

Organic inputs incorporated into the soil release their nutrients through the decomposition. This process may be slow or rapid depending on the biomass quality and soil conditions. For a period of eight months, an incubation study with litterbags was carried out in field conditions on the various types of biomass obtained from *Tephrosia vogelii*, *Tithonia diversifolia* and natural fallows. Leaves, stems and roots of *Tephrosia*, *Tithonia* and natural fallow had high decomposition rates and less than 30% of biomass were not yet decomposed after eight months of incubation. *Tithonia* leaves decayed within one month after incubation and *Tithonia* mixture had released most of the mineral N during the first month. *Tephrosia* roots and leaves had a half-life of about 2 months and higher decomposition rate than *Tithonia* roots. Tephrosia stems and natural fallow roots both low in N were the slow to decompose.

5.1. INTRODUCTION

The short term fertility effects of shrubs are associated with the fast decomposing biomass while long term effects are related to the slow decomposing materials and improvement of soil physical properties (ICRAF, 1989). Leaves and roots either rapidly decompose after shrubs are cut or remain undecomposed for long time in which case the nutrients are immobilised and unavailable to the crops (Woomer and Swift, 1994). Organic inputs are converted into available nutrients and soil organic matter through the process of biomass decomposition and mineralisation (Palm *et al.*, 1994; Zech *et al.*, 1997). The rate of biomass decomposition varies according to the C:N ratio, N, polyphenol and lignin content (Palm and Sanchez, 1991; McDonagh *et al.*, 1995) and the management. Fresh biomass decomposes faster than sun dried materials, small sized or ground materials decompose faster than coarse biomass (Nair *et al.*, 1999). Land cultivation, soil temperature, moisture, texture, mineralogy and N content influence the turnover of the organic inputs in the soil (Sanchez and van Houten, 1994).

Tephrosia vogelii and *Tithonia diversifolia* are among the high potential shrubs for biomass production in Maseno (Chapter 4). However little is known about the decomposition rates and nutrient release patterns of biomass obtained from these two shrubs (Fungameza, 1991). This study aimed at understanding decomposition rates and nutrient release patterns of biomass obtained from different plant parts of the two shrubs and natural fallow at Maseno, Kenya.

5.2. MATERIALS AND METHODS

Ten plant materials comprised of eight (fresh small roots, leaves, stems, and a mixture of leaves, twigs and stems) obtained from *Tephrosia vogelii*, *Tithonia diversifolia* and two (roots and leaves) from natural vegetation fallow (NF) were collected from nine plots corresponding to three replicates at the cutting of the six month fallow (chapter 4). The shrub stems and twigs were cut into about 5-cm length pieces. Five kilograms of each plant material were washed in distilled water then air dried under shade for a period of 48 hours after which 100 g of biomass was transferred to 7 mm mesh litterbags of 30 cm x 30 cm (Anderson and Ingram, 1993). The quantity of 100 g was equivalent to the fresh biomass inputs normally applied per 0.09-m^2 area in the on-going experiments at Maseno. For each plant material, 36 litterbags were prepared. In addition, 30 (ten plant materials x three replicates) samples were collected for moisture (oven drying at 65°C for 72 hours), followed by carbon (C), nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), polyphenol (pp) and lignin (l) determination using the procedures outlined by Anderson and Ingram (1993). The data recorded were used as reference to calculate the dry biomass weight and the C, N, P, Ca and Mg losses from the samples decomposing in the litterbags.

For biomass decomposition study, the litterbags were laid out in the field in randomised complete block design with six replicates and buried at 15-cm soil depth to simulate conventional tillage practices. The physical and chemical properties of the soils in the experimental site and the rainfall recorded during the incubation period were given in Table 3.1 and Figure3.1b. The average soil temperature varied between 20 and 23°C in 0 to 50 cm depth (Eva Ohlson: unpublished data). The litterbags were retrieved at 1, 2, 4, 8, 16, and 32-weeks intervals. Four bags from each type of plant material were randomly collected per sampling time. The content were spread out to sun dry briefly and then oven dried at 65°C after removing the extraneous materials by hand separation, sieving through a 2-mm sieve and floatation in distilled water (Varco *et al.*, 1993). The oven-dried material was weighed, ground and analysed for C, N, P, Ca and Mg content as outlined by Anderson and Ingram, (1993). Ash content was determined by ignition of sub-samples collected from each incubated and non-incubated biomass sample in a muffle furnace to a final temperature of 550^{0}C maintained for eight hours (Okalebo *et al.*, 1993). The ash content was subtracted to get ash-free biomass in which the bias due to the soil contamination in incubated biomass and its nutrient contents was eliminated.

The mathematical model for constant weight loss was fitted to the data on mass disappearance, using the single negative exponential decay function: $y_{(t)}= y_0 * e^{-kt}$, where $y_{(t)}$ is the remaining biomass of initial biomass $y_{(0)}$, t is the time in days and k is the decay rate constant (Olson, 1963; Weider and Lang, 1982; Kunhamu *et al.*, 1994; Mugendi and Nair, 1997). The decomposition rate of the above and below ground biomass obtained from different shrub species and natural fallow was statistically evaluated by ANOVA and regression methods using SAS (1982). The correlation between weight loss and nutrient release was calculated.

5.3. RESULTS

5.3.1. Chemical characteristics of the fallow biomass

Data on quality parameters of the shrubs and natural fallow biomass are grouped in Table 5.1, using the criteria outlined by Melillo *et al.*, (1982), Palm and Sanchez (1991), Lehmann *et al.* (1995), McDonagh *et al.* (1995) and Brady and Weil (1999).

Table 5.1. Quality characteristics of biomass from *Tephrosia vogelii* (Te), *Ttithonia diversifolia* (Ti) and natural fallow

Quality groupings	Plant parts	Quality parameters					
		N (g/kg)	Lignin (l), g/kg	Polyphenol (pp), g/kg	H_2O %**	PP/N ratio	(pp+l)/N ratio
1. High quality materials	Ti leaves	27-30	170	15.6	84	0.5	5.6
	Te leaves	23-29	125	26.2	71	1.0	5.8
	Te roots	25-30	114	7.1	64	0.2	4.2
2. Medium quality materials	Ti mixture*	19-23	164	11.2	75	0.5	8.2
	Te mixture	19-22	150	21.1	65	1.0	8.3
	Ti stems	19-24	145	10.9	Nd$^+$	0.5	7.1
3. Low quality materials	NF leaves	9-15	85	10.2	53	0.7	7.0
	Ti roots	11-13	136	23.9	60	2.0	13.5
	NF roots	11-15	115	5.1	24	0.4	9.7
	Te stems	10-15	120	8.0	60	0.7	11.3

* Mixture means leaves, soft twigs and stems together; + Nd means not determined; ** Water loss through drying the material.

The plant parts had different levels of N, polyphenol, lignin and water content. *Tephrosia* roots and stems and natural fallow (NF) roots contained less than 10 g polyphenol/kg while *Tephrosia* leaves contained more than 25 g polyphenol/kg. NF leaves were low in N and lignin and most of all material obtained from various species contained less than 15% lignin. NF roots that were mostly obtained from *Digitaria* sp. had low water content. *Tephrosia* stems and *Tithonia* roots had a (pp + l)/N ratio above 10.

5.3.2. Loss of biomass weight

The average constant of biomass decomposition rate (k) at each retrieval interval is given in Table 5.2. The rate of decomposition was significantly ($p < 0.01$) different among the various types of biomass. *Tithonia* leaves and mixture and *Tephrosia* roots lost more weight in the first week after incorporation into the soil. This may be due to high decomposition rate of *Tithonia* leaves and *Tephrosia* young and fine roots.

The loss in biomass weight of small roots and mixture was still high after two weeks. The same trend was observed for *Tephrosia* mixture and NF roots. The high coefficient of variation (CV) recorded during the first week indicated the great difference in water-soluble components of the buried materials and the disturbance of the soil during the placement of the litterbags.

After one month, *Tephrosia* stems, *Tithonia* root and natural fallow materials had the lowest rate of decomposition. At two months, *Tithonia* leaves were completely decomposed. At four months, the most decomposed materials were *Tithonia* mixture and natural fallow leaves followed by *Tephrosia* leaves, roots and mixture. The decomposition rate was less for *Tephrosia* stems, *Tithonia* roots and natural fallow roots.

Table 5.2. Average constant of biomass decomposition rate (k) over time

Type of biomass	7 days	14 days	28 days	56 days	112 days	224 days
Tephrosia (Te)						
Te mixture	0.011	0.017	0.017	0.013	0.009	0.010
Te roots	0.016	0.019	0.018	0.013	0.010	0.009
Te leaves	0.010	0.013	0.019	0.018	0.012	0.007
Te stem	0.009	0.013	0.011	0.007	0.006	0.005
Tithonia (Ti)						
Ti mixture	0.023	0.028	0.023	0.019	0.023	0.014
Ti roots	0.009	0.014	0.013	0.010	0.008	0.006
Ti leaves	0.049	0.050	0.056	exh.*	exh.	exh.
Nat. Fallow (NF)						
NF leaves	0.012	0.009	0.007	0.015	0.019	0.015
NF roots	0.009	0.017	0.011	0.006	0.006	0.006
$LSD_{0.05}$	0.008	0.007	0.003	0.003	0.003	0.003
CV (%)	40	30	15	19	22	31

* exh. = exhausted

Eight months after incubation, the decomposition pattern indicated that *Tephrosia* mixture and roots, *Tithonia* mixture and natural fallow leaves were the most decomposed while *Tephrosia* leaves and stems and *Tithonia* and natural fallow roots were recalcitrant.

During the incubation period, *Tithonia* mixture and natural fallow leaves showed two peaks for the constant of decomposition rate (k) at 7 and 112 days and at 14 and 112 days, respectively. This may be as a result of the different decomposition rates of these materials. The loss in biomass weight over time is plotted in Figure 5.1. *Tephrosia* stems, *Tithonia* and natural fallow roots decomposed slower than *Tephrosia* mixture, roots and leaves which in turn disappeared more slowly than *Tithonia* mixture and leaves. For natural fallow and *Tithonia diversifolia*, the various plant components decomposed in the order foliage > mixture > roots. The time required for half of the original biomass to decompose (t_{50}) was interpolated from the graphs of Figure 5.1 and results are shown in Table 5. 3. The biomass loss from *Tithonia* leaves occurred earlier than that from any other material (Tables 5.3 and 5.4). However, the slight differences observed in decomposition rate of the other materials were important if the nutrient release and plant uptake are to be synchronised.

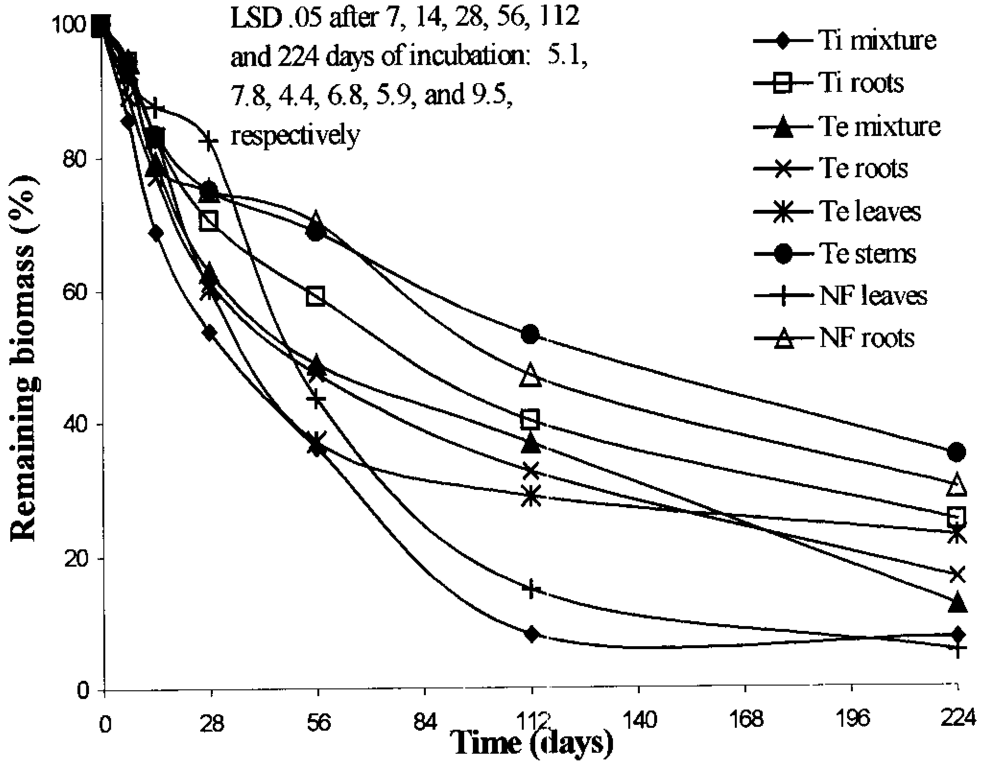


Figure 5.1. Biomass loss during the incubation period

Table 5.3. Half life time (t_{50}) in days for the various biomass

Species	Mixture	Roots	Leaves	Stems
Tephrosia vogelii	57	52	40	130
Tithonia diversifolia	34	82	14	-
Natural fallow	51	106	-	-
$LSD_{0.05}$			10	
CV (%)			13	

Table 5.4. Decomposition rate constant value (x 10^{-2}) at t_{50} for the various biomass

Species	Mixture	Roots	Leaves	Stems
Tephrosia vogelii	1.22	1.33	1.73	0.53
Tithonia diversifolia	2.04	0.84	4.95	-
Natural fallow	1.36	0.65	-	-

For all materials except Ti leaves, the average decomposition rate k obtained for a period of 224 days was positively correlated with N (r=0.10***) and water content (r=0.33***) and negatively correlated with (polyphenols + lignin)/N ratio (r=- 0.18***). Correlation with polyphenols (r=0.02***) and lignin (r=0.03***) was significant but had very little value.

5.3.3. Nutrient release during the incubation period

The concentration of N, P, Ca and Mg in biomass showed a decreasing trend during the incubation period. This decrease was particularly high for *Tephrosia vogelii* (Te) mixture, leaves and roots, *Tithonia diversifolia* (Ti) mixture and natural fallow (NF) leaves (Table 5.5).

Table 5.5. Average N, P, Ca and Mg concentration (g/kg) in some retrieved plant materials over the incubation period

Plant parts	Nut-rients	0	7	14	28	56	112	224	LSD 0.05	CV %
		←-------			Days			-------→		
Tephrosia mixture	N	19.0	18.0	17.2	14.6	17.1	15.5	14.3	6.3	21
	P	0.93	0.91	0.90	0.53	0.56	0.39	0.50	0.41	25
	Ca	9.03	7.80	4.97	2.87	3.60	4.20	1.22	1.47	17
	Mg	2.20	1.93	1.43	1.03	1.03	1.10	0.52	0.50	21
Tithonia Mixture	N	22.3	16.0	14.3	8.0	11.3	14.7	11.8	5.3	21
	P	0.90	0.77	0.93	0.53	0.40	0.45	0.40	0.39	34
	Ca	11.5	5.57	3.30	2.53	3.10	4.23	0.58	1.64	21
	Mg	3.57	2.27	1.60	1.30	1.50	1.27	0.61	0.93	30
Natural fallow leaves	N	15.4	15.1	13.8	14.2	14.1	15.2	12.9	3.6	10
	P	0.77	0.70	0.63	0.62	0.55	0.82	0.67	0.30	24
	Ca	4.23	2.40	1.48	1.18	0.84	0.67	0.35	0.57	20
	Mg	2.57	1.26	1.13	1.22	1.21	1.40	0.38	0.83	34

There was a strong positive correlation between the biomass remaining at each retrieval interval during the decomposition and the concentration of P, Ca and Mg (Table 5.6). Correlation with N was significantly positive for Te stems and NF roots while negative for Ti roots.

Data on N release over time (Figure 5.2) showed that appreciable amount of N was released within 28-day period of incubation. After one month of incubation, *T. vogelii*

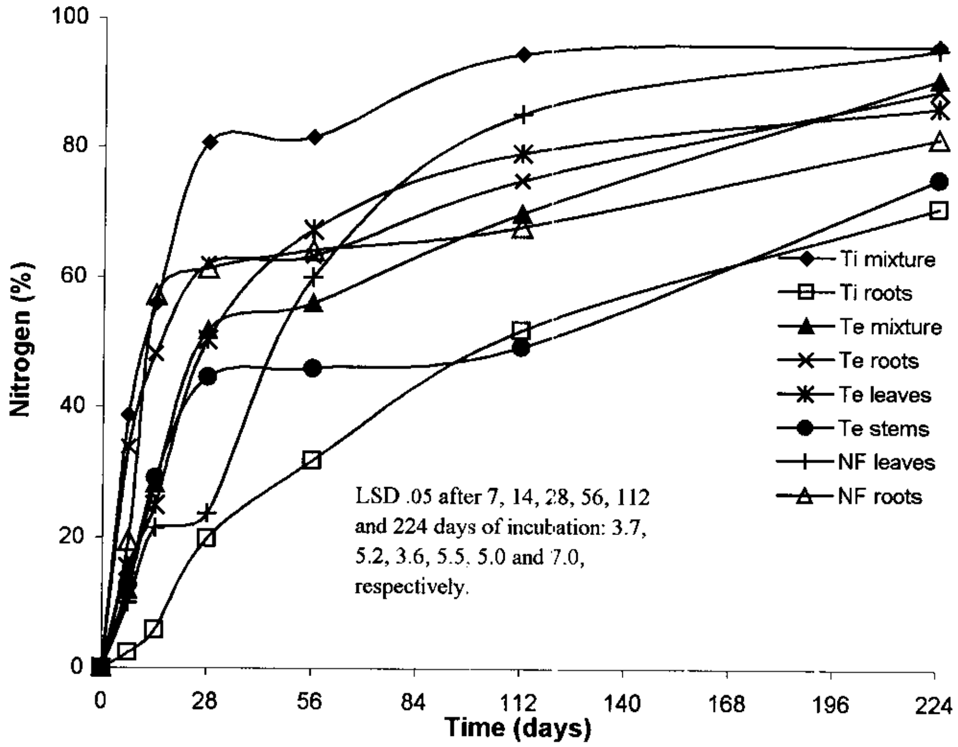


Figure 5.2. Cumulative % N released during the incubation period

Table 5.6. Correlation (r) between biomass remaining and percentage of various nutrients

Biomass types	N (p=variable)	P (p<0.005)	Ca (p<0.005)	Mg (p<0.005)
Te mixture	0.82 NS	0.87	0.89	0.94
Te roots	0	0.90	0.85	0.92
Te leaves	0.77 NS	0.85	0.89	0.89
Te stems	0.62**	0.98	0.78	0.81
Ti mixture	0.58 NS	0.87	0.73	0.89
Ti roots	-0.29*	0	0.45	0.92
NF leaves	0	0	0.76	0.60
NF roots	0.44**	0.83	0.34	0.89

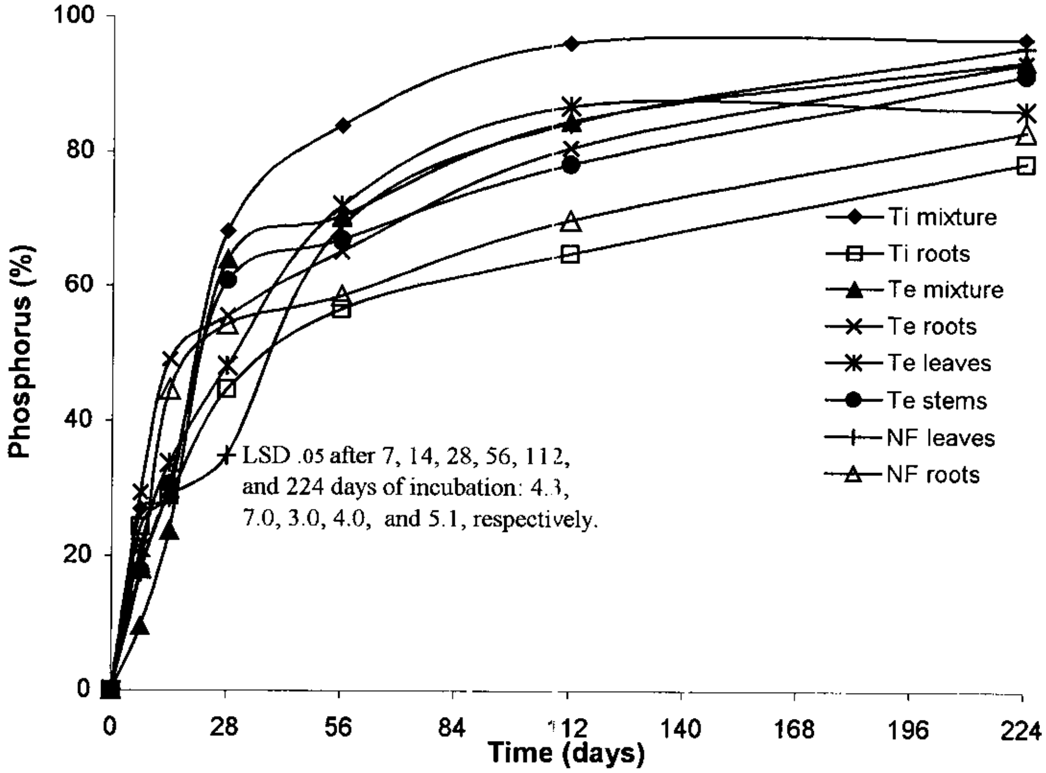
* and ** mean significant at 0.05 and 0.01 levels, respectively

roots and *Tithonia* mixture had released 65 and 80% of the initial N content, respectively. *Tithonia* roots and natural fallow leaves released less than 30% of N during the same period. From one month to four months, the rate of N released from *Tithonia* mixture and *Tephrosia* stems and roots and natural fallow roots declined. For other materials, the rate of N release started declining after two months of incubation.

More than 70% of P from *Tephrosia vogelii* (Te) mixture and stems, *Tithonia diversifolia* (Ti) mixture and natural fallow (NF) leaves were released during the 56 days of incubation (Figure 5.3). Similar amount of N was released within 100-days period for Te leaves while NF roots required more time. In case of calcium, more than 60 % of Ca were released from all plant materials except Te and Ti roots in 28-days period of incubation (Figure 5.4). In the same time 50% of Mg were released from all plant materials (Figure 5.5). Te leaves, stems and roots and Ti mixture had released about 80 % of Mg during one month of incubation while NF and Ti roots had only released about 20% of Mg in the same period.

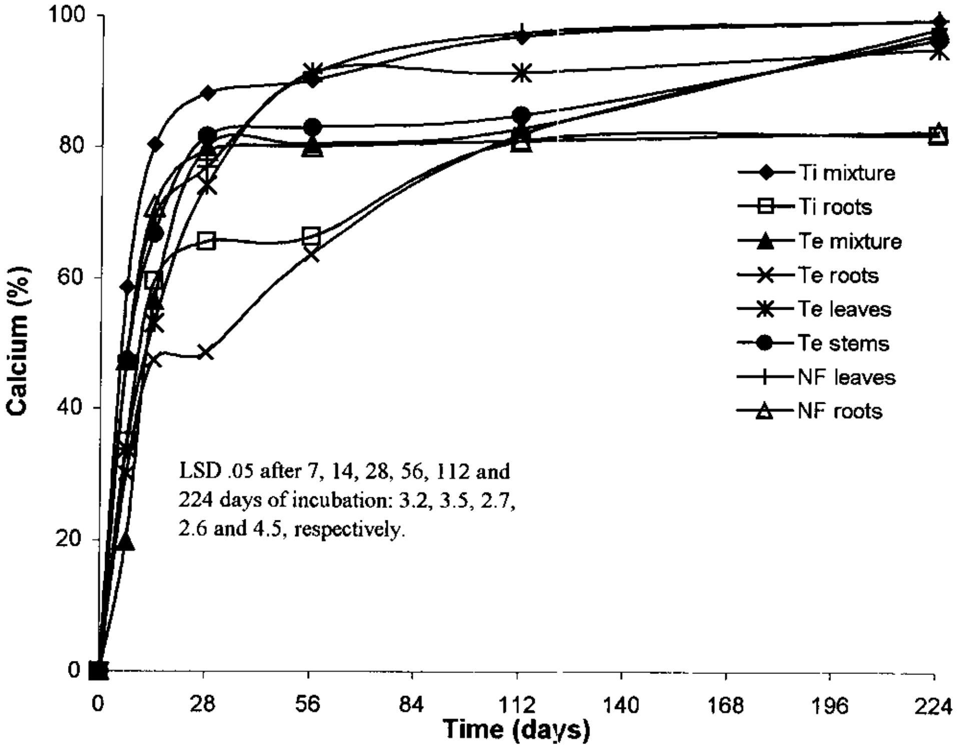
5.4. DISCUSSION

There were large variations in the decomposition rates of the organic materials obtained from the shrub and natural fallows with time (Table 5.1, Figure 5.1). The initial rapid decomposition was obtained from the high quality materials such as *Tithonia* leaves that are high in N content. Similar observations were made by Constantinides and Fownes (1994) and McDonagh *et al.* (1995). The rapid mass loss during the early decomposition stage of the organic materials was partly due to water loss and the release of water



LSD .05 after 7, 14, 28, 56, 112, and 224 days of incubation: 4.3, 7.0, 3.0, 4.0, and 5.1, respectively.

Figure 5.3. Cumulative % P released during the incubation period



LSD .05 after 7, 14, 28, 56, 112 and 224 days of incubation: 3.2, 3.5, 2.7, 2.6 and 4.5, respectively.

Figure 5.4. Cumulative % Ca released during the incubation period

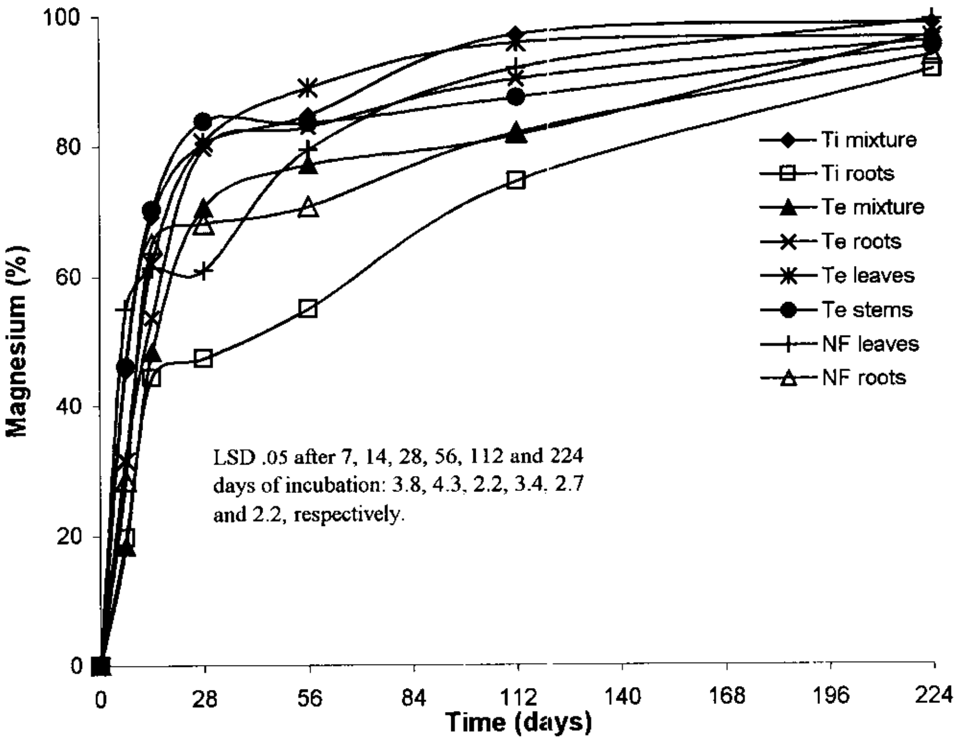


Figure 5.5. Cumulative % Mg released during the incubation period

soluble components such as sugars, amino acids and soluble phenolics (Bross *et al.*, 1995).Young plant materials are more rapidly decomposed than the old materials that contain generally a large amount of stable polysaccharides such as cellulose, hemicellulose and lignin (Zech *et al.*, 1997). Thus, green manure from the fallows should be cut and incorporated into the soil at the flowering stage of the fallow plants in the case a rapid release of nutrients is needed for a crop with short cycle. The slow loss of biomass recorded during the late stages of decomposition reflected the decline in the quality of the biomass and could be due to the decomposition of plant cellulose and lignin components and soil microbial products (Duchaufour, 1977). Nyamai (1994) also observed that the decomposition of the foliage of five agroforestry tree species started rapidly, kept the speed for some few weeks and then gradually became slow. The high coefficient of variation (CV) after 8 months of incubation indicated the increasing heterogeneity attributed to the penetration of soil and weed root into the litterbags and the difficulty in retrieving and sorting the undecomposed biomass.

The various types of biomass were grouped into high, medium and low quality materials, using the initial N concentration of more and less than 17 g/kg (McDonagh *et al.*, 1995), the critical level of lignin of 150 g/kg above which the decomposition may be delayed (Mafongoya *et al*, 1997c), lignin:N ratio (Melillo *et al.*, 1982), polyphenol:N ratio (Palm and Sanchez, 1991) and (polyphenol + lignin):N ratio less than 10 (Lehmann *et al.*, 1995). Such a grouping indicated that the differences between biomass decay patterns could be related either to N and polyphenol concentration or to water content (Table 5.1). *Tephrosia* roots decomposed faster than *Tithonia* roots because the former material contained high N and lower polyphenols than the latter. *Tithonia* N-rich leaves had also high amount of water (840 g/kg). Lignin does not regulate mass loss when it occurs at low concentration (Taylor *et al.*, 1989), but Lehmann *et al.* (1995) found that lignin influenced the decomposition rate of materials with a wide range of lignin content. In this study, mixtures, roots and natural fallow leaves were composed of materials having such a wide range of lignin content. Decomposition rate of fine and coarse roots may be similar or different due to the tree species and in this study, fine and coarse roots were mixed and referred to as small roots to reflect the real situation in the field. Plant quality may also be modified with the modification of soil fauna quality and quantity and other soil properties such as moisture, temperature, aeration, acidity and N content that regulate the activity of the decomposer microorganisms (Brady and Weil, 1999).

Assuming that plant biomass with low nitrogen content and high polyphenol and/or lignin content result in a greater proportion decomposing into stabilised soil organic matter (Woomer and Swift, 1994), the mixture of leaves and stems may be the best option to reduce the *Tithonia* carbon and nitrogen losses. This is in accordance with the findings made by Bunyasi (1997), Handayanto *et al.*(1997) and Kuo and Sainju (1998) that mixing ½ high and ½ low quality organic materials contributed to better N use through slowing the fast release of nutrients by the former and reducing immobilisation by the latter materials.

The turnover period of biomass in this study was less than a year and this agrees with the result reported by Zech *et al.* (1997) for litter in tropical rain forests. The amount of slightly to moderately decomposed but still discernible plant materials after eight months was 10%, 20% and 39% for *Tithonia* mixture, *Tephrosia* mixture and roots respectively. An understanding of whether the decomposition rate obtained with biomass buried in the litterbags is similar to that of the biomass directly incorporated into the soil is necessary, since the materials held in litterbags are less close to the soil and are less stabilised by the soil mineral clay and Al and Fe oxides (Oades, 1988). On the other hand, the biomass incorporated directly into the soil, despite its stabilisation, also decomposes rapidly due to mixing through tillage practices. Thirdly, some materials such *Tithonia* and *Digitaria* sp. roots remained undecomposed for a long time and in some cases budding occurred in the cropped plots where they were left. Under such circumstances, it became difficult to point out accurately if the biomass decomposition rates in litterbags and in the soil were similar or different.

Nutrient release and availability patterns from the incorporated biomass depend on the rate of decomposition and nutrient concentration in the tissue (Palm *et al.*, 1997). Decomposition of materials with N concentration of less than 20 g/kg (or C/N> 25) leads initially to immobilisation of mineral N (for example *Tithonia* roots), whereas materials with higher than 20 g N/kg (or C/N <25) release mineral N (Woomer and Swift, 1994). Materials with P content less than 2.5 g P/kg immobilise P, at least temporarily (Blair and Boland, 1978), but this may be modified due to the levels of lignin and polyphenol in biomass (Tian *et al.*, 1992). In this study N, P, Ca and Mg released were related to the rate of biomass loss (Figures 5.2 to 5.5). At two months after incorporation into the soil, the mean mass loss of 66% was recorded in *Tithonia* mixture indicating that a great amount of nutrients and carbon (data not shown) had been released. This agrees with Ilangovan and Paliwal (1996) who pointed out that most of the nutrients were released during the initial period of litter decomposition (from 0 to 56 days). Calcium, magnesium and phosphorus were released early even in less decomposed material because there are not or are partly structural constituents of plants (Staaf, 1980). Ilangovan and Palwal (1996) reported also that some P might be in readily leachable forms. These released nutrients may be either taken up by the growing plant, immobilised in soil minerals or micro-organisms or lost by leaching, denitrification and volatilisation. This is particularly true for N (Wilson, 1988) since high inputs of green manure that have low C/N and high NO_3^- contents do stimulate denitrification (Aulakh *et al.*, 1991) and low N recovery (Hussain and Ibrahim, 1987).

Kang *et al.* (1995) found the recovery value of N released from *Leucaena leucocephala* and *Senna siamea* prunings by the associated crop was about 20 and 30 %, respectively.

This low N recovery rate was due to poor synchrony between N demand by the crop and N release and availability from the biomass (Woomer and Swift, 1994). If an average recovery of 25 % was applied to *Tephrosia vogelii* and *Tithonia diversifolia* biomass containing 19.0 g N/kg and 21.7 g N/kg respectively (Table 4.4), incorporation of 4 Mg of such biomass would only provide about 19 and 22 kg N to a crop to which the biomass is applied. In poor soils, this amount of nutrient may partially solve N deficiency and crop yields remain low unless additional sources such as biomass or inorganic N fertiliser are supplied.

5.5. CONCLUSION

The leaves, stems and small roots of *Tephrosia vogelii, Tithonia diversifolia* and natural fallow had high decomposition rates. *Tithonia* leaves had decomposed within one month after incubation while *Tithonia* mixture had released most of its mineral N during the first month. *Tephrosia* roots and leaves also decomposed faster than *Tithonia* roots. Since *Tithonia diversifolia* above ground material released nutrients much faster than that of *Tephrosia vogelii* and natural fallow, it should be applied within the month in which the crop has high demand for nutrients. For *Tephrosia vogelii* above ground material and natural fallow leaves, which progressively released nutrients over a relative longer period of time, they should be applied two months before the peak demand for nutrients by the crop. In the areas where nutrient losses through leaching and/or denitrification are high, the incorporation of biomass from these two shrubs would improve soil fertility for a short period, generally between two and three months. After this period, N, P, Ca and Mg released may be insufficient to sustain crop production. Since data from litterbags may not completely reflect what is happening in the soil, a test plant sown in the field where biomass is applied is needed to confirm these biomass nutrient release patterns.

CHAPTER 6: EFFECT OF ADDITION OF *Tephrosia vogelii* AND *Tithonia diversifolia* BIOMASS ON MAIZE YIELDS.

6.0. ABSTRACT

Tephrosia vogelii and *Tithonia diversifolia* six-month fallows produce large amount of biomass with high nutrient content and decomposition rate. Use of locally available organic inputs for improving crop yields is an alternative to inorganic fertilisers that are not easily affordable to small-scale farmer in Western Kenya. Three treatments for each of the two shrubs above were managed as follows: fallow biomass retained, fallow biomass removed, continuous maize with shrub biomass brought and incorporated. The continuous maize crop and the natural fallow were used as control treatments. All treatments were split into two for 20-kg mineral P and no mineral P added and two consecutive maize crops sown Organic and inorganic fertiliser inputs were applied again after three cropping seasons. Shrub biomass improved the maize growth and yields by about 2.5 times compared to the control continuous cropping. Removal of above ground shrub biomass from the plot resulted in low performance of the subsequent maize. Addition of mineral P to the plots where biomass was applied increased the maize yield by about 40 % compared to the yield in no P treatments. The effect of fertiliser inputs on the maize performance was decreasing over the seasons following their application and was no longer significant on the third maize crop.

6.1. INTRODUCTION

Maize (*Zea mays* L.) is the most important food crop in Kenya (Buigutt, 1987; Central Bureau of Statistics, 1991) as it constitutes a major staple food. Kenya produced an average of 2.2 million tons of maize per year during years 1992 and 1993-1994 (Anon., 1994; Central Bureau of Statistics, 1995) from 14000 km^2 (Central Bureau of Statistics, 1995), corresponding to an average yield of 1.5 tons/ha. This low yield which ranges from 0.4 to 2.0 Mg ha^{-1} in Western Kenya (Jama *et al.*, 1997) is essentially due to disease and pest infestation (e.g., *Striga* spp.), inappropriate husbandry techniques and low soil fertility. The depletion of soil nutrients (mainly N and P) is a result of long-term continuous cropping of food crops with little or no external nutrient inputs application (Stoorvogel *et al.*, 1993) and erosion effects (Gachene *et al.*, 1997). Thus where diseases, pests and erosion are controlled, maize yields can be improved by addition of N and P to the soil, using manure, inorganic fertilisers or better a combination of organic and inorganic fertiliser inputs (Greenland, 1994).

Practising a nutrient management system where both organic and inorganic fertilisers are applied to soils having low inherent cation exchange capacity is a worthy strategy (Kang and Wilson, 1987). *Tephrosia vogelii* and *Tithonia diversifolia* produce biomass with high N content but low P. This biomass has high rates of decomposition and nutrient release patterns indicating that incorporation of such a biomass in soil as green manure at the planting period may provide some needed nutrients to the crop. Janzen *et al.* (1990) pointed out that application of fast decomposing materials might immediately benefit the current crop rather than the subsequent crop. Maize stover which is of low quality (low N and P content) is a common residue found in small-scale farms (Giller *et al.*, 1997; Karanja *et al*, 1998). Bunyasi (1997) and Kuo and Sainju (1998) reported that mixing low quality material such as cereal residues with high quality material in ratio of 0.5:0.5 contributed more positively to crop production than did the high quality material alone. In the Bunyasi's study, the ratio of 0.75 rice straw and 0.25 high quality material reduced significantly N released from the high quality material during the first six week-period following the organic input application. Whether incorporating high quality *Tephrosia* or *Tithonia* biomass alone or with maize stover available on farms may modify the rates of nutrient release, reduce N losses and at the same time the potential of N immobilisation of the cereal straws, hence ensure better nutrient management and productive cropping should be assessed.

This study was undertaken to assess the effect of *Tephrosia* and *Tithonia* fallows and biomass transfer plus maize stover on maize yields, compared to that of the natural fallow. The effect of adding mineral P fertiliser to these systems in improving maize yield was also assessed. This was achieved through two separate field experiments as explained below.

6.2. MATERIALS AND METHODS

6.2.1. Experiment 1: Assessing the potential of *Tephrosia*, *Tithonia* and natural vegetation fallows and biomass transfer for improving subsequent maize crop yields.

6.2.1. 1. Experimental layout and management

Tephrosia, *Tithonia* and natural vegetation biomass accumulated during the six month-fallow (Table 3.2) was managed as follows:

(i) Improved fallow system where roots + litter + above ground biomass were retained in the plots referred to as *Tephrosia* (TeF), *Tithonia* (TiF) fallows and natural fallow (NF),

(ii) Roots and litter retained in the plots and the rest above ground biomass removed, referred to as *Tephrosia* biomass transferred (TeT) and *Tithonia* biomass transferred (TiT),

(iii) Plots under continuous maize in which the shrub above ground biomass removed from the TeT and TiT plots (see ii above) was brought and incorporated, referred to as *Tephrosia* biomass incorporated (TeR) and *Tithonia* biomass incorporated (TiR) with maize stover produced in situ by the precedent maize.

Maize variety H 512 was planted in the above plots and its performance in terms of crop yields was compared to the continuous maize (CC) systems. Thus, there were eight treatments namely, TeF, TiF, TeT, TiT, TeR, TiR, CC and NF for comparing the effects of various systems but these treatments were in imbalance due to different rates of biomass and nutrient content (Table 6.1). The biomass for various treatments was applied in April 1997 and September 1998, using the following procedures: shrub above ground biomass and maize stover were cut into about 5-cm pieces, spread on the whole plot and then incorporated into the soil one week before planting maize. The natural fallow biomass that mainly consisted of *Digitaria sclarum* was applied as mulch without chopping. The treatments were laid out in a randomised complete block design with three replicates.

Just before planting maize, each main plot was divided into two sub-plots with 20 kg P/ha or without added mineral P. A split plot design was used for laying out the experiment. Triple superphosphate fertiliser was applied into the holes where 512 Hybrid maize was sown at a spacing of 30-cm intrarow and 75-cm interrow, with two seeds per planting hole. Maize was thinned to one plant at the first weeding (30 days after sowing), giving a population of 44 444 plants/ha. A second weeding was done at 60 days after sowing (DAP). Stalk borer was controlled by applying 3% malathion at two-week interval from 30 to 58 DAP. A second crop of maize was planted in September 1997 and a third in March 1998. No fertilisers were applied and maize stover was retained in situ. The fallows were repeated in March 1998 and first and second subsequent maize crops (fourth and fifth maize) planted in September 1998 and March 1999, respectively. Mineral P fertiliser was applied to the fourth maize only.

Table 6.1. Biomass incorporated into the soil before planting the maize and corresponding amount of N and P

Treatments*	At the end of the 1st fallow season			At the end of the 2nd fallow season		
	Biomass applied Mg/ha	N applied kg/ha	P applied kg/ha	Biomass* applied Mg/ha	N applied kg/ha	P applied kg/ha
TeF	8.7	127	7	8.8	116	5
TeF + P	8.7	127	27	9.3	123	25
TeT	4.2	53	3	3.8	41	2
TeT + P	4.2	53	23	3.9	42	22
TeR	4.4	74	4	3.0	50	3
TeR + P	4.4	74	24	3.0	50	23
TiF	10.7	150	7	18.0	230	21
TiF + P	10.7	150	27	18.5	237	41
TiT	7.0	81	4	7.5	85	8
TiT + P	7.0	81	24	8.2	97	28
TiR	3.3	69	3	9.4	134	12
TiR + P	3.3	69	23	9.4	134	32
CC	2.1	23	1	0.8	8	1
CC + P	2.1	23	21	0.9	10	21
NF	2.6	36	2	6.8	82	7
NF + P	2.6	36	22	7.3	84	27

*: See the meaning of the treatments above in Table 3.2; P is 20 kg mineral P/ha added in form of triple superphosphate.

6.2.1.2. Data collection and analyses

Maize performance and nutrient accumulation were assessed over time by sampling the first subsequent maize crop at the following stages of growth (Ritchie and Hanway, 1984): V7-V8 corresponding to vegetative stage at 7-8 leaves at 30 days after planting (DAP), V15-16 corresponding to vegetative stage at 15-16 leaves at 60 DAP, R3 corresponding to reproductive stage at initial grain filling at 90 DAP and R6 corresponding to reproductive stage at grain maturity/drying at 125 DAP. For the determination of dry matter accumulation and nutrient (N, P, K, Ca and Mg) uptake over time, six maize plants (above ground portion) were sampled randomly from each treatment at each stage of growth given above. The samples were washed with distilled water, chopped into 5-cm pieces, oven dried at 65°C for a period of 72 hours, weighed and then ground to pass through 0.5 mm sieve. The ground samples were analysed for N, P, K, Ca and Mg, using the methods described by Okalebo *et al.* (1993). Data were interpreted for biomass and nutrient accumulation, using the nutrient sufficiency ranges given by Jones *et al.* (1990), Munson and Nelson (1990) and Baldock and Schulte (1996).

Tasseling time was assessed by recording the number of plants tasseling in each plot. Records were taken every four days following the first appearance of tassels for eight successive intervals. Since tasseling percentage against time for each treatment was not quite symmetric, plotting against time raised to power 2 (Gomez and Gomez, 1984) was used to make distributions of plants tasseling more symmetric.

In order to obtain one single figure for describing the time to tasseling for each plot separately, the cumulative plant tasseling data were regressed against time squared, using the standard logistic growth curve in square time (Curnow and Mead, 1983):

$Y= A + C^* (1+e^{(-bt^2+bM)})^{-1}$, (equation 1)

where Y= % plants tasseling; A= constant (Y at time 0); C= curve asymptote tasseling value; b= parameter indicating slope at inflection point; M= square time at inflection point; t= time in days. With this non-linear regression curve, parameter b, C and M values were obtained for each plot separately whereas constant A was set at 0, to allow the curves to start at the origin. The obvious time to use is the time to 50 % tasseling of all plants present in the plot (t_{50}) (Smith, 1992), which corresponded to an average of 88.5 tasseled plants in the present study. By replacing Y with 88.5, the time t_{50} was directly estimated using the equation: $t_{50} = (M - b^{-1} * \ln (C/88.5-1))^{1/2}$ derived from the equation 1.

The average plant height was measured at the maize initial filling stage (90 DAP). At maturity (125 DAP), the above ground portion of the maize plants was harvested from an area of 28.35 m^2 (4.20 m x 6.75 m) in each sub-plot. Maize cobs were separated from the stover, air-dried and shelled. Stover samples were washed with distilled water and air-dried. Maize grains, cores and stover were weighed and used to quantify yields at 12.5 % moisture content. Sub-samples were taken, ground and used for nutrient determination (Anderson and Ingram, 1993; Okalebo *et al.*, 1993). Percentage Nitrogen Recovery (NIR %) was estimated using the formula:

NIR % = 100* (N uptake of treatment - N uptake of control)/ N initially applied.

Maize N and P uptake, t_{50} data, stover and grain yields were statistically analysed for assessing the effect of treatments, using the analysis of variance (ANOVA) for a split plot design. The treatment means were compared, using the least significant difference (LSD) (Gomez and Gomez, 1984). Correlation between nutrient uptake, biomass accumulation and maize grain yield was assessed. All statistics were performed using Genstat 3.2 computer software package (Genstat 5, 1995). In order to compare the effects of treatments over various seasons, the grain yield obtained from the control (CC) was subtracted from that of the treatments with biomass.

6.2.2. Experiment 2: Assessing the efficiency of *Tephrosia* and *Tithonia* and biomass on maize growth and yields with equal amounts of nutrients

In the improved fallow and biomass transfer experiments the amount of nutrients added was different. To assess the eventual bias caused by this difference in nutrients for *Tephrosia* and *Tithonia* systems on maize growth, a 2 x 4 experiment was designed to add the same amount of N and P from the shrub leaves/soft twigs, maize stover and mineral fertiliser (urea and triple superphosphate) and to compare their efficiency on maize yield increase. The experiment was established next to experiment 1 in March 1998. The quantity of biomass applied was based on biomass nutrient content (28.8 g N, 1.24 g P/kg for *Tephrosia*; 31.3 g N, 1.6 g P/kg for *Tithonia;* 9.1 g N, 0.4 g P/kg for maize stover) in order to have various treatments with the same amount of nutrients (72 kg N and 20 kg P/ha) (Table 2). Urea fertiliser as source of N and triple superphosphate fertiliser (source of P) were used as a control treatment.

Table 6.2. Treatments used in experiment 2

Treatments	Amount of organic* and inorganic inputs needed to give a total of 72 kg N and 20 kg P/ha
Urea	72.0 kg N + 20.0 kg P/ha
Te	2.5 Mg Te + 16.3 kg P /ha;
Ti	2.3 Mg Ti + 15.4 kg P /ha;
Mixture TeTi	1.6 Mg Te + 1.3 Mg Ti + 15.8 kg P /ha;
Urea + SM	2 Mg SM + 53.8 kg N + 18.5 kg P /ha;
Te + SM	2 Mg SM + 1.8 Mg Te + 16.3 kg P /ha;
Ti + SM	2 Mg SM + 1.7 Mg Ti + 15.8 kg P /ha;
TeTi + SM	2 Mg SM + 0.9 Mg Te + 0.85 Mg Ti + 15.8 kg P/ha.

*Te is *Tephrosia* biomass (28.8 g N, 1.24 g P/kg); Ti is *Tithonia* biomass (31.3 g N, 1.6 g P/kg); SM is maize stover (9.1 g N, 0.4 g P/kg).

This factorial experiment was laid out in a randomised complete block design with three replicates. The plot size was 5.25 m x 4.50 m. Maize growth and yields were measured following the same procedures as in experiment 1. The data were statistically analysed, using Genstat (Genstat 5, 1995) while the separation of treatment means was achieved using LSD at p level of 0.05.

6.3. RESULTS

6.3.1. Experiment 1. Assessing the potential of *Tephrosia*, *Tithonia* and natural vegetation fallows and biomass transfer for improving subsequent maize crop yields.

6.3.1.1. Effect of fallows and biomass transfer on maize growth and yield

In nitrogen and phosphorus-depleted soils such as those found at the Maseno site (Table 3.1), the addition of only one of the two elements for instance P resulted in maize N deficiency, due to an imbalance of N:P ratio. Dark green stunted maize, a symptom for phosphorus deficiency (Berger, 1962), was observed in the control plots treated with or without P. Yellowish stunted maize, which is a symptom of N deficiency was observed in the plots where only P was applied. The addition of P improved maize growth performance where shrub and natural fallow biomass was added. *Tithonia* did better than *Tephrosia* biomass during the early stage of maize growth (0 to 60 DAP). From 60 to 70 DAP, the efficiency of the two shrub biomass was similar. Maize in all the plots had turned yellowish especially where P fertiliser had been applied. At silking stage (75 DAP), maize appeared more yellowish in *Tithonia* than in *Tephrosia* and natural fallow plots.

Maize tasseling started at 67 DAP and continued for a period of about four weeks. There was a significant effect ($p < 0.01$) of biomass and inorganic phosphorus application on time t_{50} (Table 6.3). The interaction between biomass and mineral P was not significant. Biomass application shortened the time t_{50} by 1.0 to 4.6 days, while inorganic phosphorus application shortened the time by 2.8 days during the season, compared to the maize planted without fertiliser. The most shortened time to the 50 % tasseling plants was 7.4 days less and was observed with TiF treatment when applied with inorganic P. Maize height at the initial filling stage (90 DAP) was taller in plots where shrub biomass alone or with P fertiliser were applied than in other plots. Natural fallow (NF) improved the

Table 6.3. Average time (days) to 50 % tasseling for the various treatments

Treatments	Mean
Tephrosia fallow (TeF)	79.0
Tephrosia biomass transferred (TeT)	81.6
Tephrosia biomass incorporated (TeR)	80.3
Tithonia fallow (TiF)	77.3
Tithonia biomass transferred (TiT)	78.9
Tithonia biomass incorporated (TiR)	78.6
Continuous maize crop (CC)	81.9
Natural fallow (NF)	80.9
$LSD_{0.05}$	1.7
Without P	81.2
With P	78.4
$LSD_{0.05}$	0.5

subsequent maize growth particularly at the late stages and grain yields compared to continuous maize cropping (CC) (Table 6.4).

Maize growth and yields were better with *Tephrosia* and *Tithonia* fallows (TeF, TiF) and biomass incorporated (TeR, TiR) than NF. *Tephrosia* biomass transferred (TeT) had less effect on maize yield, compared to NF and negligible effect when compared to CC. This was not the case for *Tithonia* biomass transferred (TiT), which did better than NF.

Table 6.4. Maize dry matter and grain yields (Mg/ha) for various treatments at different stages of growth

Treat.	1st maize crop following the first fallow season						4th maize*
	DM** At V7-8	DM at V15-16	DM at R3***	Stover at R6	Cores at R6	Grains at R6	Biomass Mg/ha
TeF	0.16	1.28	3.73	3.35	0.41	2.92	3.25
TeT	0.09	0.72	1.99	1.56	0.33	1.37	1.49
TeR	0.19	1.05	2.85	2.87	0.55	3.27	1.02
TiF	0.03	1.82	3.55	3.81	0.47	3.37	3.45
TiT	0.16	1.22	3.20	2.80	0.40	2.65	2.45
TiR	0.27	1.57	3.58	3.07	0.65	3.73	1.76
CC	0.08	0.44	1.60	1.60	0.22	1.38	0.52
NF	0.10	0.72	2.44	1.87	0.34	1.95	1.55
$LSD_{0.05}$	0.05	0.40	0.49	0.43	0.10	0.32	1.00
No P	0.11	0.82	2.38	2.50	0.38	2.12	1.83
Plus P	0.23	1.38	3.35	2.73	0.46	2.97	2.04
$LSD_{0.05}$	0.03	0.20	0.25	0.21	0.06	0.19	0.36

*The fourth maize is the first maize following the second fallow season: only total biomass was recorded as there was drought at the maize filling stage. ** DM: dry matter; V7-8 and V14-15:

vegetative stages of growth at 7 to 8 leaves and 14 to 15 leaves, respectively; *** R 3 and R6: initial grain filling and maturity/drying stages.

With *Tephrosia* or *Tithonia*, the performance of maize following the fallow was the same to that of biomass incorporated system. *Tithonia* fallow (TiF) significantly increased maize growth and yields than *Tephrosia* fallow treatment (TeR). The effect of *Tithonia* biomass incorporated (TiR) on maize crop performance was significantly higher than that of *Tephrosia* (TeR). The amounts of maize biomass and grains produced in the treatments without phosphorus fertiliser were low when compared with those with phosphorus ($p < 0.05$). However, there was no significant interaction between various biomass and P. Maize biomass yield was positively correlated with maize grain yield ($r=90$) and cobs collected from plots where P had been applied had less water at 125 DAP compared to those without inorganic P (44% versus 37%, $p< 0.05$). The effect of biomass application on the water content of cobs at 125 DAP was not significant.

Application of 3.3 Mg of *Tithonia* or 4.4 Mg of *Tephrosia* above ground biomass (i.e., about 80 kg N and 4 kg P/ha) plus 20 kg P/ha in form of triple superphosphate increased maize yields by about 2.5 fold compared to the yields in the natural fallow and continuous maize cropping. Adding about 20 kg P/ha to the soil did not increase P concentration in the plants to the range of 4.0 to 8.0 g P/kg at V7-V8 and 2.5 to 4.0 g P/kg at R3 (Appendix 6.1). However at harvest, inorganic P application increased N, P and K accumulated in maize biomass by 13%, 1.2% and 16%, respectively. Average percentage N recovery from

Tephrosia (TeF +TeR)/2 and *Tithonia* (TiF+TiR)/2 biomass was about 32 and 41%, respectively (Table 6.5).

Table 6.5. Nutrients accumulated in maize stover and grains at harvest (125 DAP)

Treatments	N (kg/ha)			P (kg/ha)		K (kg/ha)	
	Stover	Grains	%NIR#	Stover	Grains	Stover	Grains
TeF	33	40	45	1.4	3.5	95	25
TeT	16	19	0	0.7	1.6	49	12
TeR	30	44	47	1.3	3.9	88	28
TiF	37	46	40*	1.6	4.0	108	29
TiT	28	36	67*	1.2	3.2	81	23
TiR	33	51	69	1.4	4.5	96	32
CC	16	19	0	0.7	1.7	47	12
NF	19	27	Na**	0.8	1.6	57	17
$LSD_{0.05}$	4.0	4.3	Na	0.2	0.4	14	3
Without P	26	29	Na	1.1	2.5	73	18
With P	28	40	Na	1.2	3.6	82	25
$LSD_{0.05}$	1.9	2.6	Na	0.09	0.2	6	2

NIR: nitrogen recovery; *: Na: not applicable; ** N recovery in TiF and TiT was calculated using roots as bringing the equivalent amount of nutrients as maize stover.

Percentage P recovery from mineral fertiliser was 6% while that from various biomass was about 60 %. Three tons of maize stover + three tons of grains mobilised 71 kg N, 4 kg P and 107 kg K.

6.3.1.2. Residual effect on the second maize crops following the first and second fallow seasons

Maize planted in the shrub fallow, in biomass incorporated and in *Tithonia* biomass transferred plots had better growth although stunted, than that in continuous cropping and natural fallow plots. Tasseling was irregular and delayed in all treatments. In general, there was no significant interaction between biomass and phosphorus applied in the previous seasons for stover and grain yields. However, the shrub biomass (except treatment TeT) applied in previous season had significant effect on maize yields (Table 6.6).

Table 6.6. Residual effect on yields of the second maize crops following the first and second fallow seasons

Treatments	2nd maize after the first fallow			2nd maize after the second fallow (fifth maize crop)		
	Height (cm)	Stover yield (Mg/ha)	Grain yield (Mg/ha)	Height (cm)	Stover yield (Mg/ha)	Grain yield (Mg/ha)
TeF	135	1.5	0.62	167	2.31	2.43
TeT	73	0.8	0.21	106	1.06	0.72
TeR	102	0.9	0.26	124	1.33	1.30
TiF	113	1.1	0.28	203	2.88	3.18
TiT	125	1.1	0.44	151	1.91	2.02
TiR	119	1.3	0.37	190	2.25	2.31
CC	65	0.5	0.06	79	0.69	0.51
NF	107	0.8	0.32	97	0.89	0.90
$LSD_{0.05}$	28	0.4	0.30	45	0.80	1.05
Without P	99	0.9	0.23	135	1.57	1.48
with P	111	1.1	0.41	145	1.76	1.86
$LSD_{0.05}$	6	0.2	0.06	4	0.08	0.12

The residual effect of 20-kg P/ha applied as TSP on preceding crops was still significant in terms of maize performance. The performance of the second maize crop following the second fallow season was better than the 2nd maize subsequent to the first fallow period. After the fist fallow season, relatively higher yields were obtained in the plots with *Tephrosia* fallow (TeF) compared to those in plots in which *Tithonia* fallow had been grown (TiF). This trend reversed in the maize grown after the second fallow season.

6.3.1.3. Residual effect on the third maize crop

Maize planted in *Tephrosia* and *Tithonia* biomass incorporated (TeR and TiR) and continuous maize (CC) plots grew poorly and tasseling was delayed in all the plots. Unlike the previous season, the residual effect of P on maize yield was no longer significant (Table 6.7). A slight increase ($p<0.07$) was only observed with shrub biomass particularly where *Tithonia* biomass had been applied.

Table 6.7. Maize stover and grain yields of the third maize crop (only for some treatments)

Treatment	Stover (Mg/ha)	Cores (Mg/ha)	Grain (Mg/ha)
TeR	1.93	0.28	1.44
TiR	2.95	0.41	2.33
CC	0.86	0.19	0.69
$LSD_{0.07}$	1.78	0.19	1.42
No P	1.93	0.31	1.51
Plus P	1.90	0.28	1.46
$LSD_{0.07}$	0.28	0.08	0.25

The effect of biomass and mineral phosphorus fertiliser on maize performance was decreasing over the seasons subsequent to their application (Table 6.8). This was clearly seen on maize growth of second and third maize crops (field observations). However, grain yields were too low for the 2nd maize following the 1st fallow and high for the 2nd maize subsequent to the 2nd fallow.

Table 6.8. Yield increase (Mg/ha) due to the treatments with biomass and mineral P compared to the control continuous maize

Treatments	First maize*	Second maize	Third maize	Fourth maize* (grins+ biomas)	Fifth maize
TeF-CC	1.54	0.56	Na	2.73	1.92
TeT-CC	0	0.15	Na	0.97	0.21
TeR-CC	1.89	0.20	0.75	0.51	0.79
TiF-CC	1.99	0.22	Na	2.93	2.67
TiT-CC	1.27	0.38	Na	1.93	1.51
TiR-CC	2.35	0.31	1.64	1.24	1.80
NF-CC	0.57	0.26	Na	1.03	0.39

* The maize crop that received biomass obtained from the fallows and 20 kg mineral P fertiliser. Due to the drought occurred at the maize filling stage, there was no maize grain for the fourth maize.

6.3.2. Experiment 2. Assessing the efficiency of *Tephrosia* and *Tithonia* biomass on maize growth and yields with equal amounts of N and P nutrients

Maize stover and grain yields obtained on fertilised maize crop in August 1998 and those of the residual maize planted in January 1999 are shown in Table 6.9. There were no significant differences between treatments, indicating that *Tephrosia* and *Tithonia* leaves and soft twigs were equally efficient when their biomass was applied to supply equal amounts of N and P nutrients to the maize crop. There was no significant difference in applying two tons maize stover/ha in plots where the shrub biomass was applied for improving maize yields. Due to the drought that occurred at the maize filling stage in December 1998, very few grains were obtained and none of the treatments had significant effect on biomass yield of the residual maize crop.

Table 6.9. Maize yields obtained with application of 72 kg N and 20 kg P/ha provided by *Tephrosia*, *Tithonia* and maize stover biomass and mineral fertilisers.

Factors	Yields of maize with fertiliser inputs, Sept. 98		Second maize without fertiliser application, Jan. 99
	Stover (Mg/ha)	Grains (Mg/ha)	Total biomass (Mg/ha)
High N materials (a)			
Tephrosia biomass (Te)	2.8	2.7	0.98
Tithonia biomass (Ti)	2.6	2.4	1.24
TeTi	3.2	2.8	0.96
Urea	2.6	2.6	0.80
$LSD_{0.05}$	0.8	0.7	0.35
Maize stover (b)			
0 t/ha	2.8	2.6	0.96
2 t/ha	2.8	2.7	1.02
$LSD_{0.05}$	0.6	0.5	0.25
LSD (0.05) (a x b)	1.5 NS#	1.0 NS	0.50 NS

#NS = not significant

6.4. DISCUSSION

Maseno soils are low in N and P (Table 3.1) and maize biomass obtained from the control plots was low in P and relatively high in N. This unexpected high concentration of N was a limiting factor for the efficiency use of the critical plant nutrient levels in diagnosing N needs. The more severe N deficiency shown by the first maize crop at silking stage in TiF and TiR than in TeF, TeR and NF plots could be explained by the released N dynamics during the cropping season. Since *Tephrosia* and *Tithonia* above ground biomass release about 52 and 80% of their total N respectively within the first 30 days after their incorporation into the soil (Chapter 5), it could be argued that some N from *Tithonia* biomass applied one week before planting maize was already used by the maize. This is confirmed by N recovery that was high (> 40%) in the maize stover + grains harvested where *Tephrosia* and *Tithonia* biomass had been applied. Also some of the N from *Tithonia* was probably lost through leaching (high rainfall conditions, Figure 3.1b) or denitrification (Aulakh *et al.*, 1991). Soils from TiF and TiR plots showed that at 53 DAP, mineral N had decreased at the 15 cm soil depth and increased in 30 to 60 cm depth. There is need to assess the contribution of denitrification to the decline in N obtained from *Tithonia.* A healthy maize crop that was growing after a two year-old *Tithonia* fallow in a plot adjacent to the experimental plots (data not shown) was probably an indication that a regular application of small amounts of *Tithonia* biomass at some interval before and after maize planting might improve N use efficiency by achieving better synchrony of nutrient supply and demand.

Biomass from TeF and TeR treatments released N progressively (Chapter 5) as the maize was growing. In NF plots, the biomass that was mulched started decomposing and releasing nutrients at the maize tasselling to grain filling stages. CC treatment showed N deficiency throughout the growth period. Ng Kee Kwong *et al.* (1987) and Sisworo *et al.* (1990) found that the N-use efficiency of cereal straw residues was partitioned between 5-14% and 73-84 % for the first crop and soil organic matter, respectively. Since the maize stover used in this study was low in N (about 10 g N/kg stover), CC treatment could only provide about 2 kg N/ha, which was too low to have any beneficial effect on maize growth and yield. Use of poor quality organic material alone is often insufficient for a productive agriculture (Giller *et al.*, 1997).

Tissue P in all treatments was below the critical level of 3.5 to 4.0 g P/kg (Wild, 1988), although there was an increase in maize grain yield with fallows and biomass incorporated treatments compared to continuous maize. The low P content in maize grains may indicate that the available P was not yet sufficient to meet the crop needs estimated at 18 kg P for two tons of maize grain and three tons of stover (Palm *et al.*, 1997). Okalebo (1987), Fan and MacKenzie (1994) and Mallarino (1996) found that the total P uptake by maize stalk and grain were correlated to soil available P, but the grain had a greater capacity for P luxury accumulation than the stalk. The nutrient uptake is relatively low where the nutrient supply limits the yield (Wild, 1988) and low soil P status normally leads to poor uptake of nitrate by the crop (Warren *et al.*, 1997).

Since P was rapidly released through the biomass decay (Chapter 5), the fact that the amounts of various biomass applied to the soil did not provide sufficient P to the maize crop may be due to their low P content (less than 10 kg P/ton). The organic material with less than 3 g P/kg can tie up the labile soil P (Singh and Jones, 1976; Swift, 1997) and make it less available to the plant. Phosphorus recovery from mineral P applied was low (6%) probably due to low net outcome between low mineral P rate and low P organic inputs added to acid soils that generally have high P fixation capacity (Sanchez, 1976; Jama *et al.*, 1997).

Maize in the fertilised plots started tasseling and silking 2 to 7 days earlier and had less water in cobs at harvest than in the unfertilised plots. The high amount of *Tithonia* biomass applied in TiF plots shortened the time at which half plants had tasselled (t50) by 4.6 days.

Berger (1962) pointed out that nutrient deficiencies prolonged the interval from emergence to tasseling or silking and addition of fertiliser hastened the time of silking by 4 to 10 days.

The low amount of P in *Tephrosia* and *Tithonia* biomass was a limiting factor in increasing crop yields. Lehmann *et al.* (1995) and Palm (1995) have reported such low P supply by other organic inputs. *Tithonia* fallow (TiF) plots that had received a greater amount of N, K, Ca and Mg-rich biomass produced less maize grain than *Tithonia* biomass incorporated (TiR) plots. This may have been caused by the high average ratio of N to P, which was 15:1 and 14:1 for TiF and TiR, respectively. Swift (1997) reported a maize grain yield increase of 62% (from 2.0 to 3.2 Mg/ha) obtained through the supply of *Tithonia* biomass with inorganic P that decreased N:P ratio from 12:1 to 5:1.

Application of high amounts of shrub biomass (TeF, TeR, TiF and TiR) significantly (P=0.05) increased the maize stalk biomass and grain yield, compared to the biomass from natural fallow and continuous maize crop. Similar results with *Calliandra calothyrsus* and *Leuceana leucocephala* were reported by Mafongoya *et al.* (1997b) in Zimbabwe. Thus, the amount and quality of biomass applied are important factors for improving the maize nutrient uptake, recovery and grain yield. A fast decomposing material such as *Tithonia* may have an advantage due to the fact that the response of maize to the nutrients released, especially nitrogen appears in the early stages of crop growth (Okalebo, 1987). No comparison of *Tephrosia* and *Tithonia* efficiency on maize yield could be done in the first experiment since the rates of the shrub biomass and nutrients applied were different. In the second experiment where an equal amount of N and P from leaves (including soft twigs) of

Tephrosia and *Tithonia* that have different nutrient release patterns were applied, it was observed that both shrubs biomass had similar effect on maize yield (Table 6.9). *Tithonia* biomass improved maize growth at the early stage but the effect decreased over time, particularly at the flowering-silking period, while the effect of *Tephrosia* biomass although initially low at the early stages of maize growth increased with time. This was also observed in *Tephrosia* fallow where maize started performing well even at early stage of growth probably due to the litterfall that was already decomposing thus providing nutrients to the maize crop.

The poor maize performance under biomass transferred systems (TeT and TiT) was less severe with *Tithonia* that had more litterfall (3 Mg/ha) and more small roots (1.5 Mg/ha) compared to *Tephrosia* (1 Mg of litterfall and 1 Mg of small roots/ha). This is in agreement with the observation made by Kang and Wilson (1987) that where biomass is continuously removed, the soil becomes impoverished. Maize performance in the natural fallow (NF) was slightly higher than that in the continuous cropping (CC) but less than that in the fallow and biomass incorporated treatments. This was due to the low quality/quantity of biomass and the asyncrony in nutrient release in the natural fallow system (Chapter 5).

The effect of biomass and mineral phosphorus fertiliser on maize performance was decreasing over time and was even biased for the grain yield obtained in some seasons. Most nutrients such as N, K, Ca and Mg were released in the first cropping season as shown in Figures 5.2 to 5.5 and used or lost. What was left was therefore insufficient to meet the nutritional requirements of the second and third maize crop. This is in agreement with the observation made by Cadisch *et al.* (1998) and Janzen *et al.* (1990) that the contribution of

N from plant residues applied to a previous crop was 1-4 % of the N content of the material originally applied. The too low yield obtained for the second maize following the first fallow season was due to the excess rainfall (about 1000 mm, figure 3.1b) received during the season and eventually enhanced loss of available nutrients. The reduction of maize performance by excessive soil water content was already reported by Chaudhary *et al.* (1975) and Singh and Ghildyal (1980). In plots with excessive moisture, nitrogen deficiency symptoms appear more severe probably due to bacterial denitrification that becomes high under anaerobic conditions (Tiedje *et al.*, 1984). The second maize following the second fallow season performed better because of favourable rainfall and residual nutrient contents in the soil, since the drought in the previous season may have reduced the release and leaching of nutrients and their exportation through the grain harvest.

The residual effect of P on the third maize was not significant due to the low rate of 20 kg P/ha applied in form of TSP. Sanchez *et al.* (1997) pointed out that the higher the P application rate, the strong the residual effect. Warren (1992) reported that moderate P rates of about 20-kg P/ha had a significant effect on maize yield for one to two crops following the application in the drier parts of Embu District, Kenya. The hypothesis of P loss that occurs mainly through removal by crop harvest (Smaling *et al.*, 1997) and erosion (Gachene *et al.*, 1997) was eliminated since all the maize stover was retained in the plots while erosion control measures were managed at the study site.

Finally maize crop is also sensitive to water deficit at flowering stage (Salter and Goode, 1967), and so one to two-weeks period of water stress experienced during the experimental seasons (Figure 3.1b, maize 1 and 4) reduced the maize response to biomass and P application.

6.5. CONCLUSION

The results from this study showed that there is a potential for six month-planted fallow and biomass incorporated technologies for improving maize production. The effect of the two technologies depend mostly on the quantity and quality of biomass (amount of nutrients recycled or eventually fixed) produced, the methods and time of biomass application and the processes of nutrient release and uptake by the crop (Mafongoya *et al.*, 1997c). Application of 3.5 to 5.0 Mg/ha of dry matter increased the maize yield by 2.5 times, compared to the maize yield in the nutrient-depleted-control plot with or without added mineral P. The effect of biomass applied was increased by about 40% when inorganic P was added. However there was a severe N deficiency on maize at the silking stage with a single application of high amount of *Tithonia* biomass. The effect of biomass showed a decreasing trend after one cropping season and this may reflect a low amount of nutrients stored in the soil. To achieve sustained yields of maize in depleted soils of Western Kenya requires regular fallowing and additional P inputs. Biomass incorporated technologies involve the impoverishment of the biomass transferred plot, while improving the biomass incorporated plot.

CHAPTER 7: EFFECT OF ORGANIC INPUT ON SOIL BULK DENSITY AND CHEMICAL PROPERTIES

7.0. ABSTRACT

Fallows and application of organic and inorganic inputs into the field may modify soil physical and chemical properties. Six-month fallows of *Tephrosia vogelii, Tithonia diversifolia* and natural vegetation were grown, then cut and biomass used as green manure to two subsequent maize crops. During this study soil samples were collected at the fallow cutting period, at the harvest of the 1st and 2nd maize crops following the fallows. These samples were analysed for bulk density, organic carbon, nitrogen and base content. Results showed that all the three short fallows did not significantly modify soil bulk density and chemical properties when compared to continuous maize cropping system. Only the nitrate N has decreased in *Tithonia* fallow and biomass incorporated plots. The leaching of NO_3^- was found to be high under continuous maize cropping system.

7.1. INTRODUCTION

Plant biomass is the primary source of soil organic matter (SOM), which encompasses all the organic components of soil, including living biomass, detritus and soil humus (Swift and Woomer, 1993; Brady and Weil, 1999). SOM is a key factor for soil fertility restoration and sustainable production in tropical low input agriculture systems (van Wambeke, 1995). It is an important renewable resource that has a positive influence on soil properties such as cation exchange capacity, soil stability and macro-porosity and pH buffering capacity (Juo and Kang, 1989). Under regular tillage and high temperature conditions of the tropics, SOM presents high rate of oxidation, resulting in high loss of organic matter (Lal, 1976; Wadsworth *et al.*, 1990). In a long-term maize-bean rotation experiment conducted at Kabete, Kenya, continuous cultivation with maize stover removal resulted in SOM decline after 18 years and addition of fertiliser and manure and maize stover retention reduced but did not stop the SOM decline (Kapkiyai, 1996; Swift, 1997). Similar results were reported by Kang (1993) in a 10 year-experiment conducted at IITA, Nigeria with a maize-sweet potato-cowpea rotation. When plant biomass is added to the soil, some amount is converted into SOM, the remaining being mineralised into CO_2 and other nutrient elements (Woomer and Swift, 1994). The level of SOM is then determined by the balance between % SOM lost through oxidation and erosion and that of SOM formed from fresh organic inputs added during a given period (Swift and Woomer, 1993). Inorganic cations and anions obtained from organic input mineralisation raise the levels of nutrients in soil and pH (IBSRAM, 1989; Hairiah *et al.*, 1996b). A ten year-old fallow in Ibadan Nigeria and application of farmyard manure during 8 years to a bean-maize rotation with removal of stover on an acid Oxisol in Rwanda slightly raised the soil pH (Kang, 1993; Rutunga *et al.*, 1998). However, there are few results reported on soil property improvement with organic inputs applied for a short time (one year or less). One of such study in greenhouse showed that a ten-week incubation of soil where dry *Calliandra* leaves were applied increased soil CEC and pH (Bell and Bessho, 1993).

The organic input supply may be realised through application of crop residues, compost and manure, and/or biomass obtained from agroforestry systems. For the latter case, some alternatives consist of the use of the fast growing fallows that can produce more biomass compared to continuous cropping systems or the biomass transfer technologies. A high rate of fallow growth is normally obtained where soil physical and chemical properties are adequate (van Wambeke, 1995; Sanchez *et al*, 1997), hence the SOM improvement may not be easily attained where soil fertility is very low. *Tephrosia* and *Tithonia* six month-fallows showed a good potential for biomass production even under poor soils (Chapter 4).

The objective of this study was to assess whether the six-month-*Tephrosia* or *Tithonia* fallow and the application of 2.5 to 7.0 tons of biomass obtained from the fallows have a significant effect on soil bulk density and chemical properties.

7.2. MATERIALS AND METHODS

The effect of continuous maize and natural vegetation, *Tephrosia vogelii* and *Tithonia diversifolia* one season fallows alternating with two maize crops (Table 3.2) on soil properties was assessed. Soil samples were taken by coring at the beginning of the experiment in September 1996, at the end of the first fallow, first crop and second fallow. The soil was sampled at 0 to 15, 15 to 30, 30 to 45 and 45 to 60 cm depths. Fresh soil samples for mineral N determination were taken at 0 to 15, 15 to 30, 30 to 45, 60 to 75, 90 to 105, 120 to 135 and 150 to 165 cm depths. Gravimetric soil water content at the sampling dates varied between 25 and 32% (oven dry soil basis).

Soil samples were also taken monthly from another experiment planted in March 1998, where *Tephrosia* and *Tithonia* biomass, maize stover and triple superphosphate at a rate of 72 kg N and 20 kg P/ha had been applied (Section 6.2.2, Table 6.2). The sampling methods were the same as in the first experiment except for changes in soil mineral N, which were monitored at one month-interval from 0 to 90 days after biomass application.

Soil bulk density, pH (in water), total C, total N, NH_4^+, NO_3^-, exchangeable bases and extractable P were determined according to the procedures described by Page *et al.* (1982) Dorich and Nelson (1984) and Okalebo *et al.* (1993). Analysis of variance and correlation were performed for comparing the effect of various treatments on these soil parameters, using Genstat Software Package 3.2. Inorganic N (NH_4^+ and NO_3^-) at different soil depths was evaluated using ANOVA corrected for dependent measurements (Genstat 5, 1995).

7.3. RESULTS

7.3.1. Rotational system of fallow-maize-maize-fallow

The six-month-planted fallows of *Tephrosia vogelii, Tithonia diversifolia* and natural vegetation had no significant effect on the surface soil bulk density (Table 7.1) and soil acidity status (Table 7.2). None of the three fallows modified soil organic carbon level and distribution (Table 7.3). Both NH_4^+ and NO_3^- were distributed in all the soil horizons (Table 7.4) and there was little effect of various fallows on soil mineral NH_4^+ content (Table 7.5). The level of NO_3^- was lower in the plots under the *Tithonia* fallow than those under the natural fallow and continuous maize crop (Table 7.5). Similar results were recorded at harvest of the first maize crop following the first fallow season (Table 7.6)

Table 7.1. Soil bulk density (kg m^{-3}) at the shrub cutting period

Fallow species plots	Soil depths		
	0-15cm	15-30cm	30-45cm
Tephrosia vogelii	1 280	1 300	1 420
Tithonia diversifolia	1 240	1 300	1 310
Natural fallow	1 200	1 320	1 260
Continuous cropping	1 250	1 310	1 340
F value	NS	NS	NS

Table 7.2. Average pH values (all treatments) at the end of the first fallow season and at harvest of the first maize following the fallow

Soil depth (cm)	pH $_{\text{ratio soil to water}= 1:1}$			
	Before fallow establishment (BF)	At fallow cutting time (AF)	At the maize harvest period	F value
0-15	4.5	4.5	4.5	NS
15-30	4.6	4.5	4.5	NS
30-45	5.0	4.7	4.7	NS
45-60	5.1	4.9	4.9	NS

Table 7.3. Average organic carbon content (g/kg) for various treatments*

Soil depth (cm)	B F	AF (April 1997)				
	(Sep 96)	Maize	Natural fallow	*Tephrosia*	*Tithonia*	$LSD_{0.05}$ for AF 1997.
0-15	20.0	20.1	20.5	19.3	21.3	2.5
15-30	16.0	15.6	15.6	14.8	13.9	2.5
30-45	11.0	11.7	13.4	12.3	10.7	2.5
45-60	9.0	8.7	9.8	9.8	8.5	2.5

*There were not significant differences among C data recorded at the harvest of the first maize in September 1997 (data not shown).

Table 7.4. Soil mineral NH_4^+ and NO_3^- content[3] at the end of the first fallow season and at the maize harvest.

Soil depth (cm)	NH_4^+ (kg/ha in 15-cm soil depth)			NO_3^- (kg/ha in 15-cm soil depth)		
	Initial (before starting the experiments)	At fallow cutting	At harvest of 1st maize after fallows	Initial (before starting the experiments)	At fallow cutting	At harvest of 1st maize after fallows
0-15	3.1	5.2	2.6	12	12	15
15-30	3.1	3.7	3.7	7	22	10
30-45	3.1	7.0	5.1	4	23	7
60-75	2.6	5.2	4.8	7	15	13
90-105	2.2	5.5	3.4	8	13	13
120-135	2.4	5.9	2.7	12	15	11
150-165	2.6	5.2	1.9	24	15	10
$LSD_{0.05}$		1.6	0.9		5.3	4.6

Table 7.5. Mineral NH_4^+ and NO_3^- ($kg{*}ha^{-1}{*}15cm^{-1}$) in plots under various fallows (at the end of the first fallow season)

Soil depth (cm)	NH_4^+				NO_3^-			
	CC*	NF*	TeF*	TiF*	Maize	NF	TeF	TiF
0-15	8.2	3.7	6.3	2.7	17	17	9	6
15-30	2.1	5.5	4.4	3.0	30	26	19	11
30-45	6.7	7.3	7.3	6.6	38	26	17	9
60-75	3.9	4.6	5.1	7.4	17	26	12	4
90-105	3.2	5.8	7.0	6.0	17	23	10	4
120-135	3.7	6.4	6.9	6.8	16	28	12	4
150-165	5.4	4.7	5.5	5.3	20	15	19	6
$LSD_{0.05}$	4.3 (when comparing data in the row)				16 (when comparing data in the row)			

CC= continuous maize crop, NF= natural fallow, TeF= *Tephrosia vogelii* fallow and TiF= *Tithonia diversifolia* fallow.

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[3] NO_3N and NH_4N extracted with 2N KCl; -for NO_3N determination, addition of sulphanilic acid then copperised Cd and finally 5-amino 2-naphthalene sulphonic acid, reading the absorbance at 525nm; -for NH_4N determination, addition of N1 (Na citrate, salicylate and tartrate) then N2 (Na hypochlorite and hydroxide) reagent, reading the absorbance at 655nm.

Table 7.6. Mineral NH_4^+ and NO_3^- (kg/ha) in various treatment plots at the harvest of maize in September 1997.

Soil depth (cm)	NH_4^+				NO_3^-			
	CC *	NF*	TeF*	TiF*	Maize	NF	TeF	TiF
0-15	3.8	2.4	2.8	1.5	13	19	16	14
15-30	3.9	3.6	4.0	3.3	8	12	12	6
30-45	5.7	5.2	5.0	4.3	12	9	3	4
60-75	5.6	4.4	4.6	4.5	22	17	10	4
90-105	3.7	5.0	3.0	1.8	24	15	9	4
120-135	2.4	3.4	2.7	2.1	17	13	10	4
150-165	1.5	2.9	1.5	1.9	11	15	5	8
$LSD_{0.05}$ for comparing data in the row:	1.9				8.1			

CC= continuous maize crop, NF= natural fallow, TeF= *Tephrosia vogelii* fallow and TiF= *Tithonia diversifolia* fallow.

For all fallow treatments and maize, the trend of nitrate N distribution in the soil was very different at the cutting of the first and second fallow seasons (Figure 7.1). The high nitrate N bulge found at 15 to 30 cm soil depth at the cutting of the first fallow season had decreased at the end of the second fallow season in September 1998. The probable reason was high N leaching caused by excessive rainfall received from November 1997 to January 1998 (Figure 3.1b). Compared to the three types of fallows, continuous maize cropping had higher levels of NO_3^-, which was susceptible to leaching because of low N uptake by poor performing maize crop.

For soil chemical properties, there were no significant changes due to the rotation of “six-month-fallows – maize – maize - six-month-fallows” except for the calcium, which

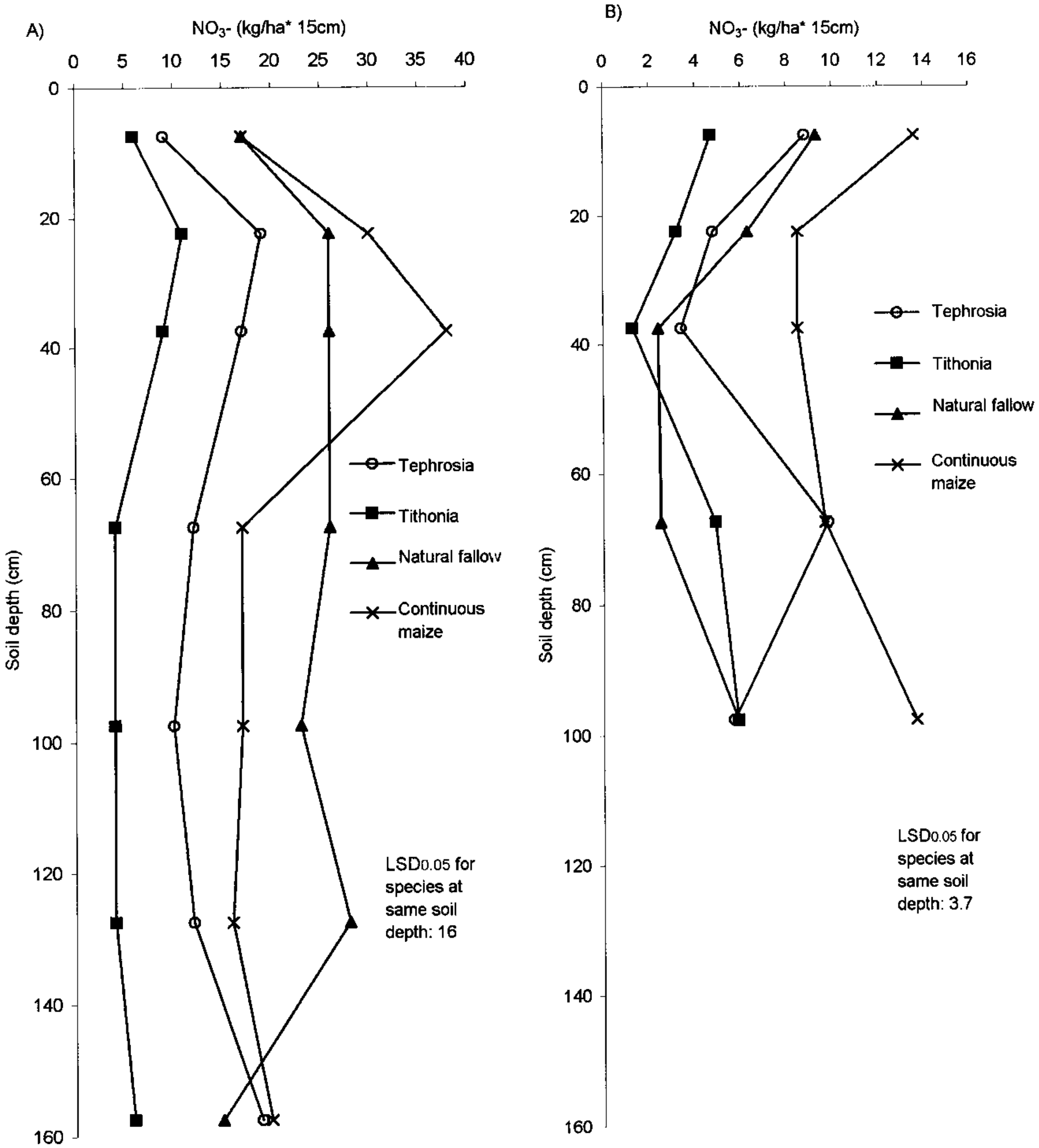

Figure 7.1. Nitrate-N distribution in the soil profile under various species at the cutting period of the first (A) and second (B) fallow seasons.

increased in the rotations including *Tephrosia vogelii* and *Tithonia diversifolia* species compared to that with natural fallow and continuous maize (Table 7.7).

Table 7.7. Chemical characteristics of surface soil (0-15 cm) at the cutting of the second fallow season in September, 1998

Parameters	Treatments				$LSD_{0.05}$
	CC*	NF*	TeF*	TiF*	
CEC($cmol_c$/kg)	14.1	15.3	14.6	15.1	2.8
K($cmol_c$/kg)	0.24	0.22	0.30	0.47	0.28
Ca($cmol_c$/kg)	0.56	0.70	1.71	1.21	0.74
Mg($cmol_c$/kg)	0.15	0.36	0.30	0.44	0.48

* CC= continuous maize crop, NF= natural fallow, TeF= *Tephrosia vogelii* fallow and TiF= *Tithonia diversifolia* fallow.

7.3.2. Maize experiment with equal amount of N and P provided by *Tephrosia* or *Tithonia* biomass, urea and TSP

Data on soil NO_3^- content obtained from this experiment showed a significant difference ($p < 0.01$) between depths (Tables 7.8 and 7.9). The four treatments had similar effect on soil NO_3^- content during the maize growth period. There was no significant interaction between treatments and depths. NO_3^- leaching was observed at 30 days after the application of organic material and this was increasing with time after the input application. At four months after biomass application, there were no significant changes on soil chemical properties (Table 7.10). Due to P applied through mineral P fertiliser and biomass, extractable P increased in Ti and TiTe plots compared to the control plots.

Table 7.8. Summary of statistical analysis on NO_3^- data obtained during the maize growth period (March to August 1998)

Parameters	Significance level ($p \leq 0.05$) at different stages of maize growth			
	0 DAP#	30 DAP	60 DAP	90 DAP
Treatments*	NS**	NS	NS	NS
Soil depths	S**	S	S	S
Treat*depth	NS	NS	NS	NS

#DAP: days after planting; * Treatments are shown in Table 6.2; ** S means significant and NS non significant.

Table 7.9. Nitrate-N distribution during the maize growth period (average of all treatments)

Depth (cm)	NO_3N ($kg*ha^{-1}*15cm^{-1}$)			
	0 DAP	30 DAP	60 DAP	90 DAP
0-15	25	20	14	14
15-30	15	35	15	15
30-45	14	14	20	20
60-75	12	12	12	20
$LSD_{0.05}$	7	9	5	4

* Same letters in the column or in the row show means no significantly different at p=0.05

Table 7.10. Chemical characteristics of the surface soil (0-15 cm) at the harvest of the maize crop fertilised with equal rates of N and P (September, 1998)

Parameters	Treatments			$LSD_{0.05}$
	Ti* Biomass	Mixture TiTe* biomass	Control (no fertiliser application)	
PH_{water}	4.5	4.5	4.4	0.23
N (g/kg)	1.8	1.8	1.8	0.1
C (g/kg)	19.0	18.7	18.4	2.6
CEC ($cmol_c$/kg)	13.0	14.2	14.0	3.0
K ($cmol_c$/kg)	0.29	0.35	0.25	0.09
Ca ($cmol_c$/kg)	0.72	0.58	0.51	0.31
Mg ($cmol_c$/kg)	0.14	0.06	0.31	0.26
P (Bray 2, mg/kg)	7	7	5	2

* Ti = *Tithonia*, Te= *Tephrosia*

7.4. DISCUSSION

There were no significant changes in soil bulk density and pH after six-month-old fallows and this was in agreement with the observation that prunings obtained from shrubs in alley cropping system and applied during 4 years at Embu, Kenya (Mugendi, 1997) and a six month-fallow of *Chromolaena odorata* in Indonesia (Hairiah *et al.*, 1996b) had no significant effect on these soil parameters. Frost and Edinger (1991), Belsky *et al.* (1993a; 1993b) and Balagopalan and Seethalakshmi (1997) reported that some agroforestry tree species increased topsoil organic matter under their canopy and decreased bulk density at 0 to 15 cm soil depth, but this was observed under trees older than 5 years. In this study, the value of bulk density remained the same in all treatments probably because of the short fallow period.

No significant changes were observed in total soil carbon content for all treatments. A soil C increase under fast multipurpose tree fallows was reported in India by George and Kumar (1998)) but only after five years of growth. Elsewhere, Gao and Chang (1996) and Swift (1997) found that total organic carbon and total nitrogen content increased in 0-30 cm soil depth after a regular application of manure for a period of 18 years. This increase was larger at 0 to 15 cm than at 15 to 30 cm soil depth. In this study, one or two applications of biomass were not enough to significantly increase soil carbon content compared to unfertilised continuous maize cropping plots. Using the method proposed by Brady and Weil (1999) for estimating humus to be obtained from plant biomass added to the soil, application of 11 tons of *Tithonia* biomass may theoretically provide an increase in soil organic carbon of 0.08 g C/kg of soil at 0 to 15 cm soil depth.

Soil nitrate N was higher in plots where biomass was applied than ammonium N. In well-drained soils, NO_3^- is the form that tends to be more represented than NH_4^+ due to the high availability of O_2 (Tisdale *et al.*; 1990; Buresh and De Datta, 1991). The amount of NO_3^- leached was higher in continuous maize cropping than in fallow systems. The same observation was made in a *Sesbania sesban* fallow experiment at Ochinga (Mekonnen *et al.*, 1997). This high NO_3^- leaching may be due to low nutrient uptake by the poor performing maize crop and to tillage that increases N mineralisation and leaching in areas where rainfall and temperatures are high (Lal, 1976; Sanchez, 1976) as is the case in Western Kenya.

In maize-cropped plots where equal amounts of N from urea, *Tephrosia vogelii* and *Tithonia diversifolia* biomass were applied, NO_3^- was leached to depths of between 40 to 75 cm within a period of 90 days after fertiliser/biomass application. Juo *et al.* (1995)

reported that large additions of green manure make the cropping system prone to losses of NO_3^- and cations through leaching and this often results in decline in pH of the soil surface. The intensity of NO_3^- loss through leaching was similar in all the plots where various sources of N fertiliser were used. However, maize planted in plots where *Tithonia* biomass was applied had severe N deficiency symptoms at 60 days after biomass application. Microbial N immobilisation and N loss through erosion could not have affected this, since *Tithonia* biomass was of high quality and erosion was controlled. The N deficiency was observed even in the experiment where high rate of N (160 kg N/ha) through *Tithonia* biomass had been applied (Section 6.2.1). In these conditions, the N deficiency might have been due to N denitrification such as that observed by Hatch *et al.* (1998) in a well drained soil of temperate zones where 58% of the mineralised N was nitrified and 36% of NO_3 formed was denitrified over a 64-days period. Since Maseno soils are acid (Table 7.2), they would be expected to contain less active denitrifier micro-organisms (Tisdale *et al.*, 1990), hence having low rate of denitrification. However, the same authors, Groffman *et al.* (1988) and Babbar and Zak (1995) stated that the rate of denitrification is highly related to water-soluble and mineralisable organic carbon of applied biomass and is increased in the presence of high soil NO_3^- concentrations. This probably was the case where *Tithonia* biomass was applied.

None of *Tephrosia vogelii*, *Tithonia diversifolia* and natural vegetation six-month-fallows had significantly increased the exchangeable bases and biomass incorporation had no effect on soil bases content at four months after its application. Different results were obtained by Juo *et al.* (1996) at Ibadan, Nigeria where soils under 15 years old fallows of *Leucaena leucocephala*, guinea grass and natural bush fallow had higher pH and effective cation exchange capacity value, C, Ca, Mg and K content than soils under continuous maize cropping. The obvious reason is that short fallows (less than one year) mostly concentrate nutrients in their above ground biomass. There is thus less amount of litter returned to the soil to have any significant impact on soil properties. With long fallows, large amount of litterfall regularly returns to the soil leading to improved soil aggregation and organic matter and its nutrient content increases (Lal, 1976; Myers *et al.*, 1994; Giller *et al.*, 1997; Balagopalan and Seethalakshmi, 1997). Young biomass of high quality obtained from short fallows decomposes very fast (Chapter 5) resulting in a flush of nutrients within a very short period. These nutrients may be lost if plants do not quickly take them up, since there is no improvement of soil properties (SOM, C.E.C) for storing more nutrients. This speculation is in agreement with the finding by Haggar *et al* (1993) that readily mineralisable N built-up in soil organic matter was more efficient for crop nutrition than direct mineralisable N added through green manure.

7.5. CONCLUSION

Six-month-planted fallows of *Tephrosia vogelii, Tithonia diversifolia* and natural vegetation did not significantly change soil bulk density and chemical properties when compared to continuous maize cropping system. This indicates that the benefit obtained from short fallows will rapidly decrease as soon as added fallow inputs are exhausted. However at the end of six month-fallow season, mineral N had decreased in *Tithonia* plots and the reason for this is not known. At 120 days after *Tithonia* biomass application, NO_3^- available in soil was low indicating that there was a high removal of N from the soil. All the processes through which the nitrate N obtained from *Tithonia* biomass was removed from the soil were not totally understood. The leaching of NO_3^- was highest under continuous maize cropping system.

CHAPTER 8: OVERALL DISCUSSION

The production of *Tephrosia vogelii* and *Tithonia diversifolia* above ground biomass by six-month-fallows varied between 4 and 6 Mg DM/ha while the small root biomass was about 1 Mg/ha for *Tephrosia vogelii* and 1.5 Mg/ha for *Tithonia diversifolia*. The biomass yield was higher in soil patches with relatively good inherent soil fertility. Such an observation is in agreement with the statement made by Sanchez *et al.* (1997) that fallow and agroforestry shrubs need some soil fertility to give an adequate amount of biomass in a short time. Most shrub plants had flowered by 160th DAP meaning that after a six-month-growth period, more woody material may start developing than high quality material particularly for *T. vogelii*. Drechsel *et al.* (1996) pointed out in Rwanda that the longer the planted fallow lasted, the more obvious were the increasing proportions of lignified material while the amount of available soft biomass remained almost constant over time.

Above ground biomass of *Tephrosia* and *Tithonia* were high in N, K and Ca but low in phosphorus. For small roots, only *Tephrosia* material had high levels of N. Palm *et al.* (1997) reported that organic inputs were generally low in P and their application does not fulfil the need of inorganic P fertiliser. The high proton consumption capacity recorded with *Tithonia* leaves indicates that these leaves when used as green manure may significantly contribute in raising soil pH and Al detoxification. Nziguheba *et al.* (1998) found that application of *Tithonia* leaves to acid soils significantly reduced soil P fixation.

The six-month-fallows of *Tephrosia vogelii*, *Tithonia diversifolia*, and natural vegetation in a sequential 'fallow-maize-maize fallow' system had no significant effect on soil bulk density and chemical properties. The reason may be the low quantity of organic and mineral inputs returned to the soil during the short fallow period. Improvement on soil properties is only possible after a long fallow period as observed on an Alfisol in Nigeria (Juo *et al.*, 1996).

The application of 3 to 7 Mg/ha of biomass from short duration-planted fallows or incorporated biomass technologies increased the maize growth performance compared to the unfertilised continuous maize crop. However, N deficiency symptoms were observed at the silking stage in the plots where *Tithonia* biomass was applied. At this stage (75 days after planting), the maize plants appeared more yellowish *in Tithonia diversifolia* than in *Tephrosia vogelii* and natural fallow plots. In plots where *Tithonia* biomass was incorporated, there was fast decomposition of *Tithonia* above ground biomass that released a large amount of nutrients in a short time (Figures 5.2-5.5; Gachengo, 1996). Such high amount is generally subjected to high losses through leaching (N, K, Ca, Mg) and probably N denitrification (Aulakh *et al*, 1991) particularly where the rainfall is high and soils acid (van Noordwijk *et al.*, 1995). Thus plant nutrients were no longer available to meet the maize crop requirements at critical stages of growth. Possible ways of reducing N losses may be through mixing these high quality with low quality materials (Browaldh, 1997; Motavalli and Diambra, 1997; Handayanto *et al.*, 1997) or continuous and regular application of small amounts of high quality biomass over the growing season.

In plots with *Tephrosia* and natural vegetation materials, decomposition was slow and N was thus progressively available to the maize. For natural vegetation, which mainly consisted of *Digitaria* sp., the material was low in N with the additional ability of couch grass to shoot. To avoid shooting, the natural vegetation biomass was applied as mulch before being incorporated into the soil at the first weeding of the maize (30 DAP). Due to late release of nutrients through decomposition, yellowish stunted maize in early stage of growth turned relatively green at tasseling-silking stage.

The application of *Tephrosia* and *Tithonia* biomass increased the maize grain yield (about 2.0 to 2.5 fold the yields in the control plots) probably by providing nutrients (Palm *et al.*, 1997; Buresh and Niang, 1998), complexing exchangeable aluminium (Hue and Amien, 1989; Tan, 1993) and making P more available (Buresh *et al.*, 1997). These responses were appreciable, similar to those obtained with application of 1.5 Mg *Tithonia diversifolia* leaves/ha in Malawi (Ganunga *et al.*, 1998) and relatively better than the maximum increase of about 2 times reported by Drechsel *et al.* (1996) in Rwanda although high crop yields were not obtained. This was in respect to the decrease of production function normally caused by high depletion of natural capital (Izac, 1997). The effect of *Tephrosia* and *Tithonia* biomass application on the maize performance decreased over seasons and was no longer significant at the third season after biomass incorporation and this may be related to the little improvement observed on soil properties (Chapter 7). Cadisch *et al.* (1998) reported similar yield decrease over three successive maize cycles with *Gliricidia* biomass applied only at the beginning of pot experiment. They also found that repeated addition of this high quality biomass at the second and third maize cycle increased not only total maize N uptake and yield but also N recovery from previous biomass applied to the first maize. The present study showed that in the system where above ground biomass was removed, the maize yields were higher in *Tithonia* than those in *Tephrosia* plots, the later yields were in turn similar to those of continuous maize crop. Such a low effect with *Tephrosia* biomass removal has also been observed in Rwanda (Balasubramanian and Sekayange, 1992). The *Tithonia* efficiency was due to the high amount of litterfall during the growth period.

Adding a moderate amount of 20 kg inorganic P/ha to the plots with *Tephrosia* and *Tithonia* biomass substantially increased the maize yields particularly in soil patches where exchangeable Al were relatively low. Similar results were reported by Buresh *et al.* (1997) for soils with low to moderate P sorption capacity and without major constraints from aluminium saturation. However, Rutunga (1997) reported that on highland acid soils of Rwanda with high level (>0.5 cmol(+)/kg soil) of Al, 22 kg P/ha applied without lime had no significant effect on crop yields. In this study, addition of P in plots where biomass was not applied had very little improvement on the maize performance and maize stover and grain yields in unfertilised continuous cropping plots were very low. This was due to the nutrient deficiency coupled by imbalances that were only corrected in the plots where organic inputs were added (Palm *et al.*, 1997). However, maize yield in this study showed that organic inputs that are generally low in P, unless applied at a very high rate (Rutunga *et al.*, 1998) or in soils with adequate levels of P need to be supplemented with inorganic P application.

The applications of moderate P rate had slightly increased available soil P (Table 7.10). This is in agreement with Buresh *et al.* (1997) who found that gradual build-up of P nutrient in the soils of Western Kenya may be achieved with regular seasonal applications of P but at sufficiently high rates. The additional condition of such an improvement is maintaining an adequate level of C in soil (Chauhan *et al.*, 1979).

The lack of significant differences in maize yields obtained with application of 20 kg P + 80 kg N/ha provided through different sources of fertilisers (*Tephrosia* and *Tithonia* biomass, maize stover, urea, triple superphosphate) showed the importance of achieving an appropriate synchrony of nutrient availability and plant nutrient demand. There are many factors such as time and method of fertiliser application, type and quality of fertilisers, soil physical and chemical properties, soil water availability, plant growth and nutrient uptake (Balasubramanian and Sekayange, 1992), that have to be at an adequate level before getting better synchrony leading to improved crop performance. Early release of nutrients from *Tithonia* biomass led to low available nutrients at the late stage of maize growth while the reverse occurred with *Tephrosia* biomass and this might be the reason for the same yield obtained with the two-shrub biomass.

For both rotational fallow and biomass incorporated systems, where an equal amount of above ground biomass obtained either from *Tephrosia* or *Tithonia* was applied, the maize plants showed similar performance in yields. The six-month-fallow had no substantial effect on soil organic matter and nutrients, which regulate numerous environmental constraints to crop productivity (Woomer and Swift, 1994). Since the effect of *Tephrosia* and *Tithonia* six-month-fallow was not significantly different from that of biomass incorporated technology when the same quantity and types of biomass were applied to improve maize yields, either of these systems may be used. The major constraint for improved fallow will be the loss of one crop season and establishment costs while for the biomass incorporated, enough amount of organic materials and labour required for its transport may not be easily available. The whole question of profitability and other socio-economic aspects of these technologies is followed by an economist. The preliminary results have already indicated that improved fallows were generally more profitable than natural fallows and maize continuous cropping in the wet highlands (Jama *et al.*, 1999) whereas in the case of biomass transfer technologies positive financial benefits were recorded only with high value crops (Niang *et al.*, 1996).

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

9.1. CONCLUSIONS

The six month-planted fallow of *Tephrosia vogelii* and *Tithonia diversisfolia* showed good potential for biomass production. The quantity of *Tithonia* biomass was higher than that of natural fallow biomass. Another important difference between shrub and natural fallow biomass was the high N content of shrub biomass. *Tithonia* leaves had the highest proton consumption capacity, indicating their adequacy as green manure for acid soils. *Tephrosia* above ground biomass released most nutrients within three to four months after incorporation while that of *Tithonia* decomposed very fast (within one month) releasing most nutrients in a short time. Application of large amounts of *Tithonia* and *Tephrosia* biomass had a significant effect on maize growth and yield performance, particularly when supplemented with inorganic P. However, it was observed that *Tithonia* biomass did not supply enough N to sustain maize growth from planting to harvesting period. Various N losses might have occurred during the growing season, hindering an adequate continuous N availability to the crop hence low maize yields. Short duration fallows or single biomass incorporation did not significantly improve soil carbon and nutrient content and their residual effect on maize yield decreased over time and this indicates that these technologies cannot sustain a high productive agriculture in highly degraded soils through a single application. However, they offer alternatives for improving rotational systems in non- or slightly depleted soils. In highly depleted soils, rotation 'fallow-maize-fallow' may be more sustainable than rotations 'fallow-maize-maize-fallow or fallow-maize-maize-maize-fallow' and addition of biomass every six months will be more beneficial to the crop than a single biomass application after every 1.5 or 2.0 years.

9.2. RECOMMENDATIONS

The use of *Tephrosia vogelii* and *Tithonia diversifolia* biomass as green manure incorporated in the soil at one week before maize planting should be supplied with mineral P fertiliser, particularly in highly depleted soils. In the case of *Tithonia* biomass, the maize crop should be top-dressed with mineral N or *Tithonia* leaves at 30 days after planting to obtain high yields. With *Tephrosia* biomass, N starter must be provided through either mineral N or application of biomass at advanced decomposition level or at three weeks before planting. The potential of repeated application of these organic inputs to improve soil nutrient build-up and sustained crop yields needs to be assessed. Since most soils in Western Kenya are depleted and fertiliser inputs are hardly applied, farmers should avoid practising continuous mono-cropping and adopt rotational systems consisting of cereals (maize, sorghum) in the long rainy season (February to August) and legumes (beans, soyabeans, groundnuts, cowpeas) in the short rainy season (September to January). The leguminous crops provide beneficial 'rotational effect' and some advantages as observed with the short improved fallows on maize crop in Maseno. However, adoption of agroforestry technologies such as improved fallows is still low in Western Kenya and therefore socio-economic studies are required in order to come up with solutions to raise the awareness.

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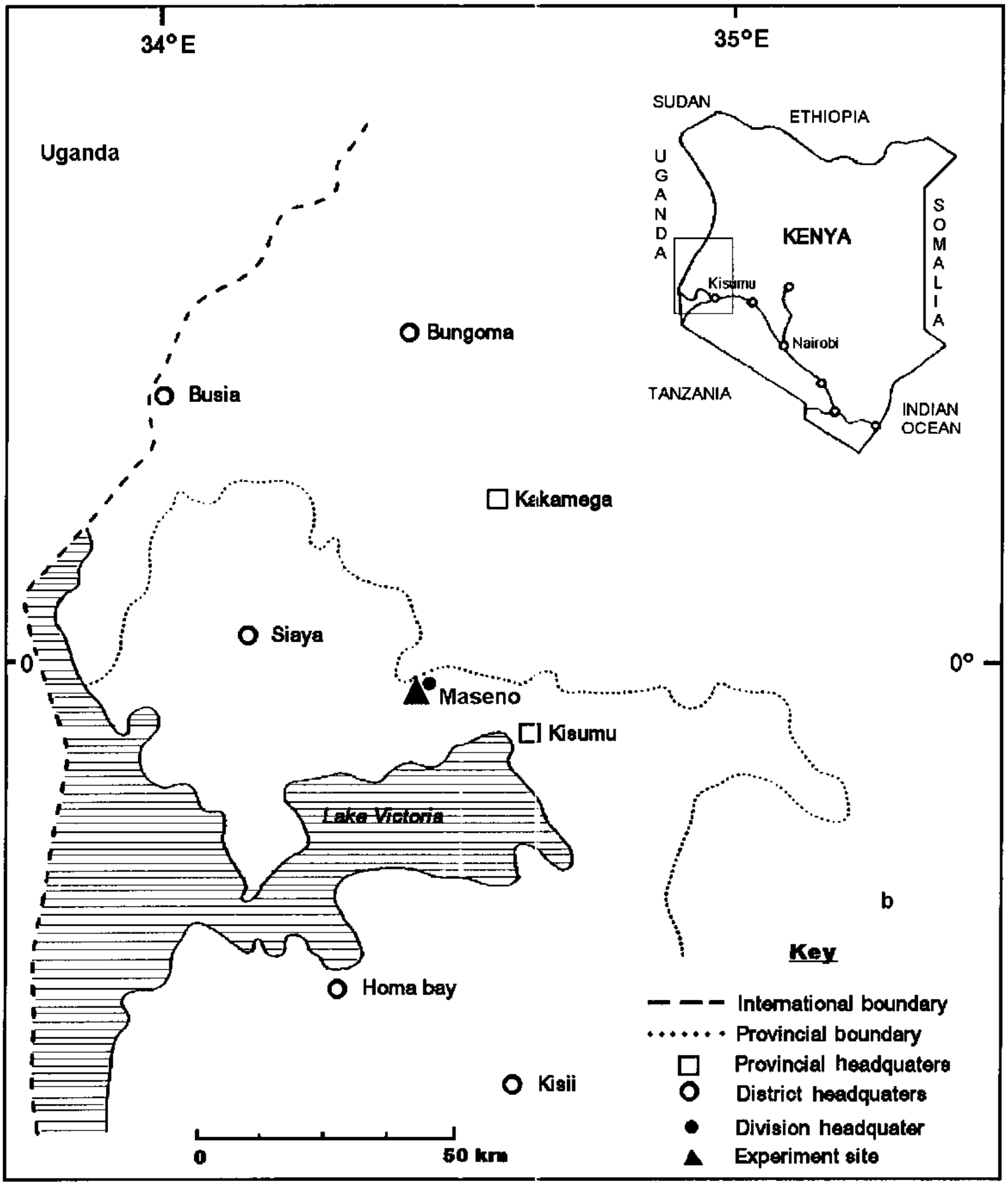
Appendix 3.1. Location of Maseno experimental site



Appendix 3.2: Description of the soil profile at the experimental site

Site characteristics

Location: Maseno Veterinary Farm, latitude 0°0' and longitude 34°35' E, elevation 1600 m above sea level.;

Date: September 20, 1996;

Soil classification: - Humic Nitisols (FAO-UNESCO, 1994);

- Typic Kanhaplohumults (Soil Survey Staff, 1996)

Land form: upland;

Parent material: basic igneous rocks of Nyanza Kavirondian System;

Micro-topography: very gently undulating, slope 4%, length>200 m; shape, regular;

Surface features: Interill erosion, ridge/ furrow;

Drainage: well drained; Ground water table: very deep ground water table (> 3 m);

Vegetation: none; Land use: land under cultivation;

Climate: Agro-climatic Zone II (ACZ II), sub-humid.

Soil profile description

Horizon	Depth	Horizon description
Ap	0-21 cm	Dark reddish brown (5YR 2/4) when moist; clay; medium weak subangular blocky structure; friable when moist, sticky and plastic when wet; common fine and medium pores; few fine roots; clear and irregular transition to:

AB	21-37 cm	Dark reddish brown (2.5YR 3/3) when moist; clay; fine and medium weak subangular blocky structure; friable when moist, sticky and plastic when wet; common fine and medium pores; very few fine roots; gradual and smooth transition to:
BA	37-55 cm	Dark reddish brown (2.5YR 3/3) when moist; clay; fine and medium subangular blocky structure; friable when moist, sticky and plastic when wet; rare clay cutans; common fine and medium pores; gradual and smooth transition to:
Bt1	55-100 cm	Dark reddish brown (2.5YR 3/4) when moist; clay; medium moderate subangular blocky structure; friable when moist, sticky and plastic when wet; common clay cutans; common fine and medium pores; clear and regular transition to:
Bt2	100-135 cm	Dark red (10R 3/4) when moist; clay; medium moderate to strong subangular and angular blocky structure, friable when moist, sticky and plastic when wet; common clay cutans; common fine and medium pores; gradual and smooth transition to:
Bt3	135-169 cm	Dark red (5YR 3/4) when moist; clay; medium moderate subangular and angular blocky structure, friable when moist, sticky and plastic when wet; common clay cutans; common fine and medium pores; very few soft Fe and Mn concretions with a diameter of less than 3 mm; gradual and smooth transition to:
	169 cm+	As Bt3

Appendix 4.1: Root characteristics of various performing maize crops at Maseno experimental site

	Average root diameter (mm)	Root length density (cm/cm^3)	Below ground stem portions (kg/ha)
Type of maize crop			
Poor maize	0.59	0.159	23
Medium maize	0.73	0.331	102
Good maize	0.65	0.425	143
Very good maize	0.69	0.746	204
$LSD_{0.05}$	0.14	0.170	114
Depth (cm)			
0-15	0.79	0.659	Na*
15-30	0.63	0.337	
30-45	0.58	0.250	
$LSD_{0.05}$	0.12	0.240	

*Na: not applicable

Appendix 4.1 (continued)

	Root biomass (kg/ha) at various soil depths		
Type of maize crop	0-15 cm	15-30 cm	30-45 cm
Poor maize	275	15	14
Medium maize	287	105	71
Good maize	820	290	114
Very good maize	2476	318	131
$LSD_{0.05}$ for treatments	79		
$LSD_{0.05}$ for depths	109		
$LSD_{0.05}$ for interaction	188		

Appendix 4.2. Average N yield (kg/ha*) of various plant parts during the two fallow seasons

Treat-ments	Litter	Above ground biomass	Small roots	Total Roots	Total N	Small roots: litter N ratio	Small roots: above ground biomass N ratio	% small root N in the total N
TeF	24	100	26	40	190	1.1	0.3	14
TeT	15	41	17	29	92	1.1	0.4	18
TiF	51	115	19	42	227	0.4	0.2	8
TiT	56	108	14	35	213	0.3	0.1	7
NF	0	55	20	20	95	0.0	0.4	21

* Roots comprise of the amount obtained from 0-45 cm soil depth.

Appendix 6.1: Average nutrient concentration of maize above ground biomass accumulated at different stages of growth in the first maize crop following the fallow

Nutrients	Biomass at V#6-7	Biomass at V14-15	Biomass at R#3	Stover at R6	Cores at R6	Grains at R6
	Average nutrient concentration (g/kg)					
N	27.3	20.4*	15.4	9.0	7.4	13.6
P	1.68*	1.29	1.04	0.35*	0.52	1.2*
K	24.1*	22.9*	78.4	50.8	54.7	18.3
Ca	2.2	3.0*	2.9*	2.8	trace	trace
Mg	2.7*	2.3	2.0	1.9	0.5	0.5

#: Various stages of maize growth; * A significant difference was obtained between the values of various treatments.