NITROGEN DYNAMICS IN AGRO-ECOSYSTEMS OF UASIN GISHU DISTRICT, KENYA

by

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CHAPTER ONE

BACKGROUND, MOTIVATION AND OBJECTIVES

1.1 Background

Uasin Gishu District in Kenya is located in the central western part of the Rift Valley between longitudes 34^o 50'E and 35^o 37'E and latitudes 00^o 03'S and 00^o 30'N. This part of the rift is typical of the western highland plateau of the Rift Valley and rises to an altitude of 1800 m above sea level (Cone and Lipscomb, 1972; Lwayo *et al*., 2001). The location of Uasin Gishu District within Kenya is displayed in Figure 1.1.

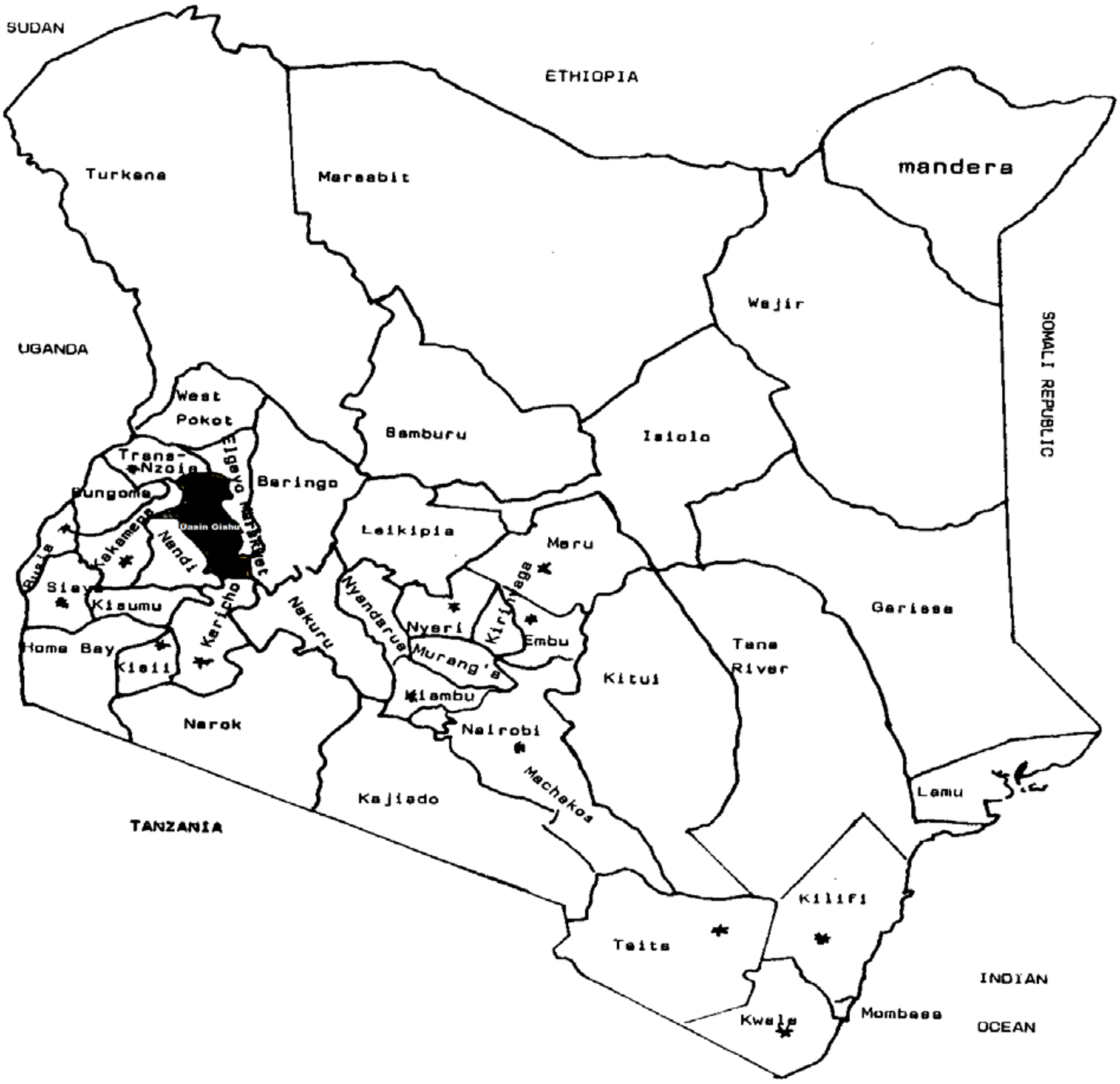

Figure 1.1 Map of Kenya and the location of Uasin Gishu District
(http://www.maps.virtualkenya.org)

Uasin Gishu District covers about 3218 km^2 that are equated to approximately 2% of the Rift Valley Province and 0.5% of Kenya land areas (Figure 1.2).

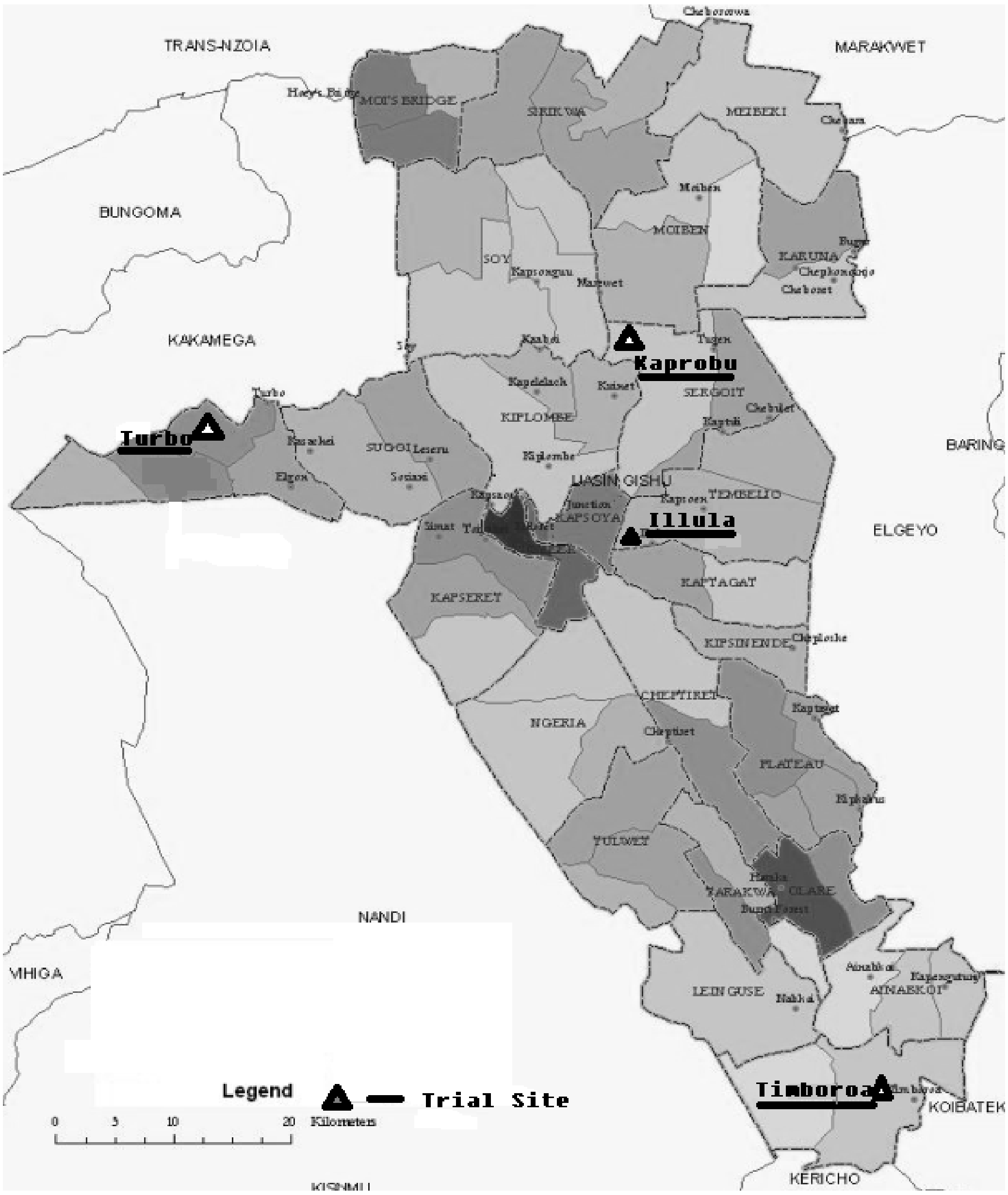

Figure 1.2 Map of Uasin Gishu District and location of the trial sites (http://www.maps.virtualkenya.org)

The district despite its relatively small land area is one of the main cereal producing areas in Kenya with crops like maize, wheat and barley. It is regarded together with the neighbouring Trans-Nzoia District as a “granary” for the country’s over 30 million people. Uasin Gishu District produces apart from cereals also subsistence crops like beans, potatoes and vegetables (District Development Plan, 2001).

For agricultural purposes three agro-ecological zones are acknowledged in the Uasin Gishu District. They are the Upper Highland Zone dominated by Nitisols, Upper Midland Zone dominated by Acrisols and Lower Highland Zone dominated by Ferralsols with patches of Gleysols in between (Eltson and Dennett, 1981; Jaetzold and Schmidt, 1983; KARI, 1997) as shown in Table 1.1.

Table 1.1 Agro-ecological zones, dominant soil types and crop potentiality in Uasin Gishu District (Adapted from Jaetzold and Schmidt, 1983)

Agro-ecological zone			Dominant soil type		Crop potentiality
Name	Location	Coverage (%)	FAO	USDA	
Upper Highland	Southern and Eastern	22	Nitisol	Alfisol	Potatoes, Pyrethrum, Wheat, Maize and Vegetables
Upper Midland	Western	11	Acrisol	Ultisol	Sunflower, Maize, Millet and Sorghum
Lower Highland	Central and Northern	67	Ferralsol with patches of Gleysol	Oxisol with patches of Aquent	Maize, Wheat, Barley and Beans on Ferralsols with natural habitat (Swamps) on Gleysols

During the 10 year period from 1995 to 2004 Uasin Gishu District produced annually an average of 2.90 tons maize ha^{-1}, 2.50 tons wheat ha^{-1} and 0.45 ton beans ha^{-1} (Table 1.2). The contribution of this district to the country's annual average production of 3 million tons of maize is little over 5%. Annual average consumption of maize is 3.5 million tons leaving 0.5 million ton as a deficit to be imported. An opportunity exists thus for Uasin Gishu District to increase maize production for the benefit of Kenya (District Development Plan, 2001).

Table 1.2 Annual production of maize, wheat and beans (t ha^{-1}) from 1995 to 2004 in Uasin Gishu District (Adapted from Uasin Gishu Agriculture Office Annual Report, 2004)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Mean
Maize	3.15	3.15	2.25	3.42	2.70	2.88	2.88	2.52	3.15	2.97	2.90
Wheat	2.25	2.88	1.80	2.70	2.55	2.70	3.15	2.25	2.70	2.70	2.50
Beans	0.90	0.63	0.36	0.63	0.18	0.36	0.45	0.45	0.45	0.13	0.45

1.2 Motivation

A general decline of soil fertility in Uasin Gishu District and the neighbouring Trans-Nzoia District was reported due to continuous cropping of land without fallowing practice, soil fertility replenishment and crop rotation practices (Woomer and Muchena, 1996; Sanchez et al., 1997; Smaling et al., 1997). Maize and wheat production in these districts are predominantly under monoculture. Small scale farmers however intercrop beans with maize. For both cereal crops the land is ploughed twice if virgin and once if fallow. Then the land is harrowed once before being planted with the relevant crop. Farmers however experience lower yields of maize, wheat and beans than expected. This is especially true with maize on the Ferralsols and Acrisols in spite the fact that hybrid cultivars are planted with near sufficient fertilization (Field Crops Technical Handbook, 2002).

The annual average yield over a ten year period was only 2.9 tons maize ha^{-1} (Table 1.2). It is believed therefore that the maize crop runs out of N before maturity due to heavy rainfall from April to August. During this period torrential rainfall that exceed 20 mm a day for more than three consecutive days is common. This torrential rainfall resulted probably in severe N losses through either leaching or denitrification that manifested in yellowish foliage (Nonaka *et al*., 1996; Patra and Rego, 1997). Such N depleted maize is displayed in Figure 1.3. Farmers have observed that higher yields of maize are more likely when rainfall is evenly distributed from April to August of the year.

Figure 1.3 Nitrogen depleted maize crop after heavy rainfall

The loss of applied N through either leaching or denitrification is not only an economical waste for farmers but may also be detrimental to the environment. Environmental problems caused by leaching are that nitrate may reach domestic wells, and eventually flow underground to surface waters, lakes and estuaries. This nitrate may result in unfit drinking water and causes eutrophication with its associated problems. The N_2 released by denitrification is quite inert and environmentally harmless, but not the NO and N_2O which are both very reactive. These oxides of nitrogen when released in the atmosphere contribute *inter alia* to the greenhouse effect and acid rain (Jackson, 2000; Brady and Weil, 2008).

Before cropping commenced the natural habitat was savanna grassland (Figure 1.4). After conversion to cropland, farmers relied initially on the inherent fertility of the soils to provide the nutritional requirements of crops. Although the farmers started using organic fertilizers like animal manure and crop residues, the application was low and could neither sustain nor maintain the fertility level of the soils. In addition, most farmers opted to burn crop residues in anticipation of early field preparation.

Figure 1.4 Natural habitat of most part of Uasin Gishu District is savanna grassland

In an attempt to restore the depleted soil fertility, a blanket recommendation of 60 kg N ha^{-1} and 26 kg P ha^{-1} was promoted for many years (Allan *et al*., 1972). Based on research by FURP (1994) the adapted recommendation by the Ministry of Agriculture is 75 kg N ha^{-1} and 26.4 kg P ha^{-1} as diammonium phosphate (DAP) at planting, followed by topdressing of 50 kg N ha^{-1} as calcium ammonium nitrate (CAN). This topdressing is recommended to be split, with half at knee high and half at tasseling for maize. However, farmers often top-dressed once at knee-high to minimize labour. Fertilization of this nature should be sufficient for maize in Uasin Gishu District to yield 6.4 t to 6.9 t of maize grain ha^{-1} (Jaetzold and Schmidt, 1983). An application of 125 kg N ha^{-1} and 83 kg P ha^{-1} is anticipated to be sufficient for a yield of 6 t of maize grain ha^{-1} in South Africa (FSSA, 2008).

Recommendation for wheat is a range of 33.3 kg N ha^{-1} to 44.5 kg N ha^{-1} and 37.5 kg P ha^{-1} to 50 kg P ha^{-1} applied as DAP at sowing. Bean crop recommendation in this district is 22.2 kg N ha^{-1} and 25 kg P ha^{-1} applied as DAP at planting. Intercrop maize and beans recommendation is 75 kg N ha^{-1} and 33 kg P ha^{-1} applied as DAP at planting (Ministry of Agriculture, Uasin Gishu District, 2004).

These blanket fertilizer recommendations are still applied in the Uasin Gishu District despite of the fact that very little knowledge is available on the yield and nitrogen response of annual crops to this approach of supplementing essential plant nutrients like nitrogen. Furthermore almost nothing is known of the spatial and temporal distribution of mineral N in soils under cropping, especially during the period of torrential rainfall when leaching and denitrification are a potential danger for N losses. Severe losses of applied N through either leaching or denitrification may decrease the nitrogen use efficiency in cropping systems causing a decrease in crop productivity and an increase of environmental pollution. Proper knowledge of all these aspects is of importance for sustainable land use in the district.

As pointed out there is currently a lack of proper knowledge on nitrogen dynamics in agro-ecosystems of Uasin Gishu District in Kenya. An agro-ecosystem is a land area where the environmental factors influencing crop yield, namely climate, slope and soil are for practical purposes homogeneous. A better knowledge into nitrogen dynamics of some agro-ecosystems in the district is essential for enhancing sustainable cropping.

1.3 Objectives

The overall objective of this study was to quantify some N dynamics under five different cropping systems in four representative agro-ecosystems of Uasin Gishu District, Kenya. Specific objectives were to:

- Determine yield and nitrogen response of annual crops grown with blanket fertilizer recommendations.
- Establish spatial and temporal distribution of mineral N in soils under cropping systems with blanket fertilizer recommendations.
- Quantify nitrogen use efficiency in sole and intercropping systems fertilized at different N rates.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Nitrogen is a colourless, odourless gas in group five (v) elements of the periodic table of elements. This inert gas forms 78.1% by volume of the earth's atmosphere from which it can be obtained by liquefaction and distillation. It also occurs as nitrates and in proteins and amino acids. The relative atomic mass of N is 14.0 and the atomic number is 7 (Parker, 1983; Hibbert and James, 1987).

The bulk of the earth's N (98%) is held in rocks and minerals. In general, this N exists as nitrides of iron, titanium and other metals or as ammonium ions held in the lattice structure of primary silicate minerals. The igneous rocks of the earth's crust hold approximately 97.8% of the global N (Bartholomew and Clark, 1965; Stevenson, 1965).

Nitrogen is the essential nutrient most required by plants. This nutrient is absorbed by plants from the soil in the greatest quantity and is the most limiting nutrient for food production (Russell and Russell, 1978; Foth, 1990; Vlassak *et al*., 1999). Nitrogen controls the rate of growth and a deficiency or excess can drastically affect crop yield (Tisdale *et al*., 1985; Vlassak *et al*., 1991; Davis *et al*., 1993; Sanchez *et al*., 1997).

Unfortunately, plants cannot metabolize atmospheric N directly into protein. Thus atmospheric N must be converted first to plant available N. In this regard biological N fixation by symbiotic and non-symbiotic soil organisms, atmospheric discharges forming N oxides, and manufacture of synthetic N fertilizers play a significant role (Wild, 1988; Giller and Wilson, 1991; Rowell, 1994; Woomer *et al*., 1998).For centuries the first two processes provided sufficient plant available N for food production.

However, due to increasing food requirements, man was forced to accelerate food production by introducing chemical fertilizers since 1880 (Finck, 1982). Nitrogen fertilizer is the most difficult to apply in the correct quantity. This is because N is very dynamic in the soil-plant system (Wild, 1988).

2.2 Nitrogen cycle in soil-plant system

The N in the soil-plant system is continuously transforming from one form to another as a result of environmental changes as well as usage by plants, micro-organisms and animals (Delwiche, 1970; Haynes, 1986; Rowell, 1994). Figure 2.1 shows the nitrogen cycle in the soil-plant system. This cycle consists of a sequence of biochemical changes wherein N is used by living organisms, transformed upon death and decomposition of the organisms and converted ultimately to its original state of oxidation (Parker and Scutt, 1960; Haynes, 1986; Singer and Munns, 2002). These changes are described in terms of fixation, mineralization, nitrification, immobilization and denitrification. Two non-biochemical processes which result in N losses are of importance also; namely leaching and volatilization (Foth, 1990). The fixation of NH_4^+ by clay minerals may be regarded also as a loss but the fixed NH_4^+ can be released in some instances.

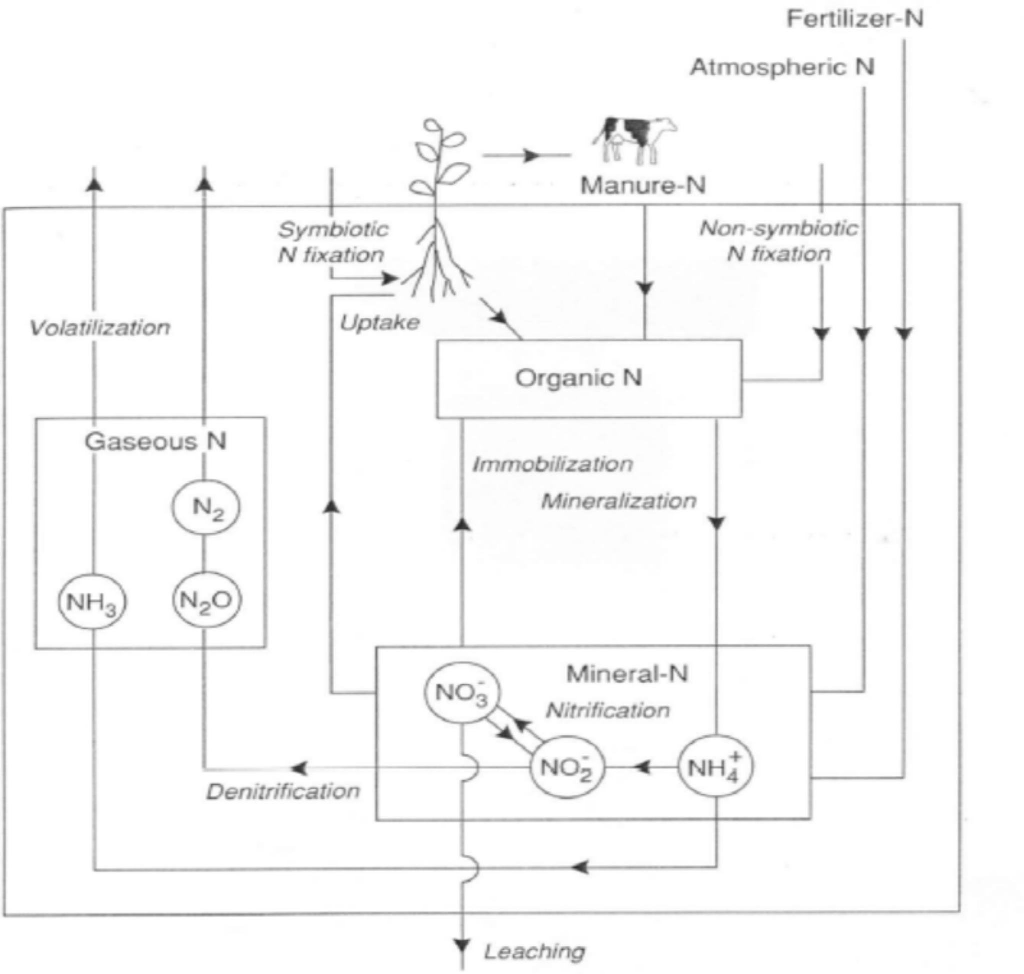

Figure 2.1 Nitrogen cycle in the soil-plant system (Adapted from Rowell, 1994).

Nitrogen fixation ($N_2 \rightarrow NH_4^+$) is accomplished by symbiotic heterotrophic *Rhizobium* bacteria as well as free living actinomycetes and blue-green algae (Peoples and Craswell, 1992). These organisms convert N_2 to NH_3 and subsequently into organic forms, which are utilizable in biological processes (Lemon and Van Houtte, 1980; Stevenson, 1982; Wild, 1988; Addiscott *et al.*, 1991). Organic N is mineralized (Organic $N \rightarrow NH_4^+$) by saprophytic and predatory heterotrophic, including bacteria, fungi and protozoa (Russell and Russell, 1978; Mueller-Harvey, *et al*., 1985; Addiscott *et al*., 1991; Rowell, 1994; Brady and Weil, 2008). The N in NH_4^+ is subject to nitrification ($NH_4^+ \rightarrow NO_2^-$, NO_3^-). Autotrophic bacteria (*Nitrosomonas* and *Nitrobacter*) accomplish this two step process with nitrite (NO_2^-) as the intermediate product and nitrate (NO_3^-) as the ultimate product (Addiscott *et al*., 1991; Anderson, 1994). In immobilization of N both NH_4^+ and NO_3^- could be utilized by microorganisms (when N is insufficient in decomposing organic residues) for their metabolic needs. This process reverts therefore NO_3^- and NH_4^+ back to organic N (Wild, 1988; Addiscott *et al*., 1991). Denitrification ($NO_3^- \rightarrow N_2$ and N_2O) is accomplished by heterotrophic bacteria (facultative and anaerobic organisms) in oxygen deficient conditions. Either nitrate or nitrite is reduced to molecular N or nitrogen oxide by microbial activities (Mosier and Hutchison, 1981). These gases escape from soil back to the atmosphere. This completes the biochemical processes (Beevers and Hageman 1980; Firestone, 1982; Parkin, 1987; Jarvis *et al*., 1991; De Klein *et al*., 1996).

Furthermore, there are two associative processes which are inclusive in the N cycle, namely the leaching of NO_3^- and volatilization of NH_3. Nitrate is susceptible to leaching due to excessive rain or irrigation since it is negatively charged and therefore not subject to adsorption in most soils (Singh and Kanehiro, 1969; Bouma and Anderson, 1977; Arshad and Coen, 1992). This process is reversed in dry spells on account of upward capillary movement of water (Birch, 1952). Researchers report that this process can return 30 to 50% of the leached N (Bartholomew and Clark, 1965; Sanchez, 1976; Weldeyohannes, 2002; Wolfgand and Juliane, 2005).

The conversion of NH_4^+ to NH_3 results in volatilization of the latter to the atmosphere. This reaction is pH dependent and NH_3 loss occurs therefore mainly from alkaline soil, especially when ammonium-containing or ammonium-forming fertilizers are surface applied. Ammonia can also be lost directly from animal dung and urine (Thomas and Troeh, 1973; Foth, 1990).

2.3 Fate of applied nitrogen in agro-ecosystems

Applied N in agro-ecosystems comes in various forms, i.e. those that come naturally from the N cycle, which are derived primarily from atmospheric N (Rowell, 1994). There is also organic N derived from plant and animal residues and remains which are decomposed to plant available NH_4^+ and NO_3^-.

Apart from naturally supplied N, farmyard manure (FYM) and chemical fertilizers are applied by farmers to the soil. The FYMs are animal wastes and plant residues prepared by farmers as compost manure while chemical fertilizers are industrial products which are manufactured to supply N and sometimes other specific plant nutrients, i.e. mixed fertilizer that contain N, P and K.

Nitrogen-containing fertilizers are *inter alia* ammonium sulphate (21% N), ammonium chloride (25% N), calcium ammonium nitrate (28% N), urea (46% N) and anhydrous ammonia (82% N). The latter is a gas at atmospheric pressure and some may be lost to the atmosphere during and after application if precautionary measures are not taken. All of the other fertilizers are available in a granular form. They are water soluble and dissolve therefore quickly after application to a moist soil.

The first fate of applied N in agro-ecosystems is volatilization of NH_3 gas into the atmosphere. As mentioned anhydrous ammonia is most susceptible. Urea is more vulnerable to NH_3 volatilization than the other three granular fertilizers and requires careful management. This process can be controlled by selecting a fertilizer least susceptible to volatilization and incorporating it into the soil at application (Shankaracharya and Metha, 1971; Sanchez, 1976; Fenn and Miyamoto, 1981; Westfall, 1984; Boswell et al., 1985; Addiscott et al., 1991; Ahn, 1993).

The fate of applied N is dependent also on denitrification which is common under anaerobic conditions. In such conditions nitrate and nitrite are reduced to nitrous oxide and dinitrogen gases. A comprehensive survey suggested that up to 30% of fertilizers' N can be lost by denitrification with an average in the range of 9% to 15%. Losses from arable soils are higher than from grassland soils, since the grassland tends to maintain lower nitrate levels (Hoeft, 1984; Parkin, 1987; Wild, 1988).

In areas of high rainfall applied N is found often in surface runoff or surface drainage since most nitrogenous fertilizers are water soluble. This process is enhanced with agriculture machines when they destroy soil structure and eventually creates hardpans and crusts in contrast to undisturbed ecosystem, i.e. a forest (Pleysier and Juo, 1981; Wild, 1988; Vogel *et al*., 1994). Dissolved N in the form of NO_3^- also ends up as through flow in streams, rivers, ponds, lakes and drainage ditches. In the waters, NO_3^- acts as fertilizer for aquatic plants, causing eutrophication with blooming plants and especially algae, which has been noticed in some inland waters (Addiscott *et al*., 1991; Courtney and Trudgill, 1993). They use the available oxygen, leaving other forms of life such as fish and water insects to suffocate in the polluted water. Water hyacinth in Lake Victoria is a current typical case in the East African region.

In many instances leaching determines the fate of applied N. Nitrate is not adsorbed on soil particle surfaces unless they carry positive charges (Wong *et al*., 1990). Thus NO_3^- is freely leached except in acidic soils of the humid tropics which may have positive charges (Wong et al., 1987; Rowell, 1994). However, the texture and structure of soil affect the rate of leaching (Rao and Reddy, 1996).

Leaching of NO_3^- manifested usually in economical loss and environmental pollution (Lal, 2001). We have not yet seen the full implication of nitrate pollution. Nitrate seeps down into the deeper layers of soil extremely slowly until eventually it reaches the groundwater. It may take 20 to 30 years to get to groundwater. In some areas of arable eastern counties of England, nitrate levels in borehole water are already beginning to exceed the European Economic Community recommendation limits, namely 11.3 mg l^{-1}. In the United Kingdom, nitrate sensitive zones have been introduced where farmers are paid to reduce nitrate pollution (Blake, 1994; Thomas and Boisvert, 1995).

Land use has a major influence on the amount of NO_3^- leaching. The amount of N lost by leaching increases as the land use intensifies. The undisturbed ecosystems such as forests lose little N by leaching, whereas intensively fertilized and irrigated horticultural crops and cereals can lose considerable amount of NO_3^- (Sanchez, 1976).

A study on wheat to predict yield, drainage and NO_3^- leaching for deep sand in the 500 mm rainfall zone in Western Australia, showed that the soil water and the soil inorganic N content at the beginning of each season had no effect on grain yields, implying that pre-sowing soil NO_3^- was largely lost from the soil by leaching. Splitting the N fertilizer application, decreased NO_3^- leaching and increased N uptake by wheat crop and increased grain yields (Asseng *et al*., 1998; Wilson *et al*., 1998).

In a study concerning NO_3^- leaching it was found that N in a soil profile was greatly affected by rainfall pattern. The peak of leached nitrate N coincides with the peak of rainfall and showing good correlation (Powlson *et al*., 1991; GaoMing *et al*., 1998).

A similar study done in the semi-arid tropics of India, using bromide as a tracer to mimic nitrate movement, showed that bromide distribution in a Vertisol was influenced strongly by rainfall. After one week with rainfall of 64 mm, although some bromide was found to a depth of 60 cm, most (40%) of it was in the top layer (0-10 cm). A total of 90% of applied bromide

was recovered to a depth of 60 cm (Patra and Rego, 1997; Toth and Fox, 1998).
In New South Wales in Australia a study was conducted in the mid 1980's on a long-term fallow management trial with different tillage and stubble practices in fallow grain cropping. This indicated that leaching of nitrate may have been the cause of low concentration of nitrate N within the root zone (Turpin *et al*., 1998).

Another study conducted by the University of Florida in the United States of America, leaching nitrate from compost amended soil columns, showed that the maximum concentration of nitrate-N in the leachate reached 246 mg. The leaching peak for nitrate occurred after the application of 300-400 ml water (Li-ye *et al*., 1997; Ottman and Pope, 2000).

Through microbial oxidation of NH_4^+ to NO_3^-, most of the fertilizer taken up from non-acidic soils is converted to nitrates a few weeks after application. Nitrate and ammonium fertilizers differ in effectiveness; nitrates tend to be quicker acting, but are subject to loss by denitrification and leaching from the time of application. Ammonium fertilizer and urea may lose N by ammonia volatilization soon after application, but denitrification and leaching losses may occur later when the ammonium has been oxidized to nitrate (Russell and Russell, 1978; Alexander, 1980; Wild, 1988).

The NO_3^- fertilizers are soluble in water and not adsorbed by the negative soil colloids. As such, they may raise the osmotic pressure of the soil solution around seedling to a damaging level if used during dry weather (Sanchez, 1976). Because of denitrification losses, nitrate should not be applied in poorly drained soils and particularly not for paddy rice or any waterlogged condition (Wild, 1988).

It has been noted also in semi-arid Kenya that, use of phosphorus fertilizer at a P deficient site reduced soil NO_3^- concentration under grass and sorghum throughout the season and increased N uptake by these crops (Warren *et al*., 1997). This phenomenon was ascribed to the more vigorous growth of grass and sorghum which resulted from improved P supply.

According to FURP (1994), results from trials on a Ferralsol at Eldoret and an Acrisol at Turbo in Uasin Gishu District, showed that N supply capacity appeared low while P availability appeared good. For sustained high yields, regular N fertilizer applications will be necessary whether from FYM or green manure or in mineral form (Palm et al., 1997; Kayombo and Mrema, 1998). When mineral N is applied regularly, it should be complemented with mulch and other organic amendments to maintain the humus (Ganry *et* *al*., 1978). When high rainfall occurs, soil aeration will probably be restricted and N losses from mineral fertilizer due to denitrification may be high (FURP, 1987; Bekunda *et al*., 1997).

Applied N is taken up by crops in variable amounts (Sanchez, 1976). For example, total N uptake by maize for yield levels of 4 to 5 t ha^{-1} is of the order of 100 to 150 kg ha^{-1}. At higher yield levels of 8 to 10 t ha^{-1}, total N uptake exceeds 200 kg ha^{-1}. Root crops like potato and cassava also remove large quantities of N. Generally, at low yield levels of 8 to 10 t ha^{-1} either potato or cassava removes about 40 kg N ha^{-1}. At higher yield levels attained with fertilization, these crops can remove over 150 kg N ha^{-1}. Removal of N by grain legumes like beans, soybeans and peanuts is 100 to150 kg ha^{-1} at yield levels of 0.5 to 1.0 t ha^{-1} (Sanchez, 1976). A large percentage of the N taken up by crops is exported from the farm in the produce. An accurate assessment of N taken up by crops from different sources is essential in minimizing environmental pollution and increasing nitrogen use efficiency (Addiscott et al., 1991; Miller and Wali, 1995; Omay *et al*., 1998).

2.4 Nitrogen use efficiencies of crops

Efficient use of N in cropping systems is often viewed from agronomic, economic and environmental perspectives. A given N management system may provide highly efficient use of N from one perspective but be relatively inefficient from another. However, application of N as fertilizer to the soil-crop system is of great essence for enhancing the productivity of crops (Bock, 1984).

The N fertilizer besides being important in crop production is an expensive commodity and application above optimum rates can cause harm to the environment. Any use of N fertilizer requires therefore specific management practices to optimize its efficiency. A central issue with fertilizer N should be to minimize losses during establishment of crops when demand for N is low and to maximize availability during vegetative and reproductive growth of crops when demand for N is high. Several factors related to the management of fertilizer N can influence its efficient use by a crop. They are *inter alia* type of fertilizer, rate of application, time of application and method of placement (Sanchez, 1976; Moll *et al*., 1982; Bock, 1984).

The N use efficiency (NUE) of a crop is a function of its genetic constitution and the environment which is made up of climate, soil and management. Hence, the NUE of a crop must be considered in the light of the many factors that interactively affect the uptake, recovery and utilization of the nutrient. Thus NUE usually has referred to relationships between yield and N rate (yield efficiency), N recovered and N rate (recovery efficiency) or yield and N recovered (physiological efficiency) (Bock, 1984). Yield efficiency is defined as the average yield increase per unit of applied N for a specified portion of a yield curve. This efficiency equals the product of recovery and physiological efficiencies.

The recovery of applied N is highly variable when results from several studies are considered. Allison (1966) is of the opinion that recovery of applied N under average field conditions is often not greater than 50% to 60% even if immobilization is taken into account. Kundler (1970) reported a range of 30% to 70% recovery of applied N by crops during the year of application with 10 to 40% of applied N incorporated into organic matter, 5 to 10% N lost by leaching and 10 to 30% N lost in gaseous form. A 50% N recovery for rice and wheat was estimated by Bartholomew (1972). These figures are applicable mainly to temperate regions since studies in the tropics are limited. However, Fox *et al*. (1974) obtained recoveries of 51% N with a post plant side-dressed application at optimum rate for maize in Puerto Rico. Only 33% N was recovered when the same rate was incorporated slightly into the soil (Sanchez, 1976).

Bartholomew (1972) argues that N recoveries of 70% to 80% by crops are physically feasible in most situations when the rate, placement and timing of the most appropriate nitrogenous fertilizer are optimized. From an agronomic perspective there is considerable opportunity for improving efficiency of N recovery by managing the fraction of plant available N in cropping systems in such a way that leaching from the root zone or immobilization by micro-organisms are restricted, Gaseous losses of applied N, especially NH_3 volatilization, can be managed relatively easily but not denitrification (Bartholomew, 1972; Owens and Johnson, 1996).

Jones (1973) reported a 70% N recovery from maize under conditions of no leaching, with the N applied before seeding or side-dressed. Nitrogen recovery by rice ranges from 30% to 50% under constant flooding and from 20% to 30% under water management practices conducive to leaching and denitrification (Sanchez, 1976). Nitrogen recovery by wheat may be as high as 50% with the best rate, timing and placement practices (Hamid, 1972).

Even the use of controlled-release N fertilizers like sulphur-coated urea can be considered to enhance NUE (Sanchez *et al*., 1973). Coated fertilizers generally out-performed non-coated fertilizers in reducing N leaching losses, stimulating plant growth and increasing tissue N concentrations. Low N concentrations in the leachate of some treatments indicated efficient nutrient use by the plant (Fox *et al*., 1974; Mikkelsen *et al*., 1994).

Under alternate oxidation-reduction conditions, nitrogen losses increase. For example nitrogen fertilizer recovery at harvest time fluctuated between 20% and 30% with conventional management practices in Peru. This very low efficiency can be increased substantially by selecting appropriate fertilizer sources and employing placement and timing practices most adequate for local situations (Sanchez and Calderon, 1971; Sanchez *et al*., 1973).

The primary objective with nitrogen fertilization should be the optimizing of farm income with the least impact on the environment (Bock, 1984). Keeney (1982) reviewed possible effects of N on environmental quality and concluded that NO_3^- and possible ozone depletion by release of N_2O into the stratosphere are the primary environmental concerns related to fertilizer N from soil-plant systems.

2.5 Conclusions

The importance of soil fertility and plant nutrition to the health and survival of all life cannot be understated. As human populations continue to increase a greater demand is placed on the ability of soils to supply essential nutrients for crop production. However, soil's native ability to supply sufficient nutrients has decreased with higher crop productivity levels associated with increased human demand for food. This is especially applicable for nitrogen.

Nitrogen is the most frequently deficient nutrient in crop production (Brady and Weil, 2008). Thus most non-legume cropping systems require N inputs. Many N sources are available for use in supplying N to crops. In addition to inorganic fertilizer N, organic N from animal manures and other waste products and from N_2 fixation by leguminous crops can supply sufficient N for optimum crop production. Understanding the behavior of N in the soil-plant system is essential for maximizing crop productivity and profitability while reducing the impacts of N fertilization on the environment. These include the biochemical processes of fixation, mineralization, nitrification, immobilization and denitrification as well as the non-biochemical processes of leaching and volatilization.

In most instances the nitrogen use efficiency of crops is low compared to that of other nutrients. This phenomenon is attributed to the dynamic nature of N in the soil-crop system. One of the greatest challenges is to develop and implement soil, crop and nitrogen management technologies that enhance plant productivity and the quality of soil, water and air.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area and sites

The study was done at four sites in Uasin Gishu District of Kenya. These study sites are: Timboroa (00° 04’ 47.53” N, 35° 31’ 07.88” E and 2604 m.a.s.l.) in the Upper Highland agro-ecological zone, Kaprobu (00° 44’ 00.00” N, 35° 18’ 57.00” E and 2100 m.a.s.l.) in the Lower Highland agro-ecological zone, Turbo (00° 37’ 23.88” N, 35° 02’ 41.07” E and 1794 m.a.s.l.) in the Upper Midland agro-ecological zone and Illula (00° 30’ 59.37” N, 35° 18’ 47.13” E and 2181 m.a.s.l.) in the Lower Highland agro-ecological zone. Each site represents an important agro-ecosystem as defined in Section 1.2. In the selection of the sites, climate, topography and soils were therefore the major factors considered. A concise description of each of these factors and some others are given for the agro-ecosystems with the Timboroa (Table 3.1), Kaprobu (Table 3.2), Turbo (Table 3.3) and Illula (Table 3.4) sites. In all four agro-ecosystems namely Timboroa (Figure 3.1), Kaprobu (Figure 3.2), Turbo (Figure 3.3) and Illula (Figure 3.4), maize, wheat and beans are commonly planted by farmers.

Table 3.1 Geology, topography, climate, vegetation and soil of the agro-ecosystem at the Timboroa site (Jaetzold and Schmidt, 1983; Schoeneberger et al., 2002)

Geology	Volcanic breccia and igneous pyroclastic rocks
Topography	On gentle crest of a ridge sloping gently towards west with a gradient of between 10-15%
Climate	Cold during wet season (April- September) and cool during dry season (November-March) with mean annual temperature of 13.3-15.7° C and mean annual rainfall of 1150-1400 mm.
Vegetation	Forest land with trees *(Dombeya goetzei, Olea africana, Polyscias fulra* and others) and kikuyu grass *(Pennisetim clandestium)*
Soil	Deep, dark red loam Nitisols with a high fertility status

Figure 3.1 Trial crops growing on a Nitisol in Upper Highland Zone at Timboroa site (2004)

Table 3.2 Geology, topography, climate, vegetation and soil of the agro-ecosystem at the Kaprobu site (Jaetzold and Schmidt, 1983; Schoeneberger *et al*., 2002)

Geology	Basaltic extrusive rocks
Topography	On flat plateau, sloping very gently towards south with a gradient of between 3-6%
Climate	Cool during wet season (April- September) and warm during dry season (November-March) with mean annual temperature of 15.1-17.9° C and mean annual rainfall of 900-1300 mm.
Vegetation	Savanna comprising grassland *(Hypharrenia rufa)* with scattered trees *(Acacia kirkii)*
Soil	Shallow, red loam Ferralsols with a low fertility status

Figure 3.2 Trial crops growing on a Ferralsol in Lower Highland Zone at Kaprobu site (2004)

Table 3.3 Geology, topography, climate, vegetation and soil of the agro-ecosystem at the Turbo site (Jaetzold and Schmidt, 1983; Schoeneberger et al., 2002)

Geology	Granite type of igneous rocks
Topography	On a gentle slope, towards west with gradient of between 10-15%
Climate	Generally warm in both wet and dry seasons with mean annual temperature of 18-20.5° C and mean annual rainfall of 900-1000 mm
Vegetation	Mixed grassland with trees and shrubs, comprising of grassland *(Graminea digitaria, Relatina* and *Hyparhemia hirta),* with trees (*Acacia kirkii, Croton macrostachyus* and *Erythrima abyssinicea)* and shrubs *(Teclea nobilis* and *Senecio sp.)*
Soil	Moderately deep to deep light brown sandy loam Acrisols, with low fertility status

Figure 3.3 Trial crops growing on an Acrisol in Upper Midland Zone at Turbo site

Table 3.4 Geology, topography, climate, vegetation and soil of the agro-ecosystem at the Illula site (Jaetzold and Schmidt, 1983; Schoeneberger *et al*., 2002)

Geology	Basaltic extrusive rocks
Topography	On a flat plateau, with gentle depression that holds draining water in wet season. The slope is slightly towards west with a gradient of between 0-3%
Climate	Cool during wet season (April- September) and warm during dry season (November-March) with mean annual temperature of 15.1-17.9° C and mean annual rainfall of 900-1300 mm.
Vegetation	Water grasses, water plants and some papyrus
Soil	Deep, dark grey loam Gleysols with a moderate fertility status

Figure 3.4 Trial crops growing on a Gleysol in Lower Highland Zone at Illula site

3.2 Experimental layouts and treatments

On account of either to dry or wet conditions from 2004 to 2008 experiments were done only in 2004, 2005 and 2007 at all four sites, hiring a piece of land from a farmer at a site for the entire study period. These hired pieces of land were fallowed, except for the adjacent sub-pieces used for the experiments. The experiments were conducted every year on a fresh fallowed sub-piece of land to avoid the carry-over effects of fertilization. Layout of experiments for the first two years was in a randomized complete block design replicated thrice. Treatments comprised sole-cropped maize, wheat, beans and intercropped maize/beans subject to the fertilization rates given in Table 3.5. An additional treatment of fallow under natural vegetation was included in 2004.

Table 3.5 Fertilization rates applied in 2004 and 2005

Crop	N rates (kg ha^{-1}) *	P rates (kg ha^{-1}) *
Sole-cropped maize	60	26.40
Sole-cropped beans	50	34.32
Sole-cropped wheat	40	17.60
Intercropped maize	60	26.40
Intercropped beans	50	34.32

*Calcium ammonium nitrate was used in N and triple superphosphate in P for maize and beans and the compound 20:20:0 for wheat.

Layout of the experiments in the year 2007 was completely randomized without any replication as the objective was to test the various rates of fertilizer on the yields of the common crops of Uasin Gishu District. Replication of treatments would have been too expensive for the budget of this study to accomplish financially. Cropping treatments were the same as in previous years but subject to a range of fertilization rates as given in Table 3.6.

Table 3.6 Fertilization rates applied in 2007

Crop	N rates (kg ha^{-1}) *	P rates (kg ha^{-1}) *
Sole-cropped maize	0, 30, 60 and120	0, 13.2, 26.40 and 52.80
Sole-cropped beans	0, 25, 50 and 100	0, 14.96, 34.32 and 88.64
Sole-cropped wheat	0, 20, 40 and 80	0, 8.80, 17.60 and 35.20
Intercropped maize	0, 30, 60 and 120	0, 13.20, 26.40 and 52.80
Intercropped beans	0, 25, 50 and 100	0, 14.96, 34.32 and 88.64

*Calcium ammonium nitrate was used in N and triple superphosphate in P for maize and beans and the compound 20:20:0 for wheat.

3.3 Characterizations of soils

Before the onset of the experiments in 2004, a soil profile pit was dug in each experimental site. The soil of each pit was described and classified according to Hodgson (1978). The details are given in Table 3.7.

Table 3.7 Soil profile Descriptions of the trial sites

Timboroa site: Humic Nitisol		
Horizon	Depth	Description
A	0-16cm	Dark brown red soil, crumby and friable with a lot of grass and plant roots
E	16-36cm	Red brown, less dark, friable with less roots than A horizon
B	36-76cm	Red clay soil, friable with little murram, less roots than E horizon
B/C	76- 06cm	Murram mixed with red soil, friable.
C	>106cm	Murram mixed with red soil, friable and a few weathered rocks.

Kaprobu site: Rhodic Ferralsol

Horizon	Depth	Description
A	0-15cm	Dark brown, crumby, friable, with numerous grass roots.
E	15-45cm	Brown, friable crumby with less grass roots than A horizon
B	45-68cm	Brown friable clay soil (slightly smooth and sticky) with fewer grass roots.
B/C	68-83cm	Mixture of brown clay soil and murram
C	>103cm	Murram with a few weathered basalt rocks

Turbo site: Orthic Acrisol

Horizon	Depth	Description
A	0-28cm	Dark grey, sandy loam, friable with a lot of grass roots
E	28-49cm	Dark grey brown sandy loam with roots but less than A horizon
B	49-72cm	Dark brown sandy clay loam, friable with a few weathered stones
B/C	72-116cm	Brown sandy clay mixed with loose weathered rocks
C	>136cm	Brown sandy clay soil with more weathered rocks

Illula site: Mollic Gleysol

Horizon	Depth	Description
A	0-10cm	Dark grey soil crumby with slight sticky clay with grass roots
E	10-20cm	Dark grey brownish with fewer grass roots, smooth and sticky clay
Bt	20-37cm	Black grey brownish clay with smooth and sticky clay
B	37-67cm	Black grey light brownish clay wet and sticky
B/C	67-92cm	Black whitish clay very wet and sticky
C	>112cm	Black whitish and grey yellowish, very wet and sticky clay

3.4 Soil sampling for laboratory analyses

Four topsoil (0-15 cm) and four subsoil (15-30 cm) samples were randomly collected prior to the study from the area at each site where the 2004, 2005 and 2007 experiments were done. These samples were properly mixed to make composites. The composites were dried in the open at room temperature and sieved through a 2 mm screen before being analyzed (Figure 3.5) with standard procedures (Section 3.7.1).

Figure 3.5 Samples being analyzed in soil laboratory, Chepkoilel campus of Moi University

For organic C and total N analyses the samples were further ground and passed through a 60 mesh screen. Analyses were almost similar for the topsoil and subsoil at a site and therefore only the means for 0-30 cm depth are displayed (Table 3.8). The fertility level of the soil at all four sites was low which justifies fertilization for cropping, especially, P, K, Ca and Mg.

3.5 Agronomic practices

The recommended agronomic practices for the district (Field Crops Technical Handbook, 2002) were generally followed. Every year before onset of rain in mid-March the sites were properly ploughed and harrowed. Then plots measuring 10 m ×10 m were demarcated for planting of the crops.

Upon onset of rain, maize and beans were planted in their allocated plots while the wheat plots were kept weed free until the month of May when they were planted. Certified seeds of the maize cultivar Hybrid 614D, wheat cultivar Kongoni and bean cultivar Rosecoco were used. Sole-cropped and intercropped maize were planted at a spacing of 75 cm between rows and 30 cm in rows. The spacing of sole-cropped beans was 50 cm between rows and 10 cm in rows and that of intercropped beans 75 cm between rows and 15 cm in rows. Wheat was sowed at seed rate of 100 kg ha^{-1} (Field Crops Technical Handbook, 2002).

Table 3.8 Some physical and chemical properties of the soils at the trial sites

Trial site	Timboroa	Kaprobu	Turbo	Illula
Soil type	Nitisol	Ferralsol	Acrisol	Gleysol
Bulk density (g cm^3)	1.4	1.5	1.6	1.5
Particle density (g cm^3)	1.9	1.8	2.7	2.0
Sand (%)	62	53	65	39
Silt (%)	24	16	10	29
Clay (%)	14	31	25	32
pH (H_2O)	4.8	5.3	5.3	5.7
EC_e (ds m^{-1})	0.2	0.2	0.2	0.4
Organic C (%)	4	2	2	2
Total N (%)	1.1	0.6	0.6	0.7
C:N	12	13	12	12
Total P (%)	0.3	0.3	0.2	0.1
Extractable P (mg kg^{-1})	3.1	1.6	0.7	1.2
Exchangeable K (mg kg^{-1})	61.7	56.7	19.6	30.8
Exchangeable Na (mg kg^{-1})	24.7	23.8	26.8	33.6
Exchangeable Ca (mg kg^{-1})	214.0	242.8	220.5	367.4
Exchangeable Mg (mg kg^{-1})	11.6	Trace	12.0	Trace
Exchangeable acidity (%)	2.8	0.4	0.4	0.4
CEC ($cmol_c$ kg^{-1})	24.3	19.8	18.3	19.5

Calcium ammonium nitrate (CAN) and triple superphosphate (TSP) were used with maize and beans while the compound 20:20:0 fertilizer was used with wheat (Table 3.5 and 3.6). In the latter case the compound was mixed with the seed. This mixture was broadcast and lightly incorporated into the soil. In the case of beans all the CAN and TSP was band placed with the seed. This was not the case with the maize since the band placement of CAN was split by half at planting with the maize seed and half at knee high close to the stems. All the TSP for the maize crop was band placed with the seed.

3.6 Data collection

Data collected under the study were rainfall, crop yields and soil analyses as described in the next three sub-sections.

3.6.1 Rainfall data

Rainfall gauges were installed at all four sites. These gauges were used to measure rainfall in 2004 and 2005. Rainfall was unfortunately not recorded in 2007 due to logistical reasons.

3.6.2 Crop data

Grain and residue yields were determined annually on every plot when the crops were ready for harvesting. An area of 100 m^2 was harvested to obtain grain yields. Residue yields were measured on an area of only 4 m^2. Grain and residue samples were also collected from every plot to establish their moisture content after drying. Then the samples were milled for the analysis of N and P. All 2004 and 2005 samples were analyzed. Analyses of 2007 samples were restricted to those from the 0 and 60 kg N ha^{-1} rates. The analysis procedure is described in Section 3.7.2.

3.6.3 Soil data

In 2004 soil samples were collected from every plot for the determination of mineral N, namely NH_4^+ and NO_3^-. The initial sampling was early April before any application of fertilizer (Day 0), followed by a second sampling late April (Day 15) and then in May (Day 30), June (Day 60), July (Day 90) and December (Day 270). An auger was used to collect samples from two randomly selected locations in a plot at depth intervals of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm. Samples for each depth interval were mixed to obtain composites before being placed into a cooler box to be taken to the laboratory where they were kept in a fridge until analyzed. A description of the analysis procedure follows below.

3.7 Analytical procedures

Standard analytical procedures were applied for soil and plant analyses. Thus the procedures are dealt with very concisely here.

3.7.1 Soil analyses

The core-ring method as described by Rowell (1994) was used for the determination of bulk density and particle density. Particle size distribution was established with the hydrometer method (Bouyoucos, 1962). A pH meter with glass electrode was used to measure pH in a 1:2.5 soil to water suspension and electrical conductivity was recorded in a saturated paste with a conductivity meter (Anderson and Ingram, 1993). The Nelson and Sommers (1975) method was used to measure organic C. Block digestion was applied to obtain total N and P in solution, whereafter the N and P were quantified with colorimetry (Anderson and Ingram, 1993). Colorimetric methods were used for the determination of NH_4 and NO_3 after extraction with potassium sulphate (Okalebo *et al*., 2002). The Olsen extractant was used to extract P for colorimetrical determination (Anderson and Ingram, 1993; Okalebo *et al*., 2002). Exchangeable cations were quantified by flame photometry (Na and K) and atomic absorption (Ca and Mg) after extraction with ammonium acetate (Anderson and Ingram, 1993). Potassium chloride was used as an extractant for exchangeable acidity and determination was done with titration (Anderson and Ingram, 1993; Okalebo *et al*., 2002).

3.7.2 Plant analyses

The grain and residues were digested in a block digester with sulphuric acid, hydrogen peroxide, lithium sulphate and selenium mixture to obtain N and P in solution. Both N and P were determined by colorimetry (Anderson and Ingram, 1993; Okalebo *et al*., 2002).

3.8 Statistical data analysis

The data were subjected to analysis of variance (ANOVA) using the Genstat computer package (Payne, 1996) and Statistical Analysis System (SAS, 2000). Least significant difference (LSD) at 5% level was used to compare between means.

CHAPTER FOUR

YIELD AND NITROGEN RESPONSE OF ANNUAL CROPS GROWN WITH BLANKET FERTILIZER RECOMMENDATIONS

4.1 Introduction

Ranges of cropping systems are practiced in the Uasin Gishu district. They include inter alia the sole-cropping of maize, wheat and beans. The latter is often also intercropped with maize, but not with wheat. However, variations in altitude, rainfall, temperature and soils have marked differences in the cropping patterns and their yields (Jaetzold and Schmidt, 1983). For example, wheat performs well at the cooler and higher altitudes of the Timboroa area, whereas maize is the preferred cereal at the lower and warmer altitude of the Turbo area where intercropping to a certain extent is practiced (Jaetzold and Schmidt, 1983; Ferguson et al., 2002; Field Crops Technical Handbook, 2002).

Over a period, research findings have provided information regarding crops and yield variations for specific areas in the district, along with agronomic and fertilizer practices (KARI Annual reports 1990s and early 2000s). However, farmers still rely on blanket recommendations of fertilizers for major cereals. For maize Allen et al. (1978) recommends 60 kg N ha^{-1} plus 26 kg P ha^{-1}, while FURP (1994) recommends 75 kg N ha^{-1} plus 26 kg P ha^{-1}. Likewise, the recommendations for wheat are 87 kg of diammonium phosphate for the 2nd, 3rd and 4th years respectively, while 130 kg 11:52:0 (NPK) ha^{-1} is recommended for new land planted for the first time with a crop (Field Crops Technical Handbook, 2002). For beans also farmers still prefer a blanket recommendation.

There is strong evidence that yield and nitrogen response of crops vary not only to the agro-ecological zones but also to the soils within each zone (FAO, 1995; Field Crops Technical Handbook, 2002). As mentioned earlier three agro-ecological zones are distinguished which comprise the Upper Highland (UH), Lower Highland (LH) and Upper Midland (UM) zones (Section 3.1). Each of the zones is further divided indicating dominant use: UH into UH1 (sheep-dairy), UH2 (pyrethrum-wheat) and UH3 (wheat-barley) sub-zones; LH into LH1 (tea-dairy), LH2 (wheat/maize-pyrethrum) and LH3 (wheat/maize-barley) sub-zones; and UM into UM3 (marginal coffee) and UM4 (sunflower-maize) sub-zones (Jaetzold and Schmidt, 1983; Gershumy and Smillie, 1986).

The soils dominating in the agro-ecological zones are Nitisols in the Upper Highland zone, Acrisols in the Upper Midland zone and Ferralsols with patches of Gleysols in the Lower Highland zone. Nitisols are deep, well-drained, red soils in the humid tropics. They are much sought after by farmers because of their high productivity despite a high phosphate-fixing capacity which renders phosphate unavailable to plants. Ferralsols represent the classical, deeply weathered, red or yellow soils of the humid tropics. Most of these soils have good physical properties but their chemical fertility is poor which has resulted in moderate productivity. Acrisols have higher clay content in the subsoil than in the topsoil as a result of especially clay migration. These soils are not rewarding to low-input farming since they are susceptible to erosion and have a low inherent fertility. Gleysols are wetland soils that in many instances are saturated with water for long periods. These soils are used for arable cropping only if they are adequately drained for long enough periods (Jaetzold and Schmidt, 1983).

This study was carried out to quantify the yield and nitrogen response of annual crops grown with blanket fertilizer recommendations on dominant soils within the agro-ecological zones of Uasin Gishu District in Kenya. The ultimate aim was to establish the suitability of the agro-ecological zones and their soils for common crops grown in the district.

4.2 Procedure

Details on the methodology of this study are presented in Chapter 3. However, for convenience a concise description follows. Sole-cropped maize (60 kg N ha^{-1} and 26.4 kg P ha^{-1}), wheat (40 kg N ha^{-1} and 17.6 kg P ha^{-1}) and beans (50 kg N ha^{-1} and 34.3 kg P ha^{-1}) as well as intercropped maize (60 kg N ha^{-1} and 26.4 kg P ha^{-1}) and beans (50 kg N ha^{-1} and 34.3 kg P ha^{-1}) were grown in 2004 and 2005 with blanket fertilizer recommendations at four distinct sites. The sites were Timboroa in sub-zone UH3 (wheat-barley) of the Upper Highland zone, Kaprobu in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone, Turbo in sub-zone UM4 (sunflower-maize) of the Upper Midland zone, and Illula in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone. Timboroa, Kaprobu, Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively. The crop parameters that were quantified for comparison of years and sites are grain, residue and biomass (grain plus residue) yields as well as harvest indices (grain/biomass). Furthermore the nitrogen content (grain and residue) and uptake (grain, residue and biomass) were also compared for years and sites.

4.3 Results

4.3.1 Sole-cropped maize

4.3.1.1 Yield

The grain, stover and biomass yields that realized at the four sites in the two years are summarized in Table 4.1

Table 4.1 Grain, stover and biomass yield in sole-cropped maize

Grain yield (t ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.4	4.2	2.6	3.1	3.1a	0.5
2005	2.0	2.1	1.9	1.8	2.0b	
Mean	2.2b	3.2a	2.3b	2.5ab		
LSD (α 0.05)	0.7					
Year x site	ns					
CV (%)	22.0					

Stover yield (t ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	4.2	6.2	5.2	5.3	5.2a	0.4
2005	4.2	5.4	4.1	4.7	4.6b	
Mean	4.2c	5.8a	4.7bc	5.0b		
LSD (α 0.05)	0.6					
Year x site	ns					
CV(%)	9.1					

Biomass yield (t ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	6.6	10.5	7.8	8.3	8.3a	0.7
2005	6.2	7.3	6.0	6.5	6.5b	
Mean	6.4b	8.9a	6.9b	7.4b		
LSD (α 0.05)	0.9					
Year x site	ns					
CV (%)	9.5					

Harvest index

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.3	0.4	0.3	0.4	0.4a	0.04
2005	0.3	0.3	0.3	0.3	0.3b	
Mean	0.3a	0.3a	0.3a	0.3a		
LSD (α 0.05)	ns					
Year x site	ns					
CV (%)	12.2					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

Grain yield varied from 1.8 t ha^{-1} at Illula in 2005 to 4.2 t ha^{-1} at Kaprobu in 2004. As could be expected the highest stover yield (6.2 t ha^{-1}) was measured also in 2004 at Kaprobu but the lowest stover yield (4.1 t ha^{-1}) realized in 2005 at Turbo. The biomass yield ranged therefore from 6.0 t ha^{-1} at Turbo in 2005 to 10.5 t ha^{-1} at Kaprobu in 2004.

None of these yields were affected significantly by the interaction between years and sites. However, mean yields across sites were significantly higher in 2004 than in 2005. The mean yields across years were significantly higher at Kaprobu than at the other three sites where yields were about similar.

Very low harvest index values were calculated. Only the mean harvest index values across sites differed significantly, viz. 0.3 in 2005 against 0.4 in 2004.

4.3.1.2 Nitrogen content

The N contents in the grain and in the stover are displayed in Table 4.2

Table 4.2 Grain and stover nitrogen content in sole-cropped maize

Grain N content (%)

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.1	2.9	2.9	2.7	2.7	ns
2005	2.1	2.6	2.9	2.8	2.6	
Mean	2.1b	2.8a	2.9a	2.8a		
LSD (α 0.05)	0.3					
Year x site	ns					
CV (%)	9.3					

Stover N content (%)

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.1	0.9	1.2	0.9	1.0	ns
2005	1.1	0.9	1.1	0.9	1.0	
Mean	1.1a	0.9b	1.1a	0.9b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	6.1					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

Grain N content ranged for both years from 2.1% at Timboroa to 2.9% at Turbo. The stover N content was lower as expected and varied between 0.9% (Kaprobu and Illula in both years) and 1.2% (Turbo in 2004).

Neither the main effect of years nor the interaction of years and sites affected the grain or stover N contents significantly. The mean grain content across years was significantly lower at Timboroa than at the other three sites. However, Timboroa and Turbo had significantly higher stover N contents than Kaprobu and Illula.

4.3.1.3 Nitrogen uptake

The uptake of N by grain, stover and biomass is given in Table 4.3

Table 4.3 Grain, stover and biomass nitrogen uptake in sole-cropped maize

Grain N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	50.4	121.8	74.2	84.3	82.7a	7.0
2005	42.4	54.6	54.3	50.8	50.5b	
Mean	46.4c	88.2a	64.3b	67.5b		
LSD (α 0.05)	10.0					
Year x site	14.1					
CV (%)	11.9					

Stover N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	46.5	55.8	61.4	47.3	52.7a	5.5
2005	47.0	49.2	43.9	43.0	45.8b	
Mean	46.8ab	52.5a	52.6a	45.1b		
LSD (α 0.05)	7.8					
Year x site	11.0					
CV (%)	12.7					

Biomass N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	96.9	177.8	135.6	131.6	135.4a	6.25
2005	89.4	103.8	98.2	93.8	96.3b	
Mean	93.2c	140.8a	116.9b	112.7b		
LSD (α 0.05)	8.9					
Year x site	12.05					
CV (%)	12.3					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

Grain N uptake varied from 42.4 kg ha^{-1} at Timboroa in 2005 to 121.8 kg ha^{-1} at Kaprobu in 2004. However, stover N uptake was lowest in 2005 at Illula (43 kg ha^{-1}) and highest in 2004 at Turbo (61.4 kg ha^{-1}). Thus biomass N uptake ranged between 89.4 kg ha^{-1} at Timboroa in 2005 to 177.8 kg ha^{-1} at Kaprobu in 2004.

Nitrogen uptake by grain, stover and biomass was affected significantly by the interaction of years and sites. At most sites, uptake of N was higher in 2004 than 2005.

Generally, highest N uptake realized at Kaprobu, followed by either Turbo or Illula and then Timboroa.

4.3.2 Sole-cropped wheat

4.3.2.1 Yield

The yields recorded at the four sites in two years with respect to grain, straw and biomass are presented in Table 4.4

Table 4.4 Grain, straw and biomass yield in sole-cropped wheat

Grain yield (t ha^{-1})						
Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.4	0.9	0.3	1.6	1.3a	0.1
2005	2.2	0.7	0.3	1.6	1.2b	
Mean	2.3a	0.8c	0.3d	1.6b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	8.4					
Straw yield (t ha^{-1})						
Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.3	0.5	0.1	0.9	0.7	ns
2005	1.0	0.9	0.4	0.8	0.8	
Mean	1.2a	0.7b	0.3c	0.9b		
LSD (α 0.05)	0.2					
Year x site	ns					
CV (%)	24.5					
Biomass yield (t ha^{-1})						
	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	3.7	1.4	0.4	2.5	2.0	ns
2005	3.3	1.5	1.1	2.5	2.1	
Mean	3.5a	1.5c	0.8c	2.5b		
LSD (α 0.05)	0.8					
Year x site	ns					
CV (%)	15.1					
Harvest index						
Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.3	0.4	0.3	0.4	0.3	ns
2005	0.3	0.6	0.3	0.3	0.4	
Mean	0.3b	0.5a	0.3b	0.3b		
LSD(α 0.05)	0.1					
Year x site	ns					
CV(%)	19.5					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

A large variation in grain yield realized, namely from 0.3 t ha^{-1} at Turbo in both years to 2.4 t ha^{-1} at Timboroa in 2004. The straw and biomass yields show similar trends as grain yield.

None of these yields were affected significantly by the interaction between years and sites. Only mean grain yield across sites differed significantly between 2004 and 2005 with a marginal 0.1 t ha^{-1}. The mean grain yield across years increased significantly in the order of Turbo, Kaprobu, Illula and Timboroa. A similar trend is observed also with straw and biomass yields.

Harvest index was affected only by sites. The value of 0.3 at Timboroa, Turbo and Illula was significantly lower than the value of 0.5 at Kaprobu.

4.3.2.2 Nitrogen content

A summary of the N content in the grain and in the straw is presented in Table 4.5

Table 4.5 Grain and straw nitrogen content in sole-cropped wheat

Grain N content (%)

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	3.9	3.5	3.6	3.8	3.7a	0.1
2005	3.6	3.4	3.5	3.5	3.5b	
Mean	3.7a	3.4c	3.6b	3.6b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	2.2					

Straw N content (%)

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.4	1.5	1.5	1.3	1.4	ns
2005	1.4	1.3	1.5	1.3	1.4	
Mean	1.4b	1.4b	1.5a	1.3c		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	5.5					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

Neither the grain N content nor the straw N content was affected significantly by the interaction of years and sites. However, the mean grain N content across sites differed significantly between 2004 and 2005 with values of 3.7% and 3.5% respectively. The mean grain N content across years was lowest at Kaprobu and highest at Timboroa. These values of 3.4% and 3.7% differed significantly from one another and also with the 3.6% of both Turbo and Illula. Moreover, the lowest and highest mean straw N content across sites realized at Illula and Turbo with values of 1.3% and 1.4% respectively.

4.3.2.3 Nitrogen uptake

The uptake of N by the grain, straw and biomass is displayed in Table 4.6

Table 4.6 Grain, straw and biomass nitrogen uptake in sole-cropped wheat

Grain N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	92.9	31.2	10.7	60.3	48.8a	2.5
2005	79.2	23.6	10.6	56.0	42.4b	
Mean	86.0a	27.4c	10.7d	58.2b		
LSD (α 0.05)	3.6					
Year x site	5.1					
CV (%)	6.4					

Straw N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	17.9	7.8	1.8	11.3	9.7b	0.6
2005	14.4	11.3	5.6	10.8	10.5a	
Mean	16.2a	9.6c	3.7d	11.1b		
LSD (α 0.05)	0 .8					
Year x site	1.2					
CV (%)	6.5					

Biomass N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	110.8	39.0	12.5	71.6	58.5a	1.5
2005	93.6	34.9	16.2	66.8	52.9ab	
Mean	102.2a	37.0c	14.4d	69.3b		
LSD (α 0.05)	2.2					
Year x site	ns					
CV (%)	6.5					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

In all three cases uptake was affected significantly by the interaction of years and sites. Large variations in N uptake were therefore recorded of which the trends are very similar. For example with respect to N uptake by the grain, straw and biomass lowest and highest values were in 2004 at Turbo and Timboroa, respectively. The differences amount to 82.2 kg ha^{-1} for grain, 16.1 kg ha^{-1} for straw, and 98.3 kg ha^{-1} for biomass.

4.3.3 Sole-cropped beans

4.3.3.1 Yield

The yields recorded at the four sites in two years with respect to grain, trash and biomass are presented in Table 4.7

Table 4.7 Grain, trash and biomass yields in sole-cropped beans

Grain yield (t ha^{-1})

Year	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.3	0.8	0.4	0.9	0.6a	0.1
2005	0.2	0.6	0.2	0.4	0.3b	
Mean	0.2b	0.7a	0.3b	0.7a		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	24.5					

Trash yield (t ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.5	1.5	0.5	1.3	1.0a	0.1
2005	0.4	1.0	0.3	0.9	0.6b	
Mean	0.5c	1.3a	0.4c	1.1b		
LSD (α 0.05)	0.2					
Year x site	ns					
CV (%)	15.3					

Biomass yield (t ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.8	2.3	0.9	2.2	1.6a	0.2
2005	0.6	1.7	0.5	1.3	1.0b	
Mean	0.7b	2.0a	0.7b	1.7a		
LSD (α 0.05)	0.3					
Year x site	ns					
CV (%)	16.0					

Harvest index

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.4	0.3	0.4	0.4	0.4a	0.03
2005	0.3	0.3	0.4	0.3	0.3b	
Mean	0.4b	0.3c	0.4a	0.4b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	10.6					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

A large variation in grain yield realized, namely from 0.2 t ha^{-1} at both Timboroa and Turbo in 2005 to 9 t ha^{-1} at Illula in 2004. In respect of the trash, the yield varied between 0.3 t ha^{-1} at Turbo in 2005 and 1.5 t ha^{-1} at Kaprobu in 2004. Like trash yield, the lowest (0.5 t ha^{-1}) and highest (2.3 t ha^{-1}) biomass yields were recorded at Turbo in 2005 and at Kaprobu in 2004.

None of these yields were affected significantly by the interaction between years and sites. However, mean yields across sites and years were significantly higher at Kaprobu than at the other three sites in 2004 than 2005.

Harvest index values were like that of sole-cropped maize namely very low, ranging between 0.3 and 0.4. Despite this small difference, the mean harvest index values differ significantly across sites and across years.

4.3.3.2 Nitrogen content

The N content of the grain and the trash is displayed in Table 4.8

Table 4.8 Grain and trash nitrogen content in sole-cropped beans

Grain N content (%)

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	5.8	5.9	6.1	5.6	5.9	ns
2005	6.3	6.3	5.9	5.4	6.0	
Mean	6.0a	6.1a	6.0a	5.5b		
LSD (α 0.05)	0.3					
Year x site	ns					
CV (%)	4.3					

Trash N content (%)

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.7	1.6	1.6	1.7	1.6	ns
2005	1.8	1.6	1.7	1.5	1.7	
Mean	1.8a	1.6b	1.7b	1.6b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	4.6					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

In both cases the lowest and highest N contents were measured in 2005. Grain N content ranged from 5.4% at Illula to 6.3% at both Kaprobu and Timboroa, and trash N content from 1.5% at Illula to 1.8% at Timboroa. Across years was the grain N content was significantly lower at Illula than at the other three sites, and the trash N content significantly higher at Timboroa than at the other three sites.

4.3.3.3 Nitrogen uptake

The N uptake by bean grain, trash and biomass is shown in Table 4.9

Table 4.9 Grain, trash and biomass nitrogen uptake in sole-cropped beans

Grain N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	17.9	46.3	22.7	50.7	34.4a	0.8
2005	12.6	34.4	11.8	21.8	20.1b	
Mean	15.2d	40.4a	17.3c	36.2b		
LSD (α 0.05)	1.1					
Year x site	ns					
CV (%)	3.3					

Trash N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	8.6	23.6	8.2	21.4	15.4a	0.3
2005	7.2	15.7	5.2	13.2	10.3b	
Mean	7.9c	19.6a	6.7d	17.3b		
LSD (α 0.05)	0 .4					
Year x site	ns					
CV (%)	2.4					

Biomass N uptake (kg N ha^{-1})

Years	Sites					
	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	26.5	69.9	30.9	72.1	49.9a	0.3
2005	19.8	50.1	17.0	35.0	30.5b	
Mean	23.2c	60.0a	24.0c	53.6b		
LSD (α 0.05)	0.8					
Year x site	ns					
CV (%)	2.8					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

For all three parameters the interaction between sites and years were significant. The lowest N uptake by grain (11.8 kg ha^{-1}), trash (5.2 kg ha^{-1}) and biomass (17.0 kg ha^{-1}) realized at Turbo in 2005. The highest N uptake was recorded in 2004. This amounted to 50.7 kg ha^{-1} by grain (Illula), 23.6 kg ha^{-1} by trash (Kaprobu) and 72.1 kg ha^{-1} by biomass (Illula).

4.3.4 Intercropped maize

4.3.4.1 Yield

The grain, stover and biomass yields at the four sites in the two years are shown in Table 4.10.

Table 4.10 Grain, stover, biomass and harvest index yields in intercropped maize

Grain yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.9	3.2	1.9	2.4	2.6a	0.3
2005	1.9	1.9	1.6	2.0	1.8b	
Mean	2.4a	2.5a	1.8b	2.2ab		

LSD (α 0.05) 0.4
Year x site ns
CV (%) 14.1

Stover yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	5.5	6.2	3.4	4.4	4.9a	0.7
2005	3.2	3.2	3.2	2.9	3.1b	
Mean	4.3ab	4.7a	3.3c	3.7bc		

LSD (α 0.05) 1.0
Year x site ns
CV (%) 19.7

Biomass yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	8.4	9.4	5.4	6.9	7.5a	0.9
2005	5.0	5.1	4.8	4.5	4.8b	
Means	6.7ab	7.2a	5.1c	5.7bc		

LSD (α 0.05) 1.3
Year x site ns
CV (%) 16.9

Harvest index

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.3	0.3	0.4	0.3	0.4	ns
2005	0.4	0.4	0.3	0.4	0.4	
Mean	0.4	0.4	0.4	0.4		

LSD (α 0.05) ns
Year x site ns
CV (%) 4.3

ns = not significant. Means followed by similar letters in a row are not significantly (α 0.05) different

Grain yield varied from 1.6 t ha^{-1} at Turbo in 2005 to 3.2 t ha^{-1} at Kaprobu in 2004. As could be expected the highest stover yield (6.2 t ha^{-1}) was recorded also in 2004 at

Kaprobu but the lowest stover yield (2.9 t ha^{-1}) manifested in 2005 at Illula. The biomass yield ranged from 4.5 t ha^{-1} at Illula in 2005 to 9.4 t ha^{-1} at Kaprobu in 2004.

These yields were not affected significantly by the interaction between years and sites. Mean yields across sites were significantly higher in 2004 than in 2005. Across years, the highest yields were measured at Kaprobu, followed by Timboroa, Illula and Turbo.

The differences in harvest index between years and among sites were not significant.

4.3.4.2 Nitrogen content

The nitrogen content in the grain and stover are given in Table 4.11

Table 4.11 Grain and stover N content in intercropped maize

Grain N content (%)

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.1	2.9	2.9	2.7	2.7	ns
2005	2.1	2.6	2.9	2.8	2.6	
Mean	2.1b	2.8a	2.9a	2.8a		
LSD (α 0.05)	0.2					
Year x site	ns					
CV (%)	4.8					

Stover N content (%)

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.1	0.9	1.2	1.0	1.0	ns
2005	1.1	0.9	1.1	0.9	1.0	
Mean	1.1a	0.9b	1.1a	1.0b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	4.1					

ns = not significant, Means followed by similar letters in a row are not significantly (α 0.05) different

Grain N content ranged from 2.1% at Timboroa (2004 and 2005) to 2.9% at Kaprobu (2004) and Turbo (2005). However, stover N content varied between 0.9% at Kaprobu (2004 and 2005) and Illula (2005) to 1.2% at Turbo (2004).

Neither the grain N content nor the stover N content was affected significantly by the interaction between years and sites. This can be attributed to the fact that years had no significant effect on either grain N content or stover N content across the sites. However, across years the grain N content was significantly lower at Timboroa than the other three sites. The stover N content across years was significantly higher at Timboroa and Turbo than at Kaprobu and Illula.

4.3.4.3 Nitrogen uptake

The N uptake of grain, stover and biomass of intercropped maize is displayed in Table 4.12

Table 4.12 Grain, stover and biomass nitrogen uptake in intercropped maize

Grain N uptake (kg N ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	60.3	92.8	56.0	64.5	68.4a	1.0
2005	39.6	48.6	46.3	55.6	47.5b	
Mean	50.0d	70.7a	51.2c	60.0b		
LSD (α 0.05)	1.4					
Year x site	2.0					
CV (%)	2.0					

Stover N uptake (kg N ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	60.7	55.8	40.1	43.1	49.9a	0.5
2005	35.3	29.1	34.2	26.7	31.3b	
Mean	48.0a	42.4b	37.2c	34.9d		
LSD (α 0.05)	0.7					
Year x site	1.0					
CV (%)	1.4					

Biomass N uptake (kg N ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	121.0	148.6	96.1	107.6	118.3a	0.8
2005	74.9	77.7	80.5	82.3	78.9b	
Mean	98.0b	113.2a	88.3c	95.0b		
LSD (α 0.05)	1.05					
Year x site	1.5					
CV (%)	1.7					

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

Uptake of N by the grain varied from 39.6 kg ha^{-1} at Timboroa in 2005 to 92.8 kg ha^{-1} at Kaprobu in 2004. Stover N uptake ranged from 26.7 kg ha^{-1} at Illula in 2005 to 60.7 kg ha^{-1} at Timboroa in 2004. The resultant biomass N uptake varied therefore from 74.9 kg ha^{-1} at Timboroa in 2005 to 148.6 kg ha^{-1} at Kaprobu in 2004.

The uptake of N by grain and stover were both affected significantly by the interaction between years and sites which was not the case with N uptake by biomass. For the latter N uptake across sites was higher in 2004 than in 2005. Kaprobu showed the highest biomass N uptake across years, followed by Timboroa, Illula and Turbo.

4.3.5 Intercropped beans

4.3.5.1 Yield

The grain, trash and biomass yields at the four sites in the two years are shown in Table 4.13.

Table 4.13 Grain, trash, biomass and harvest index yields in intercropped beans

Grain yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.1	0.1	0.1	0.1	0.1	ns
2005	0.1	0.2	0.1	0.2	0.1	
Mean	0.1b	0.2a	0.1b	0.2a		
LSD (α 0.05) 0.04						
Year x site ns						
CV (%) 22.2						

Trash yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD (α 0.05)
2004	0.1	0.2	0.1	0.2	0.2b	0.1
2005	0.1	0.5	0.1	0.3	0.3a	
Mean	0.1b	0.4a	0.1b	0.3a		
LSD (α 0.05) 0.1						
Year x site ns						
CV (%) 42.7						

Biomass yield (t ha^{-1})

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.2	0.4	0.2	0.4	0.3	Ns
2005	0.2	0.4	0.2	0.6	0.3	
Means	0.2b	0.4a	0.2b	0.5a		
LSD (α 0.05) 0.1						
Year x site ns						
CV (%) 22.0						

Harvest index

	Sites					
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	0.3	0.4	0.3	0.4	0.4a	0.003
2005	0.3	0.4	0.3	0.4	0.3b	
Mean	0.3b	0.4a	0.3c	0.4a		
LSD (α 0.05) 0.004						
Year x site ns						
CV (%) 1.8						

ns = Not significant. Means followed by similar letters in a row are not significantly (α 0.05) different

In 2004 the grain yield was very low, namely 0.1 t ha^{-1} at all sites. A slightly higher grain yield of 0.2 t ha^{-1} realized at Kaprobu and Illula in 2005. The trash yield ranged from 0.1 t ha^{-1} at Timboroa and Turbo in 2004 to 0.5 t ha^{-1} at Kaprobu in 2005. As a result of these grain and trash yields the biomass yields were the same per site regardless of the year, except at Illula where 0.4 and 0.6 t ha^{-1} realized in 2004 and 2005 respectively. Very low harvest index values were estimated. In both years the values varied between 0.3 and 0.4.

All sites registered the same index values in both years. Neither any of the yields nor the harvest index was affected significantly by the interaction between years and sites. The harvest index across sites was significantly higher in 2004 than in 2005.Generally, across years significantly lower grain, trash and biomass yields manifested at Timboroa and Turbo than Kaprobu and Illula.

4.3.5.2 Nitrogen content

The N content in the grain and trash are shown in Table 4.14.

Table 4.14 Grain and trash nitrogen content in intercropped beans

Grain N content (%)

			Sites			
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	5.8	5.9	6.1	5.6	5.9	ns
2005	6.3	6.3	5.9	5.4	6.0	
Mean	6.0a	6.1a	6.0a	5.5b		
LSD (α 0.05)	0.3					
Year x site	ns					
CV (%)	4.2					

Trash N content (%)

			Sites			
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	1.7	1.6	1.6	1.7	1.6	ns
2005	1.8	1.6	1.7	1.5	1.7	
Mean	1.8a	1.6b	1.7b	1.6b		
LSD (α 0.05)	0.1					
Year x site	ns					
CV (%)	4.7					

ns = not significant. Means followed by similar letters in a row are not significantly (α 0.05) different

For both parameters the lowest and highest values were recorded in 2005. Grain N content ranged from 5.4% at Illula to 6.3% at Timboroa and Kaprobu. The range of trash N content was from1.5% at Illula to 1.8% at Timboroa.

The grain N content across years was significantly lower at Illula than at Timboroa, Kaprobu and Turbo. However, significant lower trash N contents were recorded across years at Kaprobu, Turbo and Illula than at Timboroa.

4.3.5.3 Nitrogen uptake

The N uptake by grain, trash and biomass is shown in Table 4.15

Table 4.15 Grain, trash and biomass nitrogen uptake in intercropped beans

Grain N uptake (kg ha^{-1})

			Sites			
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	4.0	8.3	4.3	7.8	6.1a	0.5
2005	3.2	9.4	3.0	10.9	6.6a	
Mean	3.6b	8.9a	3.6b	9.3a		
LSD (α 0.05) 0.7						
Year x site 1.0						
CV (%) 8.6						

Trash N uptake (kg ha^{-1})

			Sites			
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	2.2	3.6	2.1	3.5	2.8b	0.2
2005	1.8	7.9	1.7	5.2	4.2a	
Mean	2.0c	5.7a	1.9d	4.4b		
LSD (α 0.05) 0.2						
Year x site 0.3						
CV (%) 5.1						

Biomass N uptake (kg ha^{-1})

			Sites			
Years	Timboroa	Kaprobu	Turbo	Illula	Mean	LSD(α 0.05)
2004	6.2	11.9	6.4	11.3	9.0b	0.3
2005	5.0	17.3	4.7	16.1	10.8a	
Mean	5.6b	14.6a	5.6b	13.7ab		
LSD (α 0.05) 0.5						
Year x site ns						
CV (%) 6.8						

ns = not significant. Means followed by the similar letters in a column or row are not significantly (α 0.05) different

In all instances the lowest and highest uptake manifested in 2005. The lowest N uptake in grain (3 kg ha^{-1}), trash (1.7 kg ha^{-1}) and biomass (4.7 kg ha^{-1}) were recorded at Turbo. However, the highest N uptake in grain (10.9 kg ha^{-1}) and trash (5.2 kg ha^{-1}) was measured at Illula and in biomass (17.3 kg ha^{-1}) at Timboroa.

The N uptake by grain and trash was affected significantly by the interaction between years and sites. This interaction had no significant effect on biomass N uptake. However, biomass N uptake across years differed significantly between sites.

4.4 Discussion

The yield and nitrogen response of sole-cropped maize, wheat and beans as well as intercropped maize and beans with blanket fertilizer recommendations were investigated in 2004 and 2005 at four distinct sites of Uasin Gishu District. They are Timboroa in sub-zone UH3 of the Upper Highland zone, Kaprobu in sub-zone LH3 of the Highland zone, Turbo in sub-zone UM4 of the Upper Midland zone, and Illula in sub-zone LH3 of the Lower Highland zone. Timboroa, Kaprobu, Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively. Crops typically cultivated are wheat-barley at Timboroa, wheat/maize-barley at Kaprobu, sunflower-maize at Turbo and wheat/maize at Illula.

4.4.1 Yield

The grain yield of sole-cropped maize, wheat and beans averaged for the four sites over the two years at 2.55 t ha^{-1} (Table 4.1), 1.25 t ha^{-1} (Table 4.4) and 0.48 t ha^{-1}(Table 4.7), respectively. In comparison with grain yields of sole-cropped maize and beans, the respective intercropped maize and beans realized lower average grain yields of 2.20 t ha^{-1} (Table 4.10) and 0.10 t ha^{-1} (Table 4.13). Thus with the exception of sole-cropped beans, the other four crops' grain yields were lower than the reported mean grain yield of 2.9 t ha^{-1} for maize, 1.55 t ha^{-1} for wheat and 0.45 t ha^{-1} for beans from 1995 to 2004 in the Uasin Gishu District (Table 1.2). The grain yield potential for the district is estimated however far higher at 7.0 t ha^{-1} for maize and 2.9 t ha^{-1} for wheat (Field Crops Technical Handbook, 2002). Estimation of grain yield potential for beans is 1.5 -2.0 t ha^{-1} (Landon, 1991).

Analyses of variance on the grain yields of the studied crops showed significant differences across sites and between seasons, but the interaction effects of sites and seasons were not significantly different. Compared to 2005, higher grain yields realized across sites in 2004 with sole-cropped maize (3.1 vs. 2.0 t ha^{-1}), wheat (1.3 vs. 1.2 t ha^{-1}) and beans (0.6 vs 0.3 t ha^{-1}) as well as intercropped maize (2.6 vs. 1.8 t ha^{-1}) probably on account of more rain that was better distributed. The only exception was with intercropped beans which gave the same yields in the two seasons, namely only 0.1 t ha^{-1} (Table 4.1, 4.4, 4.7, 4.10 and 4.13).

The differences observed between sites with the grain yields of maize, wheat and beans manifested as could be expected to a large extent also in their respective stover, straw and trash yields and hence the biomass yields of the crops. However, noteworthy is the low harvest indices calculated for all studied crops, indicating that they experienced some or other stress during the physiological ripening phase (Table 4.1, 4.4, 4.7, 4.10 and 4.13).

An explanation for the inconsistency in grain yields among sites is not obvious. In some instances grain yield differences between sites may be attributed to climate difference and in other instances to soil differences. For example the mean annual rainfall for the two seasons was 723 mm at Timboroa with a Humic Nitisol, 677 mm at Illula with a Mollic Gleysol, 535 mm at Kaprobu with a Rhodic Ferralsol, and 529 mm at Turbo with a Orthic Acrisol (Appendix 1). The overall difference in rainfall between 2004 and 2005 was 83 mm in favour of 2004.

Nonetheless, it is apparent that Kaprobu is suitable for maize production, but average in wheat and bean production. On the other hand, Timboroa is suitable for wheat production, but poor in maize and bean production. Illula and Turbo can be regarded as respectively average and poor for maize, wheat and bean production. A golden thread is therefore lacking, indicating that blanket fertilizer recommendations should be avoided.

4.4.2 Nitrogen content

For the two seasons, mean grain N content of sole and intercropped maize was 2.1% at Timboroa and ranged from 2.8 to 2.9% at Kaprobu, Turbo and Illula. Sole-cropped wheat realized over the two seasons the highest mean grain N content at Timboroa (3.7%) followed by either Turbo or Illula (3.6%) and then Kaprobu (3.4%) over the two seasons. The mean grain N content of sole and intercropped beans ranged from 6.0 to 6.1% at Timboroa, Kaprobu and Turbo with a lower value of 5.5% at Illula. Observations between sites for the N content of maize stover, wheat straw and bean trash showed almost similar trends as the crops' grain N content, although the values are lower. Across sites, neither the mean grain N content of maize, wheat and beans nor their respective mean stover, straw and trash N content differed between seasons (Table 4.2, 4.5, 4.8, 4.11 and 4.14).

These nitrogen contents of the crops' grain and residue exceeded in most instances the reference values reported in literature (e.g. Bergman, 1992; Voss, 1993; FSSA, 2008) on which estimations of nitrogen removal by grain and residue are based. The latter values for maize, wheat and soybeans are with regard to grain 1.5, 2.2 and 4.2% and residue

1.2, 0.5 and 0.8%, respectively. This phenomenon could be attributed to luxurious uptake of this essential plant nutrient by the crops. No obvious reason(s) can be given now.

4.4.3 Nitrogen uptake

The crops' mean biomass N uptake for the two seasons will be dealt with as it mirrors to a large extent the N uptake by the grain of maize, wheat and beans and their respective stover straw and trash over this period (Table 4.3, 4.6, 4.9, 4.12 and 4.15). The average biomass N uptake of sole-cropped maize ranged from 93.2 kg ha^{-1} at Timboroa to 140.8 kg ha^{-1} at Kaprobu. For intercropped maize the biomass N uptake was slightly lower and varied between 88.3 kg ha^{-1} at Turbo to 113.2 kg ha^{-1} at Kaprobu. Thus, at all four sites the biomass N uptake by sole and intercropped maize exceeded the blanket N application of 60 kg ha^{-1} (Table 3.5).

Compared to either sole or intercropped maize, sole-cropped wheat realized a larger range of biomass N uptake: 14.5 kg ha^{-1} at Turbo, 37.0 kg ha^{-1} at Kaprobu, 69.3 kg ha^{-1} at Illula and 102.2 kg ha^{-1} at Timboroa. The blanket N application of 40 kg ha^{-1} was exceeded therefore at Timboroa and Illula but not at Kaprobu and Turbo. Biomass N uptake of intercropped beans (5.6 kg ha^{-1} at both Timboroa and Turbo to 14.6 kg ha^{-1} at Kaprobu) was distinctly lower than the biomass N uptake of sole-cropped beans (23.2 kg ha^{-1} at Timboroa to 60 kg ha^{-1} at Kaprobu).

Only the biomass N uptake of sole-cropped beans at Illula and Kaprobu exceeded the blanket N application of 50 kg ha^{-1}. Biomass N uptake exceeded the blanket N application in many instances implying that especially maize and to lesser extent wheat and beans benefit on the supply of N from soil through mineralization of organic reserves. This may ultimately lead to an exhaustion of the organic reserves, viz a viz organic matter which play an important role in soil quality (Kundler, 1970). Organic matter is often regarded as the key determinant of soil quality due to its vital influence on soil physical, chemical and biological conditions (Weil and Magdoff, 2004).

In this study the N uptake by biomass per ton of grain produced, averaged 45.4, 44.6 and 89.3 kg for sole-cropped maize, wheat and beans, respectively. The corresponding values were for intercropped maize 44.8 kg and beans 66.0 kg. Total uptake of N by sole and intercropped maize was therefore similar but not for sole and intercropped beans. These estimated values exceeded the reported values in literature (e.g. Bergmann, 1992; Voss, 1993 and FSSA, 2008) which are 27, 30 and 45 kg N t grain^{-1} for maize, wheat and beans, respectively. This phenomenon is further evidence of stress during the physiological ripening phase of the crops.

The data on biomass N uptake is a clear confirmation that blanket N fertilizer recommendation for crops in the Uasin Gishu District will not be sustainable in the long-term. An effort should be made to establish guidelines for site-specific N recommendations taking into account differences in climate, soil and crops.

The evidence with the yield and nitrogen response data of potential physiological stress of the crops justifies a thorough investigation. Establishment of the cause is of great importance for the implementation of suitable management practices to reduce or even avoid such stress. The stress may be not due to N only but also to other nutrients like P, K, Ca and Mg (Table 3.8). As pointed out earlier the contents of these nutrients are low in the soils of all four sites. It is well known that there is an interaction between nutrients which may have either antagonistic or synergistic effects on crop growth and development (Havlin et al., 2014). An improvement of crop productivity will be only possible with a holistic view towards nutrient management.

4.5 Conclusions

Based on yield results of this study it can be concluded that Kaprobu with a Rhodic Ferralsol is suitable for maize production, but average in wheat and bean production. On the other hand is Timboroa with a Humic Nitisol suitable for wheat production, but poor in maize and bean production. Illula with a Mollic Gleysol and Turbo with a Orthic Acrisol can be regarded as respectively average and poor for maize, wheat and bean production. Moreover, at all four sites the sole-cropped maize and beans performed better than the intercropped maize and beans. The grain N content of maize, wheat and beans and their respective stover, straw and trash N content differed little if at all between the four sites. This is probably due to the N content of the crops and inherent properties and therefore not influenced by environmental factors like climate and soil. Generally, the contents implying luxurious uptake of this nutrient for reason(s) unknown. Uptake of N by the crops differed distinctly between sites on account of the yields realized. The biomass N uptake exceeded the blanket N application in many instances, indicating that establishment of site-specific guidelines are essential for sustainable cropping in Uasin Gishu District.

CHAPTER FIVE

SPATIAL AND TEMPORAL DISTRIBUTION OF MINERAL NITROGEN IN SOILS UNDER CROPPING SYSTEMS WITH BLANKET FERTILIZER RECOMMEDATIONS

5.1 Introduction

Irrespective of the cropping system in sub-Saharan Africa, nitrogen is often the first limiting nutrient, across many agro-ecosystems comprising a divergent range of soils (Woomer and Muchena, 1996; Uyovbisere *et al*., 1997; Yusuf *et al*., 2003; Bekunda *et al.,* 2007). A wide range of N fertilizers and rates, including manures, has been used in sub-Saharan Africa to improve the availability of this macronutrient for uptake and improved yields (FURP, 1994; Giller *et al*., 1997; Okalebo *et al.,* 2007).

Requirements for N differ with crops and their genotypes, soils and environmental factors. There are also well-known losses of N (e.g. through volatilization, surface runoff and leaching) which contribute to reduced N availability (Ramos, 1996; Smaling *et al.*, 1997; Tilman, 1999; Nielsen, 2006). Although N is available from early stages in cropping seasons, through the N flush mechanism or the “Birch effect” of organic N sources, the fate of N during cropping seasons is not well understood across cropping systems, soils, fertilizer rates and methods of application (Birch, 1960).

Mineral nitrogen in most tropical soils shows a marked seasonal fluctuation. Nyamangara (2007) mentioned the distribution patterns consist of: (i) A slow nitrate buildup in the topsoil during the dry season; (ii) A large but short-lived increase at the onset of the rainy season; and (iii) A rapid decrease during the rest of the rainy season due to crop uptake and N leaching.

When short-term drought occurs during the rainy season, mineral N showed a sharp build-up and then gradual decreases. These short-term peaks, called “flushes”, were first described by Hardy in 1946. Subsequent work in Africa by Birch and others has substantiated their existence in a wide range of soils’ conditions (Birch, 1958; 1960; Sanchez, 1976; Stephens, 1962; Wong and Nortcliff 1995).

The accumulation of nitrate in the topsoil during the dry season may be explained by the existence of the process of nitrification at soil moisture tensions of 15 to 80 bars (Semb and Robinson, 1969). This condition is similar to what is found in Uasin Gishu District of Kenya. Although the topsoil may be drier than the tensions indicated, the subsoil may have enough moisture to support mineralization.

Since most of the water movement during the dry season is upward by capillary flow, nitrates previously present or recently mineralized in the subsoil may move up and accumulate in topsoil of tropical regions. Wetselaar (1961; 1962) found evidence of dramatic nitrate build-ups in the top 5 cm. He explained that nitrate is mineralized in the subsoil, where adequate moisture existed in the dry season and accumulated just below the soil surface crust, where capillary conductivity is broken (Sanchez, 1976).

Wild (1972) monitored the nitrate content of a soil profile in northern Nigeria for two years. His results indicated an upward movement of nitrate during the dry season. Levels of nitrates are always high after a long dry spell and are the source of a sudden green flush in tropical plants at onset of the rains (Landon, 1991). This nitrate may have been leached into subsoil during the previous rainy season (Pratt, 1984; Durieux *et al.,* 1995; Wong and Nortcliff 1995).

Within a few days after the heavy rains, dramatic increases in mineral nitrogen take place. In the field N may range from 23 to 121 kg N ha^{-1} within 10 days (Semb and Robinson, 1969). The sharpness of the peaks is directly proportional to the duration and intensity of the preceding dry period. These sharp increases are accompanied by similarly sharp decreases caused by rapid leaching in the rainy season.

As the rainy season progresses, the mineral nitrogen supply is reduced by plant uptake, leaching and denitrification. Nitrogen uptake by crops depends on rapid establishment of a crop with numerous root systems. Leaching of N is rapid in sandy soils, while it is not the case in clayey soils (Kinjo and Pratt, 1971).

Mineral nitrogen in the form of ammonium is rapidly converted to nitrate in the soil system by microorganisms, especially in well aerated soil above 5°C and acidification is usually the net result. However, as the organic N is mineralized into ammonium and not quickly nitrified into nitrate, some losses occur in the form of ammonia volatilization that escapes into the atmosphere, especially from alkaline and/or calcareous soils (Fenn and Miyamoto, 1981; Hageman, 1984).

Leaching, denitrification, immobilization and ammonia volatilization are the processes known to be of practical significance in lowering availability of N to plants. Leaching and denitrification usually are considered of greatest importance (Legg and Meisinger, 1982; Jokela and Randall, 1997).

As described above N fluctuates in soils as the season progresses due to N build-up from capillary movement during the dry season, large increases at the onset of rain and decreases during the rest of the rainy season as the crops utilize the N in the soil; also N leaches to the lower horizons of the profile and denitrifies to the atmosphere (Bartholomew, 1972; Van Raij and Camargo, 1974; Sanchez, 1976). However, studies on mineral N dynamics are rather scanty in the sub-Saharan region mainly due to limited laboratory facilities, restrictions in methodologies and personnel to do the analyses. This reflects a significant gap in our knowledge on the dynamics of N in cropping systems of the tropics (Okalebo, 2010).

The objective of this study was therefore to monitor the fate of N applied as mineral fertilizer, and possibly the organic N and N flush from the Birch effect in four agro-ecosystems of the Uasin Gishu District comprising of different soils and cropping systems. In essence this study was done to better understand the spatial and temporal distribution of N in the soil profiles during cropping. Information on the distribution of the major mineral forms of N (NH_4^+ and NO_3^-) which are available for plant uptake during cropping within soil profiles is needed towards enhanced knowledge on N uptake utilization and losses during a cropping season and also to obtain more information on N application regimes. This knowledge should be particularly useful to the farmers and other stakeholders in Uasin Gishu District, who are currently looking for suitable fertilizer N sources, rates and times of application.

5.2 Procedure

Details on the methodology of this study are presented in Chapter 3. For convenience, however, a concise description follows. Sole-cropped maize (60 kg N ha^{-1} and 26.4 kg P ha^{-1}), wheat (40 kg N ha^{-1} and 17.6 kg P ha^{-1}) and beans (50 kg N ha^{-1} and 34.3 kg P ha^{-1}) as well as intercropped maize (60 kg P ha^{-1} and 26.4 kg P ha^{-1}) and beans (50 kg P ha^{-1} 34.3 kg P ha^{-1}) were planted in 2004 and 2005 with blanket fertilizer recommendations at four distinct sites.

The sites were Timboroa in sub-zone UH3 (wheat-barley) of the Upper Highland zone, Kaprobu in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone, Turbo in sub-zone UM4 (sunflower-maize) of the Upper Midland zone, and Illula in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone. Timboroa, Kaprobu. Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively.

Soil sampling for the determination of mineral N, namely NH_4^+ and NO_3^- separately was done only in 2004 (Appendix 2). The initial sampling was early April before any application of fertilizer (Day 0), followed by a second sampling late April (Day 15) and then in May (Day 30), June (Day 60), July (Day 90) and December (Day 270). An auger was used to collect samples from each plot at depth intervals of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm. Standard colorimetric methods were applied for the determination of either NH_4^+ or NO_3^-, following extraction with potassium sulphate.

5.3 Results

5.3.1 Timboroa site

The change in mean mineral N content across cropping systems and depth intervals in the Humic Nitisol of Timboroa site from April to December 2004 is displayed in Figure 5.1. Ammonium showed a gradual build-up from day 0 to day 30, followed by a gradual decline to day 90. After day 90 there was a slight build-up of ammonium to day 270. Nitrate on the other hand showed a sharp build-up from day 0 to day 60. From day 60 to day 270 nitrate declined sharply.

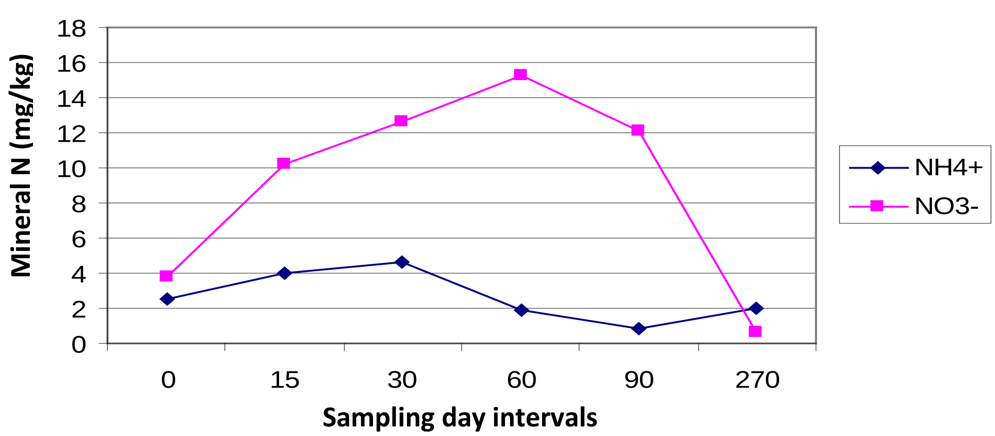

Figure 5.1 Change in mean mineral N content across cropping systems and depth intervals in the Humic Nitisol of Timboroa site from April to December 2004

These observed trends in mean ammonium and nitrate contents across cropping systems and depth intervals (Figure 5.1) also manifested to a large extent in each of the five depth intervals that were sampled at six intervals. The content of ammonium remained relatively constant over depth in the Humic Nitisol per sampling interval, except for the day 15 and day 30 intervals (Figure 5.2). For these two sampling intervals ammonium content decreased notably from the first to third depth interval and then stayed almost constant.

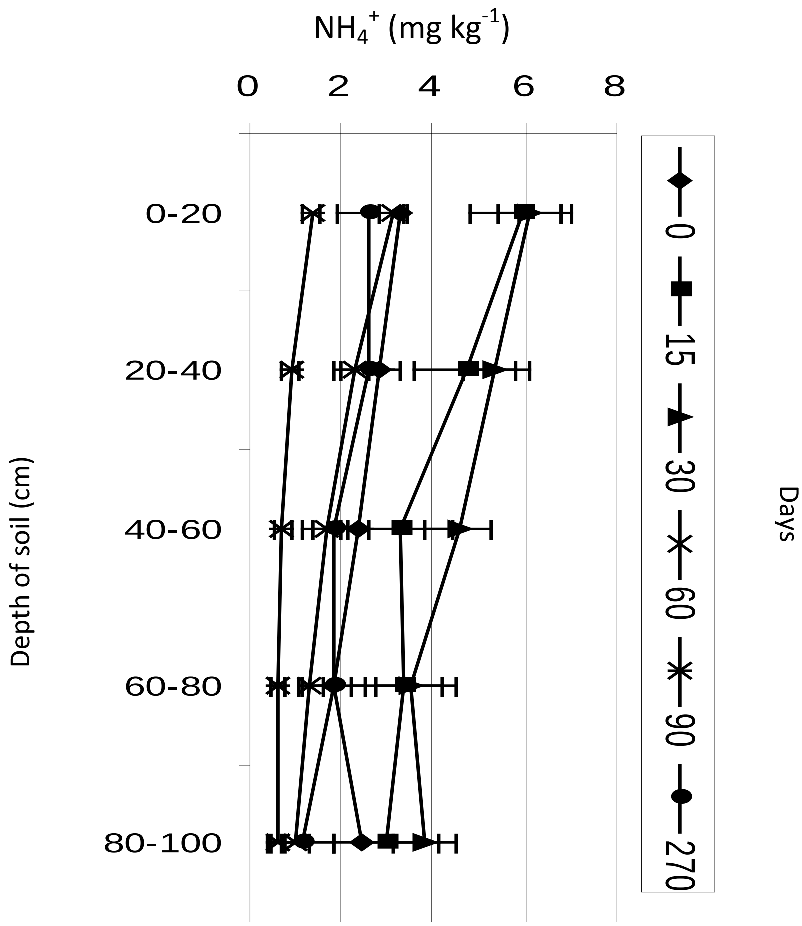

Figure 5.2 **Change of mean ammonium content across cropping systems in the Humic Nitisol of Timboroa site for different depth and sampling intervals.**

In all five depth intervals higher nitrate contents were measured at day 0 than at day 270, however, the values remained almost constant over the depth intervals for each of these two sampling intervals (Figure 5.3). This was not true for the other four sampling intervals, namely day 15, day 30, day 60 and day 90. For these sampling intervals nitrate content declined from the first to third depth interval and then increased from the third to fifth depth interval.

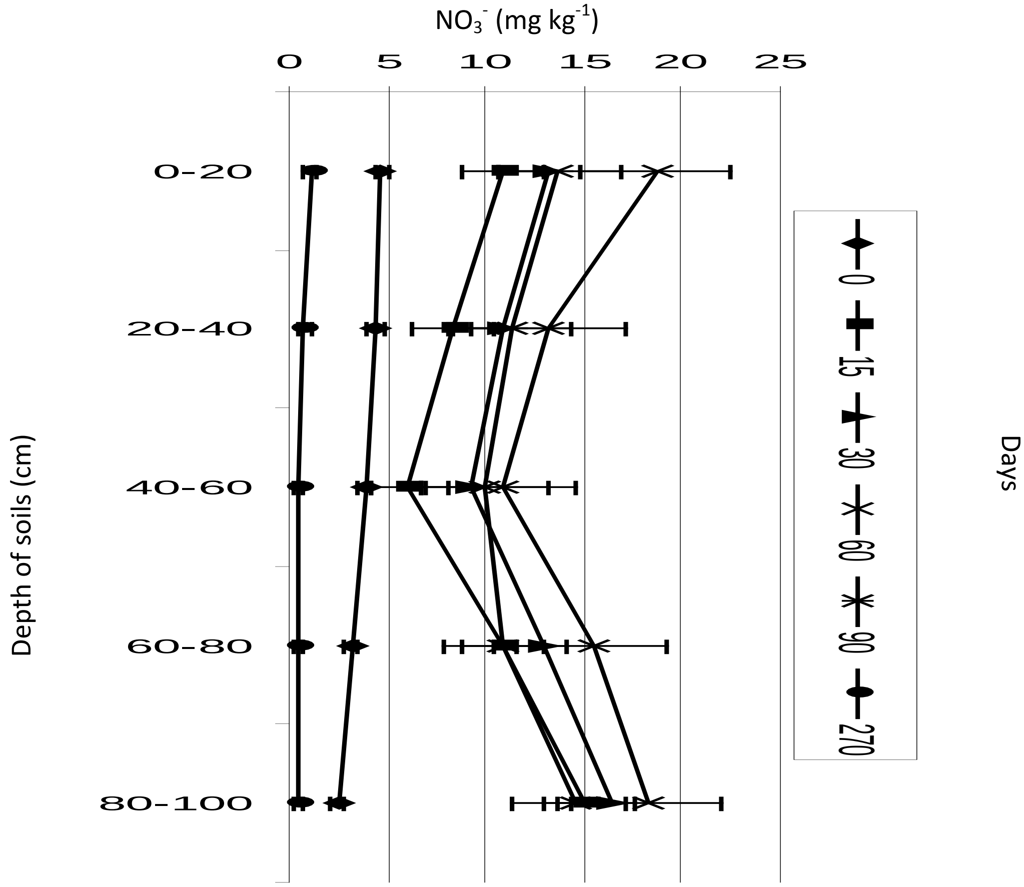

Figure 5.3 Change of mean nitrate content across cropping systems in the Humic Nitisol of Timboroa site for different depth and sampling intervals.

The interaction effects of cropping system and sampling interval on mean contents of ammonium to 100 cm depth in the Humic Nitisol of Timboroa site in 2004 is presented in Table 5.1. Neither the cropping system nor its interaction with sampling interval affected the ammonium contents significantly. However, significant differences were recorded between sampling intervals with the lowest value (0.83 mg kg^{-1}) at day 90 and the highest value (4.66 mg kg^{-1}) at day 30.

Table 5.1 Interaction effects of cropping system and sampling interval on mean ammonium content (mg kg^{-1}) to 100 cm depth in the Humic Nitisol of Timboroa site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	2.51	5.47	4.85	1.99	0.64	2.17	2.94	ns
Bean	2.48	2.28	4.08	1.93	0.56	2.30	2.27	
M/B[1]	2.43	3.76	4.62	1.74	0.91	1.88	2.56	
Wheat	2.66	3.29	5.02	1.96	0.98	1.69	2.60	
Fallow	2.67	5.38	4.74	1.73	1.06	1.98	2.93	
Mean	2.55b	4.04a	4.66a	1.87b	0.83c	2.00b		
LSD(α 0.05)	0.77							
Crop x interval	ns							
CV (%)	21.83							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

Table 5.2 Interaction effects of cropping system and sampling interval on mean nitrate content (mg kg^{-1}) to 100 cm depth in the Humic Nitisol of Timboroa site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	3.79	9.73	12.9	17.37	8.70	0.28	8.80b	2.25
Bean	3.72	9.53	11.83	12.50	10.51	0.33	8.07c	
M/B[1]	3.55	8.17	10.02	10.96	7.53	0.55	6.80c	
Wheat	4.02	12.22	14.84	17.53	16.45	1.21	11.05a	
Fallow	3.67	11.53	13.31	17.93	17.25	0.85	10.74ab	
Mean	3.75c	10.24b	12.58b	15.26a	12.09b	0.64d		
LSD(α 0.05)	2.46							
Crop x interval	ns							
CV (%)	20.52							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

However, mean nitrate contents to 100 cm depth in this soil were significantly influenced by both cropping system or sampling interval but not their interaction (Table 5.2). Irrespective of sampling interval, realized the lowest nitrate content (6.8 mg kg^{-1}) with intercropped maize and beans, and the highest nitrate content (11.1 mg kg^{-1}) with sole-cropped wheat. The lowest (0.6 mg kg^{-1}) and highest (15.3 mg kg^{-1}) nitrate contents regardless of cropping system were recorded at day 270 and day 60, respectively.

5.3.2 Kaprobu site

Figure 5.4 displays the change in mean mineral N content across cropping systems and depth intervals in the Rhodic Ferralsol of Kaprobu site from April to December 2004. The periodic analysis of ammonium in this soil showed a build-up from day 0 to day 15, followed by a sharp decline to day 30 where after it remained almost constant today 60. However, from day 60 to day 90 a gradual increase and from day 90 to day 270 a gradual decrease in ammonium content were recorded. Like for ammonium, nitrate build-up occurred from day 0 to day 30 but then stayed almost constant until day 90. From day 90 to 270 the nitrate content decreased to a level lower than at day 0.

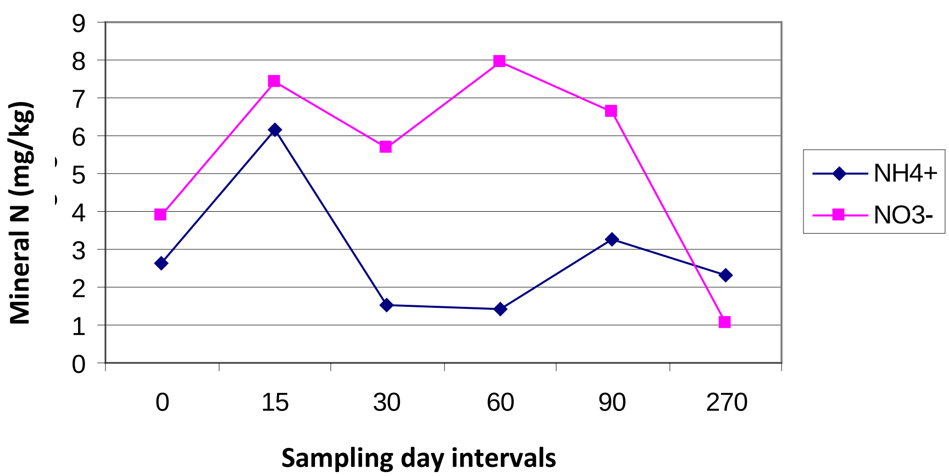

Figure 5.4 Change in mean mineral N content across cropping systems and depth intervals in the Rhodic Ferralsol of Kaprobu site from April to December 2004.

The content of ammonium at five of the sampling intervals, viz. day 0, day 30, day 60, day 90 and day 270 stayed relatively constant for the five depth intervals that were sampled (Figure 5.5). However, day 15 was the exception since the ammonium content declined notably from the first to fourth depth interval. A very similar trend was observed with day 15 and day 30 sampling intervals in the Humic Nitisol of Timboroa site (Figure 5.2).

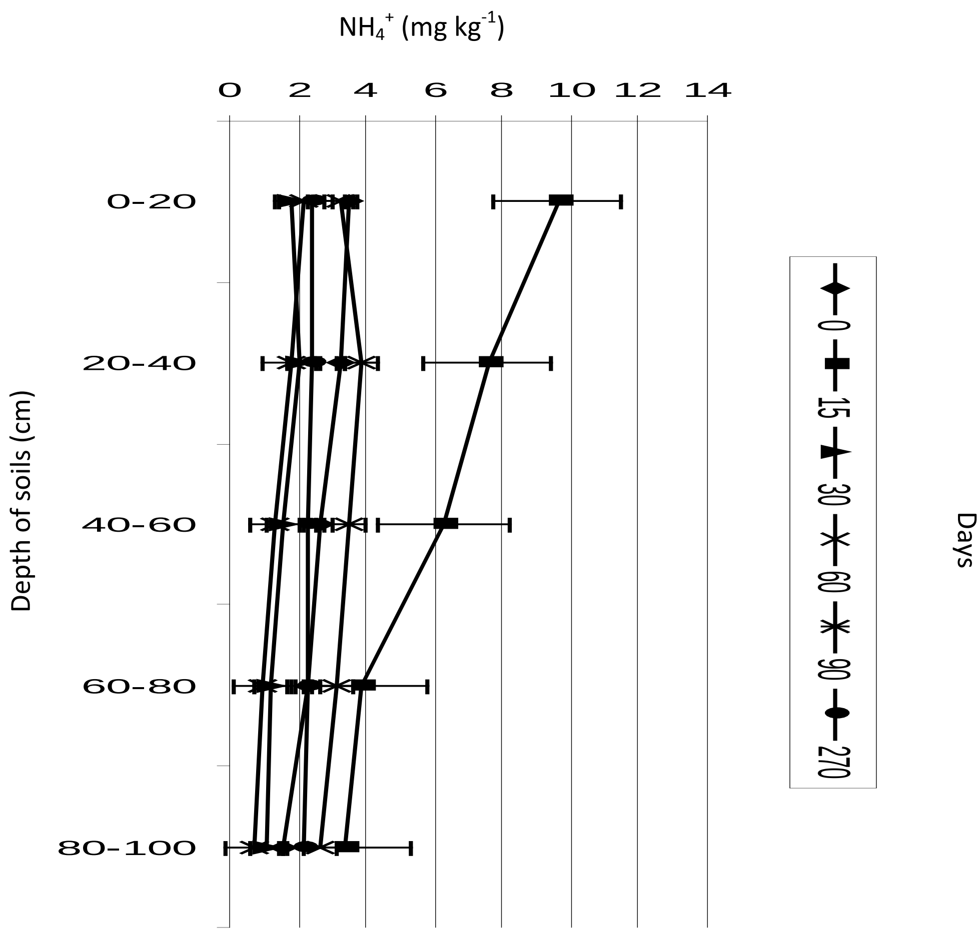

Figure 5.5 Change of mean ammonium content across cropping systems in the Rhodic Ferralsol of Kaprobu site for different depth and sampling intervals.

In the case of nitrate it was also the day 15 sampling interval that differed from the other five sampling intervals as depicted in Figure 5.6. For this sampling interval nitrate showed a very similar trend as ammonium (Figure 5.5) in this Rhodic Ferralsol, and as the nitrate in the Humic Nitisol at day 15, day 30, day 60 and day 90 sampling intervals (Figure 5.3).

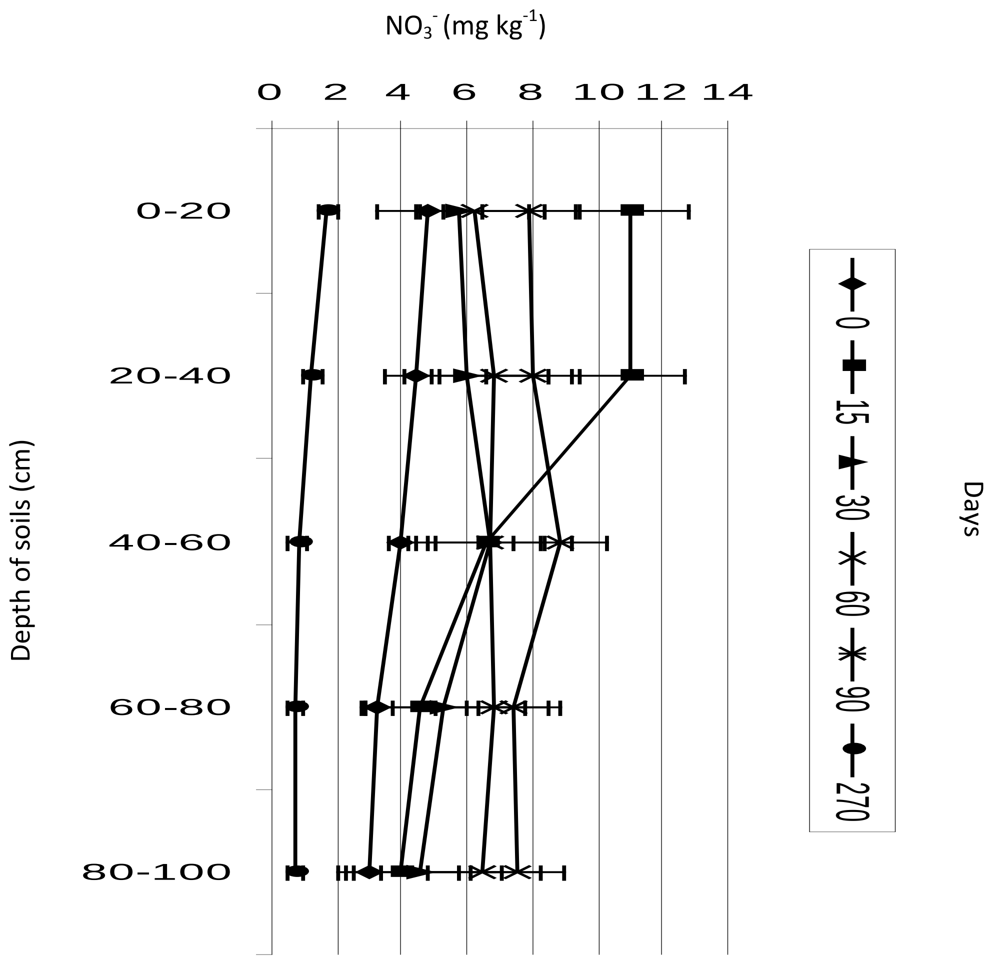

Figure 5.6 Change of mean nitrate content across cropping systems in the Rhodic Ferralsol of Kaprobu site for different depth and sampling intervals.

Neither the cropping system nor its interaction with the sampling interval had any significant effect on the mean contents of either ammonium (Table 5.3) or nitrate (Table 5.4) to 100 cm depth in this soil. Sampling interval had however a significant effect on both these parameters. The lowest (1.6 mg kg^{-1}) and highest (6.14 mg kg^{-1}) ammonium contents across cropping systems were recorded at day 30 and day 15, respectively. In the case of nitrate the lowest (1.0 mg kg^{-1}) and highest (8.0 mg kg^{-1}) contents across the cropping systems were measured at day 270 and day 60, respectively.

Table 5.3 Interaction effects of cropping system and sampling interval on mean ammonium content (mg kg^{-1}) to 100 cm depth in the Rhodic Ferralsol of Kaprobu site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	2.67	5.32	2.06	2.86	3.53	2.47	3.12	ns
Bean	2.62	8.41	1.77	0.94	3.53	2.36	3.27	
M/B[1]	2.57	5.94	1.16	0.93	2.91	2.34	2.64	
Wheat	2.69	4.40	1.46	0.88	3.12	2.57	2.52	
Fallow	2.71	6.61	1.28	1.60	3.28	1.81	2.88	
Mean	2.65bc	6.14a	1.55d	1.41d	3.27b	2.31cd		
LSD(α 0.05)	0.95							
Crop x interval	ns							
CV (%)	24.8							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

Table 5.4 Interaction effects of cropping system and sampling interval on mean nitrate content (mg kg^{-1}) to 100 cm depth in the Rhodic Ferralsol of Kaprobu site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	3.80	7.23	7.73	6.69	4.62	0.98	5.18	ns
Bean	3.87	8.06	5.72	7.23	8.13	0.81	4.43	
M/B[1]	3.91	7.32	2.85	5.88	3.27	1.43	4.11	
Wheat	4.08	7.96	4.79	8.67	6.58	1.57	5.61	
Fallow	3.86	6.55	7.18	11.31	10.46	0.42	6.63	
Mean	3.90c	7.42ab	5.65bc	7.96a	6.61ab	1.04d		
LSD(α 0.05)	2.05							
Crop x interval	ns							
CV (%)	28.6							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

5.3.3 Turbo site

The change in mean mineral N content across cropping systems and depth intervals in the Orthic Acrisol of Turbo site from April to December 2004 is presented in Figure 5.7. Ammonium gradually build-up from day 0 to day 15 and then remained at that level to day 30. After day 30 ammonium declined gradually to day 60 and then stayed at that level to day 270. In contrast to ammonium, nitrate built up sharply from day 0 to day 15, followed by a gradual decline from day 15 to day 270.

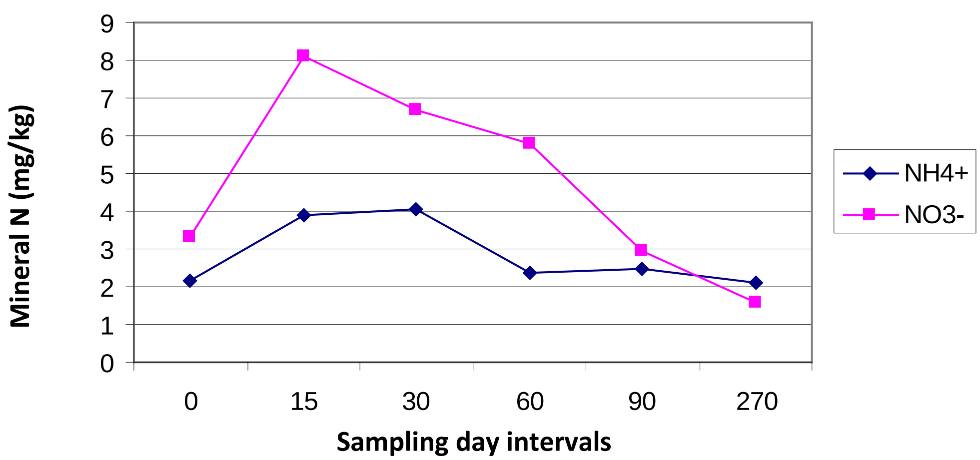

Figure 5.7 Change in mean mineral N content across cropping systems and depth intervals in the Orthic Acrisol of Turbo site from April to December 2004.

The ammonium content at all six of the sampling intervals, viz. day 0, day 15, day 30, day 60, day 90 and day 270 remained almost constant for the five depth intervals that were sampled (Figure 5.8). However, the six sampling intervals can be grouped clearly into two concerning their ammonium levels. Notably day 0, day 60, day 90 and day 270 sampling intervals had lower levels of ammonium than day 15 and day 30 sampling intervals. In this Orthic Acrisol the ammonium content of the latter two sampling intervals did not decline down the profile like those in either the Rhodic Ferralsol or Humic Nitisol profiles (Figure 5.2, 5.5 and 5.8).

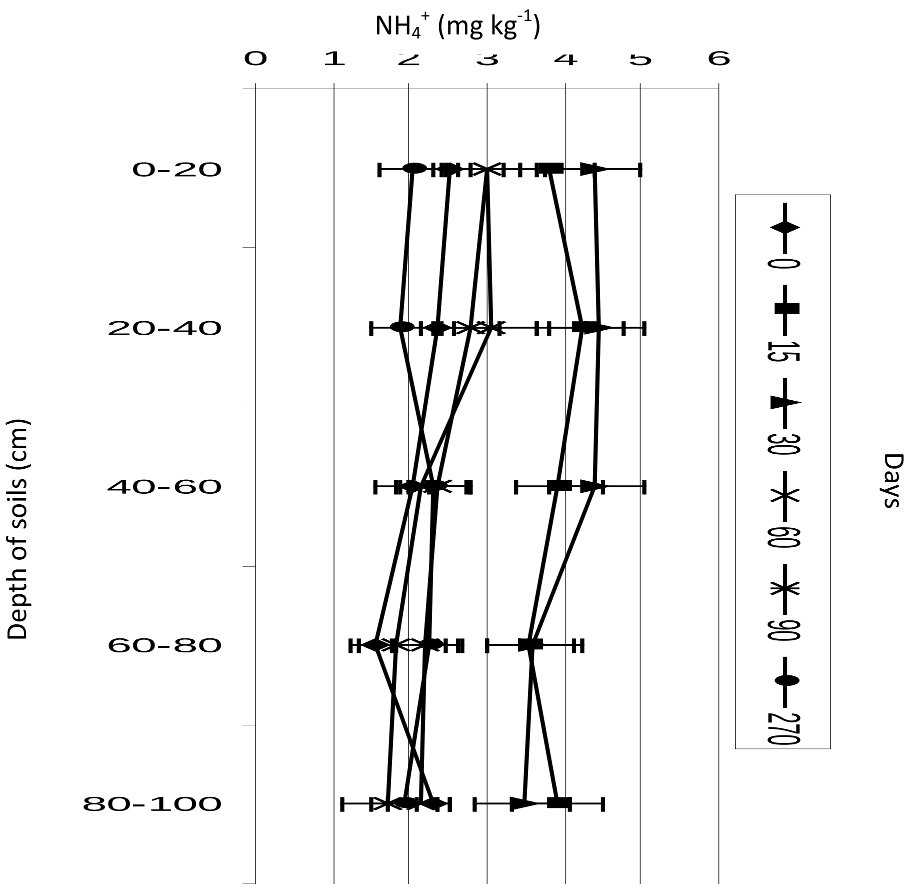

Figure 5.8 Change of mean ammonium content across cropping systems in the Orthic Acrisol of Turbo site for different depth and sampling intervals.

In the case of nitrate it was also the day 15 sampling interval that differed from the other five sampling intervals (Figure 5.9). The nitrate content for this sampling interval was high in the first two depth intervals and then declined sharply in the next three depth intervals of the Orthic Acrisol profile. This trend was very similar to the trends recorded with nitrate in the Rhodic Ferralsol (Day 15 sampling interval) and the Humic Nitisol (Day 15, 30, 60 and 90 sampling intervals) as shown in Figures 5.3, 5.6 and 5.9, respectively.

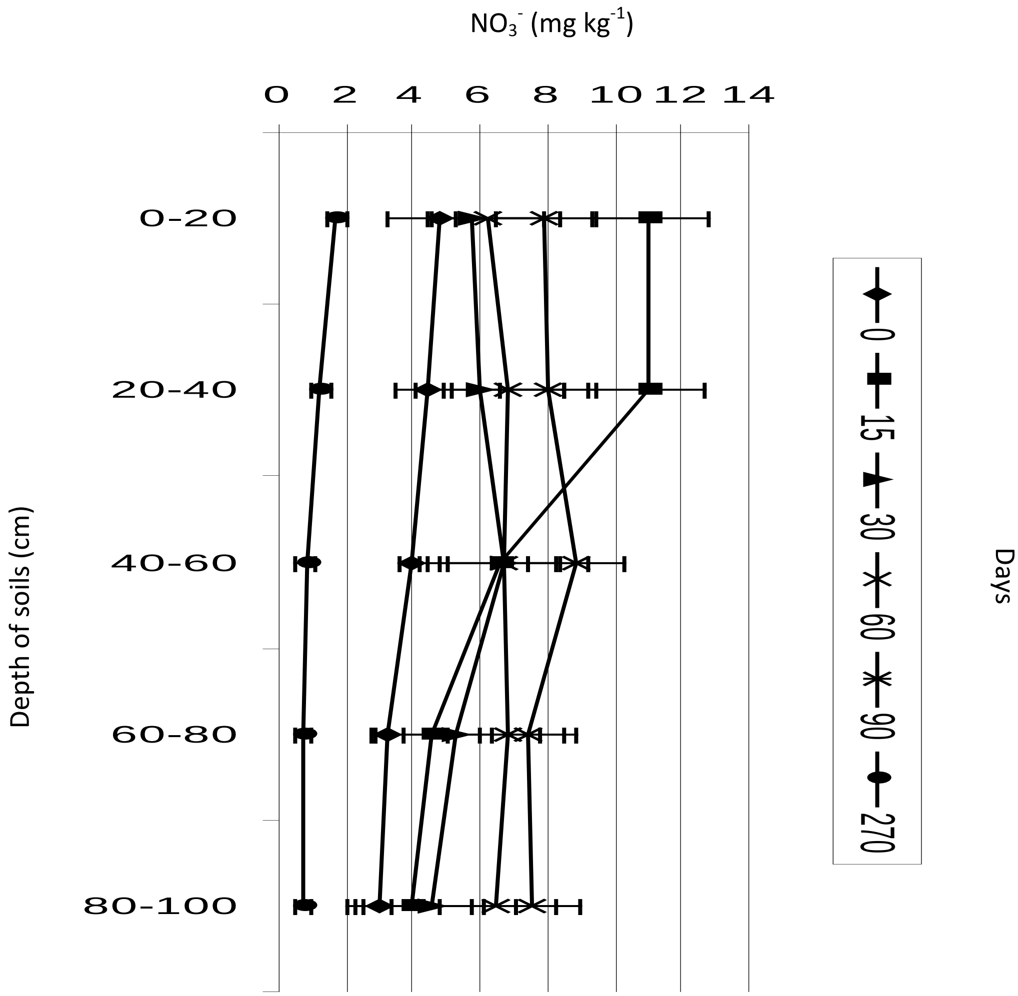

Figure 5.9 Change of mean nitrate content across cropping systems in the Orthic Acrisol of Turbo site for different depth and sampling intervals.

Like for the Rhodic Ferralsol of the Kaprobu site neither the cropping system nor its interaction with the sampling interval had a significant effect on the contents of ammonium (Table 5.5) and nitrate (Table 5.6) to 100 cm depth in the Orthic Acrisol of the Turbo site. The sampling intervals had, however, significant effects on the ammonium content as well as the nitrate content. Ammonium ranged from 2.0 mg kg^{-1} at day 270 sampling interval to 4.1 mg kg^{-1} at day 30 sampling interval. Day 270 sampling interval also gave the lowest nitrate (1.6 mg kg^{-1}) but day 15 sampling interval gave the highest nitrate (8.1 mg kg^{-1}).

Table 5.5 Interaction effects of cropping system and sampling interval on mean ammonium content (mg kg^{-1}) to 100 cm depth in the Orthic Acrisol of Turbo site in 2004

	Sampling intervals (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	2.01	3.43	4.18	2.87	1.83	1.84	2.69	ns
Bean	2.17	3.36	4.03	2.26	2.17	1.95	2.66	
M/B[1]	2.14	4.38	3.92	2.21	2.38	2.02	2.84	
Wheat	2.32	3.92	4.03	2.55	3.02	2.23	3.01	
Fallow	2.15	4.31	4.12	1.87	3.09	2.41	2.99	
Mean	2.16bc	3.88a	4.06a	2.35bc	2.50b	2.04c		
LSD(α 0.05)	0.45							
Crop x interval	ns							
CV (%)	11.9							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

Table 5.6 Interaction effects of cropping system and sampling interval on mean nitrate content (mg kg^{-1}) to 100 cm depth in the Orthic Acrisol of Turbo site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	2.96	6.97	7.40	6.02	1.76	0.52	4.27	ns
Bean	3.08	6.74	6.54	5.82	4.08	1.89	4.69	
M/B[1]	3.43	8.69	6.95	5.36	2.43	1.77	4.82	
Wheat	3.42	8.50	6.47	7.12	3.79	1.74	5.17	
Fallow	3.63	9.22	6.22	4.55	2.62	1.89	4.69	
Mean	3.30c	8.08a	6.72b	5.77b	2.94c	1.56d		
LSD(α 0.05)	1.05							
Crop x interval	ns							
CV (%)	16.8							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

5.3.4 Illula site

Figure 5.10 displays the change of mean mineral N content across cropping systems and depth intervals in the Mollic Gleysol of Illula site from April to December in 2004. This figure indicates a sharp build-up of ammonium from day 0 to day 15, followed by a sharp decline from day 15 to day 60. After day 30 ammonium increased slightly to day 90 and then decreased slightly to day 270. The change of nitrate in this Mollic Gleysol was marginal compared to the changes of nitrate in the Humic Nitisol, Rhodic Ferralsol and Orthic Acrisol. However, nitrate increased gradually from day 0 to day 15 and then decreased gradually to day 30. From day 30 the nitrate increased again gradually to day 90, followed by a decrease to day 270.

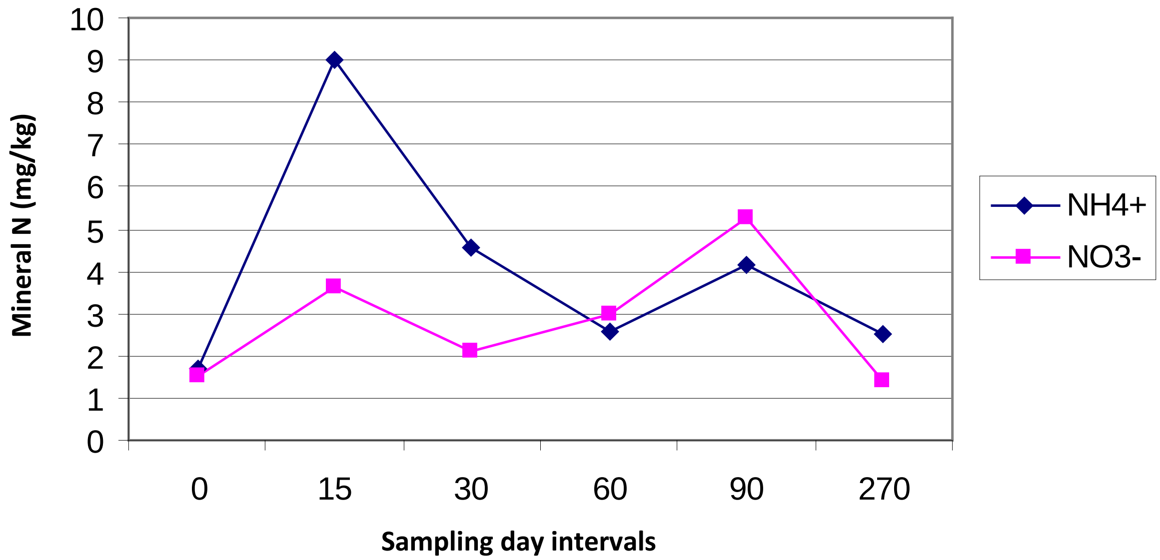

Figure 5.10 Change of mean mineral N content across cropping systems and depth intervals in the Mollic Gleysol of Illula site from April to December 2004.

The content of ammonium at four of the sampling intervals, namely day 0, day 60, day 90 and day 270 remained relatively constant for the five depth intervals that were sampled (Figure 5.11). However, for the day 15 and day 30 sampling interval ammonium decreased from the first depth interval to the third depth interval and then stayed almost constant for the remaining depth intervals. The 15 day sampling interval had for every depth interval a higher ammonium content than the 30 day sampling interval.

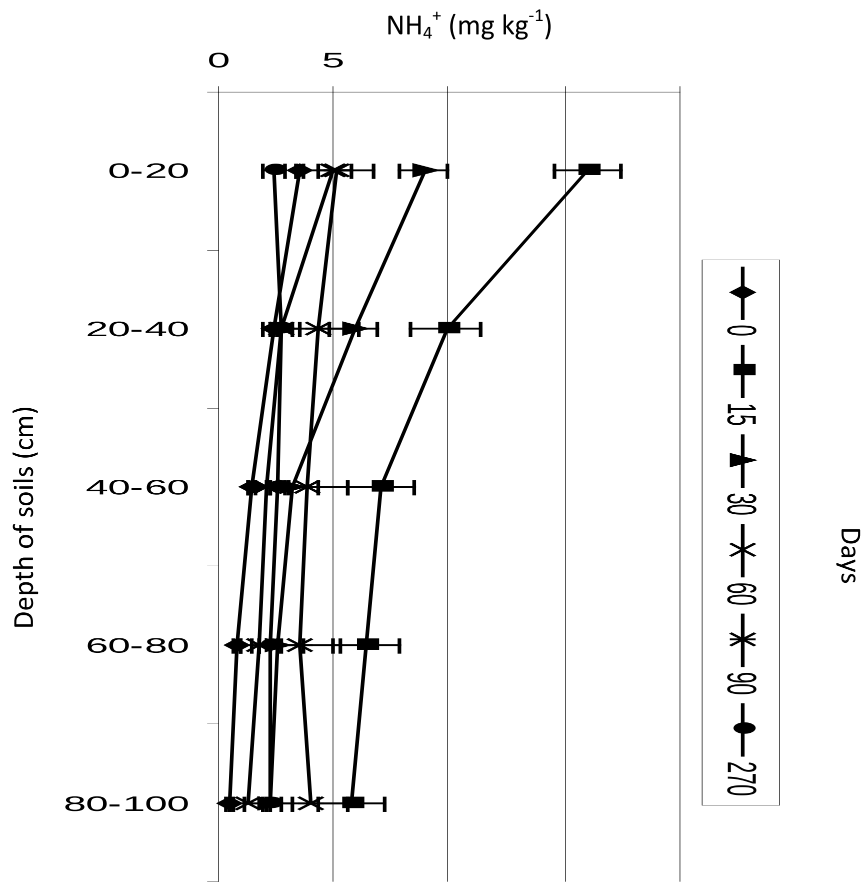

Figure 5.11 Change of mean ammonium content across cropping systems in the Mollic Gleysol of Illula site for different depth and sampling intervals.

An almost similar trend evolved for nitrate in the Mollic Gleysol (Figure 5.12). The content of nitrate for day 0, day 60, day 90 and day 270 sampling intervals remained almost constant irrespective of depth interval. However, for day 15 and day 30 sampling intervals the nitrate declined sharply from the first to second and then gradually to the third depth interval. The nitrate content of these two sampling intervals then stayed constant.

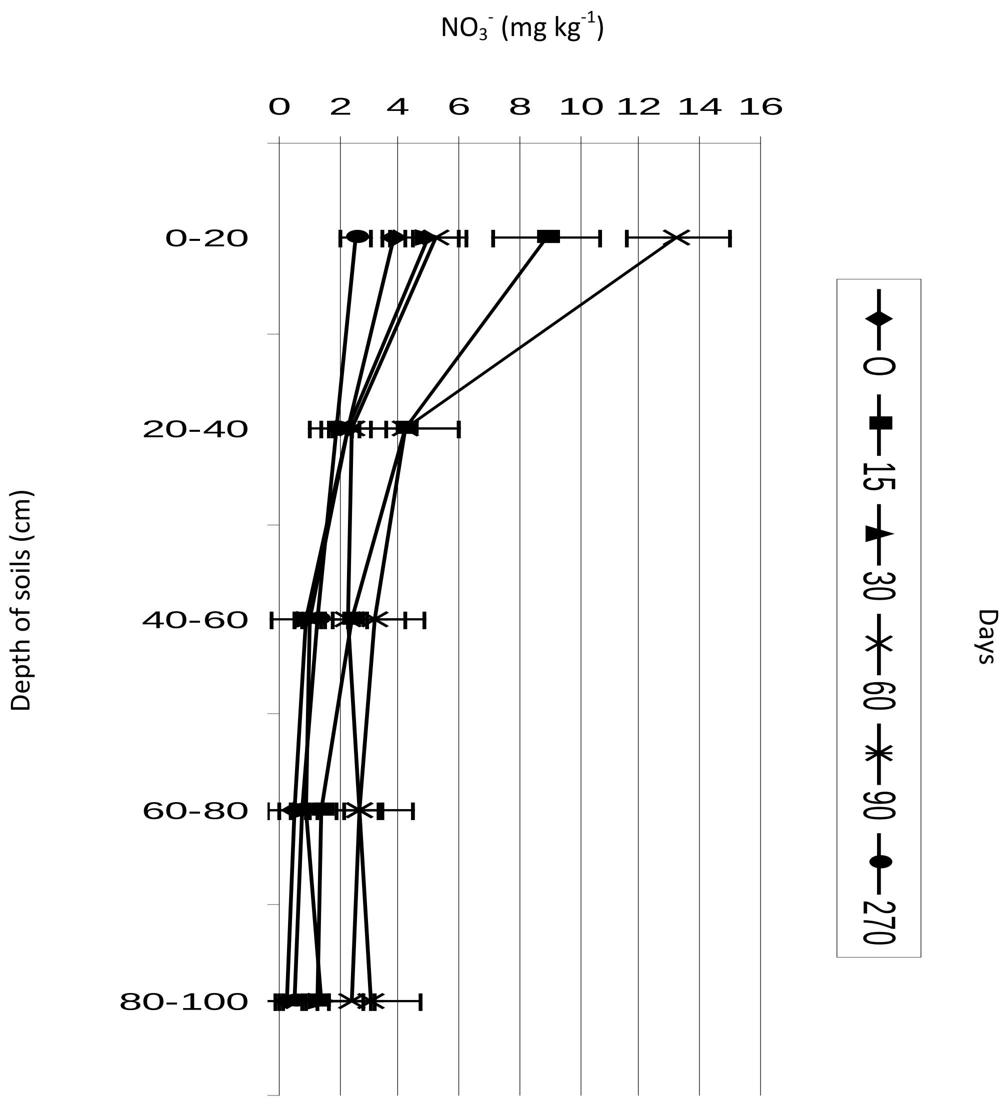

Figure 5.12 Change of mean nitrate content across cropping systems in the Mollic Gleysol of Illula site for different depth and sampling intervals.

Neither the cropping system nor its interaction with the sampling interval affected contents of ammonium (Table 5.7) to 100 cm depth in the Mollic Gleysol. Both ammonium and nitrate were, however, significantly affected by sampling interval. The content of ammonium ranged from 1.7 mg kg^{-1} at day 0 to 9.0 mg kg^{-1} at day 15. For nitrate the lowest (1.4 mg kg^{-1}) and highest (5.1 mg kg^{-1}) values were measured at day 270 and day 90, respectively.

Table 5.7 Interaction effects of cropping system and sampling interval on mean ammonium content (mg kg^{-1}) to 100 cm depth in the Mollic Gleysol of Illula site in 2004

	Sampling interval (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	1.72	7.79	4.71	3.35	5.61	2.26	4.24	ns
Bean	1.67	8.73	4.75	2.93	5.00	2.91	4.33	
M/B[1]	1.68	8.59	4.48	2.46	2.23	2.12	3.59	
Wheat	1.77	9.94	5.25	2.09	2.18	2.63	3.98	
Fallow	1.74	10.09	3.67	2.06	5.70	2.52	4.30	
Mean	1.72c	9.03a	4.57b	2.58c	4.14b	2.49c		
LSD(α 0.05)	1.23							
Crop x interval	ns							
CV (%)	22.7							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

Table 5.8 Interaction effects of cropping system and sampling interval on mean nitrate content (mg kg^{-1}) to 100 cm depth in the Mollic Gleysol of Illula site in 2004

	Sampling intervals (days)							
Crop	0	15	30	60	90	270	Mean	LSD
Maize	1.97	3.59	2.51	3.30	3.59	1.45	2.73	ns
Bean	1.17	2.53	1.86	2.46	3.87	1.74	2.27	
M/B[1]	1.47	0.80	1.77	2.56	3.01	1.27	1.81	
Wheat	1.64	4.43	1.89	3.98	5.57	1.25	3.11	
Fallow	1.46	4.59	2.42	2.61	10.23	1.29	3.77	
Mean	1.54bc	3.19b	2.09bc	2.98bc	5.25a	1.40c		
LSD(α 0.05)	1.7							
Crop x interval	ns							
CV (%)	47.1							

[1]Intercropped maize and beans. ns= not significant. Means followed by the same letters in a column or row are not significant (α 0.05) different.

5.3.5 Comparison of sites

Some results on the mean ammonium (Table 5.9) and nitrate (Table 5.10) contents to 100 cm soil depth in 2004 are presented here which enables a comparison of the four sites that were studied. Neither the site nor its interaction with the sampling interval had a significant effect on ammonium content. However, significant differences in ammonium content between sampling intervals were noted. The ammonium contents range from 2.1 mg kg^{-1} at day 60 to 5.8 mg kg^{-1} at day 15.

Table 5.9 Interaction effects of experimental site and sampling interval on mean ammonium content (mg kg^{-1}) to 100 cm soil depth in 2004

	Sampling interval (days)							
Site	0	15	30	60	90	270	Mean	LSD
Timboroa	2.55	4.04	4.66	1.87	0.83	2.00	2.66	ns
Kaprobu	2.65	6.14	1.55	1.41	3.27	2.31	2.89	
Turbo	2.16	3.88	4.06	2.35	2.50	2.09	2.84	
Illula	1.71	9.03	4.57	2.78	4.14	2.49	4.12	
Means	2.27b	5.77a	3.71b	2.10b	2.69b	2.22b		
LSD (α 0.05)	1.88							
Crop x interval	ns							
CV (%)	39.9							

ns = not significant. Means followed by the same letters in column or row are not significant (α 0.05) different.

The nitrate content was significantly affected by either the site or sampling interval but not their interaction. Content of nitrate ranged from 2.8 mg kg^{-1} in the Mollic Gleysol at Illula to 9.9 mg kg^{-1} in the Humic Nitisol at Timboroa. Day 270 sampling interval had the lowest (1.2 mg kg^{-1}) and day 60 sampling interval the highest (8.0 mg kg^{-1}) nitrate contents.

Table 5.10 Interaction effects of experimental site and sampling interval on mean nitrate content (mg kg^{-1}) to 100 cm soil depth in 2004

	Sampling intervals (days)							
Site	0	15	30	60	90	270	Mean	LSD
Timboroa	3.75	10.24	12.58	15.26	12.09	0.64	9.90a	2.97
Kaprobu	3.90	7.42	5.66	7.96	6.61	1.04	5.43b	
Turbo	3.30	8.08	6.71	5.77	2.94	1.56	4.73b	
Illula	1.54	3.64	2.09	2.96	5.26	1.40	2.82b	
Mean	3.12bc	7.35a	6.76ab	7.99a	6.73ab	1.16c		
LSD (α0.05)	3.64							
Crop x interval	ns							
CV (%)	43.9							

ns = not significant. Means followed by the same letters in column or row are not significant (α 0.05) different.

5.4 Discussion

The movement of either ammonium or nitrate in soil under sole-cropped maize, wheat and beans as well as intercropped maize and beans was investigated from April to December 2004 at four distinct sites of Uasin Gishu District. They are Timboroa in sub-zone UH3 of the Upper Highland zone, Kaprobu in sub-zone LH3 of the Highland zone, Turbo in sub-zone UM4 of the Upper Midland zone, and Illula in sub-zone LH3 of the Lower Highland zone. Timboroa, Kaprobu, Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively. Crops typically cultivated are wheat-barley at Timboroa, wheat/maize-barley at Kaprobu, sunflower-maize at Turbo and wheat/maize at Illula.

At each of the 16 treatment combinations comprising four experimental sites by four cropping systems the distribution of either ammonium or nitrate was monitored in the soil for six sampling intervals (day 0, day 15, day 30, day 60, day 90 and day 270) in five depth intervals (0 – 20 cm, 20 – 40 cm, 40 – 60 cm and 80 – 100 cm). The results presented earlier showed similarities as well as dissimilarities with regard to the factors studied and the discussion will focus mostly on these aspects.

The mean nitrate content across cropping systems and depth intervals in the Humic Nitisol of Timboroa site, Rhodic Ferralsol of Kaprobu site and Orthic Acrisol of Turbo site exceeded the mean ammonium content at most sampling intervals (Figure 5.1, 5.4 and 5.7). This was not true for the Mollic Gleysol of Illula site where the mean ammonium content across treatments and depth intervals exceeded the mean nitrate content at most sampling intervals (Figure 5.10) This phenomenon can probably be attributed to the fact that nitrification was retarded in the Mollic Gleysol due to poor aeration which was not the case in the Humic Nitisol, Rhodic Ferralsol and Orthic Acrisol which were better drained (Sanchez, 1976; Karlen *et al*., 2001)

However, despite this dissimilarity either ammonium or nitrate built up in all four soil types from day 0 before any fertilizer was applied until they peaked after some time before a decline started to day 270 at harvesting (Figure 5.1, 5.4, 5.7 and 5.10). The levels of ammonium and nitrate were small and almost similar at the first and last sampling interval, namely 2 to 4 mg kg^{-1} each. However, levels of 4 to 9 mg kg^{-1} for ammonium and 5 to 16 mg kg^{-1} for nitrate were recorded when they peaked. In most instances ammonium (day 15 to day 30) peaked sooner and shorter than nitrate (day 15 to day 90) probably on account of mineralization that preceded nitrification (Semb and Robinson, 1969; Sanchez, 1976; Tiessen *et al*., 1994). However, this was the opposite of which Wetselaar (1962) found in Australia.

Further it is noteworthy that the four soil types differed with regard to the rate at which either ammonium or nitrate increased and decreased in them. In this regard climatic conditions and soil characteristics may have played an important role on account of their effects on microbial activity. During the nine month study period from April to December in 2004 rainfall amounted to 654 mm at Timboroa, 538 mm at Kaprobu, 502 mm at Turbo and 625 mm at Illulu (Appendix 1). This resulted in a mean monthly rainfall of 73 mm, 60 mm, 42 mm and 70 mm at Timboroa, Kaprobu, Turbo and Illulu, respectively. The differences in mean monthly rainfall at the four sites could manifested in different soil water contents. Temperature was not recorded at the four sites, however, reported mean annual temperatures over the long term are 14.5°C for Timboroa, 16.5°C for Kaprobu, 19.3°C for Turbo and 16.5°C for Illula. It can be assumed that the soil temperature differed accordingly at the four sites. Both soil water content and soil temperature could influence microbial N transformations in the experimental soils. Other contributing factors may be the soils' organic matter and clay contents (Table 3.8). In the upper 30 cm soil of Timboroa, Kaprobu, Turbo and Illula clay contents of 14%, 31%, 25% and 32% were measured, respectively. The organic C in this soil layer of Timboroa (4%) was twice that of Kaprobu, Turbo and Illula (2%). It is well established that microbial N transformations are enhanced by higher contents of organic matter and clay in soils.

These observed trends in mean ammonium and nitrate contents across cropping systems and depth intervals also manifested to a large extent also in each of the five depth intervals that were sampled at six intervals over the nine month period of monitoring. The content of ammonium remained relatively constant over depth for most sampling intervals at the four sites (Figure 5.2, 5.5, 5.8 and 5.11). Exceptions were at either the day 15 and day 30 sampling intervals For these two sampling intervals ammonium content declined from the first to the third or fourth depth interval and then stayed almost constant. A similar trend evolved for nitrate for the day 15 and day 30 sampling intervals, namely a decline from the first to the third or fourth depth interval whereafter it stabilized to a large extent (Figure 5.3, 5.6, 5.9 and 5.12). The fact that the positively charged ammonium and the negatively charged nitrate decreased both with depth may be an indication that leaching probably played a minor role since the mobility of the two ions differ (John and Hollocher, 1977). However, this decline of either ammonium or nitrate may be ascribed rather to the crops' high demand for N as a result of their strong vegetative growth during this period (Terry and McCants, 1970).

It is interesting to note that across sampling intervals neither the mean ammonium content (Table 5.1, 5.3, 5.5 and 5.7) nor the mean nitrate content (Table 5.2, 5.4, 5.6 and 5.8) to 100 cm depth was affected significantly by the cropping systems employed at the four sites. The only exception was the nitrate content at Timboroa that ranged from 6.8 mg kg $^{-1}$ under intercropped maize and beans to 11.1 mg kg $^{-1}$ under sole-cropped wheat. However, the content of ammonium and nitrate differed both significantly between sampling intervals, indicating that cropping systems were less prominent to sampling intervals concerning this interaction.

Similarly, sampling intervals were superior to experimental sites concerning their interaction effects on the mean ammonium content to 100 cm soil depth (Table 5.9). This was not true for the mean nitrate content to 100 cm soil depth since both experimental sites and sampling intervals influenced this parameter significantly (Table 5.10). This is an indication that the climatic conditions together with the soil characteristics referred to earlier affected the transformation and/or transport processes of N during the nine month monitoring period.

Based on this discussion it is clear that there are several similarities and dissimilarities regarding the movement of mineral N in the different soils of Uasin Gishu District in Kenia when various cropping systems are employed. The intensity of the transformation and transport processes of N differed, however, between soil type and cropping system combinations. This aspect should be properly taken into account when designing fertilization programs for N that could lead to better crop productivity without environmental pollution. Only then would sustainable cropping in agro-ecosystems of sub-Saharan Africa be achievable

5.5 Conclusions

The mean nitrate content across treatments and depth intervals in the Humic Nitisol of Timboroa site, Rhodic Ferralsol of Kaprobu site, Orthic Acrisol of Turbo site exceeded the mean ammonium content at most sampling intervals but in the Mollic Gleysol of Illula site the pattern was reversed. Either ammonium or nitrate built up in all four soil types from day 0 before any fertilizer was applied until the two parameters peaked after some time before a decline started to day 270 at harvesting. Ammonium (day 15 to day 30) peaked sooner and shorter than nitrate (day 30 to day 60). The content of ammonium and nitrate remained relatively constant over depth for most sampling intervals, except for day 15 and day 30 where the contents declined from the first to the third or fourth depth interval. Sampling intervals had a superior effect to either experimental site or cropping system concerning mineral N content. All these aspects should be properly taken into account when designing a fertilization program for N to improve crop productivity and prevent environmental pollution in Uasin Gishu District.

CHAPTER SIX

NITROGEN USE EFFICIENCY IN SOLE- AND INTERCROPPING SYSTEMS FERTILIZED AT DIFFERENT NITROGEN RATES

6.1 Introduction

Nitrogen is one of the most critical inputs that define crop productivity and yield under field conditions, and must be supplemented to meet the food production demands of an ever-increasing world population (Sanchez, 1976; Giller *et al.,* 1997). This view also applies for Kenya where cropping is of great importance for the well-being of the country's citizens. However, it is to be noted that inorganic N fertilizers are expensive and their prices vary widely between and within cropping seasons in most areas of Kenya (FURP, 1994; Laboso, 2003; Mulagoli, 2003). This is also the case in the Uasin Gishu District where maize, wheat and beans are the common crops.

Efficient utilization of N fertilizer is essential to ensure better value for investment as well as to minimize the adverse impacts of the accumulation of reactive N species in the environment (Huggins and Pan, 1993; Balasubramanian, 2003; Nielsen, 2006; Pathak *et al*., 2008). It is therefore important to identify the fertilizer rates and times of application, including the method of application, which result in the most efficient use of N. The average nitrogen use efficiency (NUE) established with many field trials is approximately 33% and a substantial proportion of the remaining 67% is lost into the environment especially in intensively cropped areas (Pathak *et al*., 2008).

The objective of this study was to quantify the efficiency of N use in the sole- and intercropping sytems practiced in the Uasin Gishu District of Kenya. Application of inorganic N at different rates allows the estimation of yield, recovery and physiological efficiencies (Gardner *et al.,* 1977; Moll *et al.,* 1982; Bock, 1984; Prasad and Power, 1997; Swarp, 2002; Singh *et a*l., 2008 and Prasad, 2009). These efficiencies are used to evaluate the management of N application. The efficiency of N application depends inter alia on losses by leaching, surface runoff, denitrification and volatilization (Cassmann *et al.,* 2002; Krauss, 2004; Nielsen, 2006).

6.2 Procedure

Details on the methodology of this study are presented in Chapter 3. However, for convenience a concise description follows. Sole-cropped maize, wheat and beans as well as intercropped maize and beans were planted in 2007 at four distinct sites. Treatments comprised of four N levels in factorial combination with four P levels, including a zero application of either N or P in all instances. The sites were Timboroa in sub-zone UH3 (wheat-barley) of the Upper Highland zone, Kaprobu in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone, Turbo in sub-zone UM4 (sunflower-maize) of the Upper Midland zone, and Illula in sub-zone LH3 (wheat/maize-barley) of the Lower Highland zone. Timboroa, Kaprobu, Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively.

The N uptake by grain and residue for all cropped plots at every site was calculated using the relevant yields and N content and hence that of total biomass by summation of N uptake values for grain and residue. Then the yield (Ye), recovery (Re) and physiological (Pe) efficiencies of N were calculated (See Bock, 1984 and Prasad, 2009 for details) as follows:

$$Y_e = \left(\frac{Y_1 - Y_0}{N_1}\right) \tag{6.1}$$

$$R_e = \left(\frac{NR_1 - NR_0}{N_1}\right) \times 100 \tag{6.2}$$

$$P_e = \left(\frac{Y_1 - Y_0}{NR_1 - NR_0}\right) \tag{6.3}$$

Where Y_1 and Y_0 represents the grain yield and NR_1 and NR_0 the N uptake by total biomass at fertilizer application levels of N_1 and N_0, respectively.

6.3 Results

6.3.1 Sole-cropped maize

6.3.1.1 Nitrogen yield efficiency

The N yield efficiency of sole-cropped maize (Table 6.1) showed that the Kaprobu site was the most efficient, followed by the Illula, Turbo and Timboroa sites respectively. In the case of Timboroa (14.2 kg grain kg N applied^{-1}) the highest efficiencies manifested with an application of 60 kg N ha^{-1}. This was not the case at Turbo (21.7 kg grain kg N applied^{-1}) and Illula (23.3 kg grain kg N applied^{-1}) where the highest efficiencies realized with an application of 30 kg N ha^{-1}.

Table 6.1 Grain yield and nitrogen yield efficiency of sole-cropped maize

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	1450	1900	1600	1800
Y_1 30	1800	2650	2250	2500
Y_1 60	2300	3600	2300	2650
Y_1 120	2300	3200	2650	2700
	Nitrogen yield efficiency (kg grain kg N applied^{-1})			
Y_e 30	11.67	25.00	21.67	23.33
Y_e 60	14.17	28.33	11.67	14.17
Y_e 120	7.08	10.83	8.75	7.50
Mean Y_e	11.00	21.40	14.00	15.00

6.3.1.2 Nitrogen recovery efficiency

The recovery efficiency of N by sole-cropped maize (Table 6.2) at Timboroa, Kaprobu and Illula sites declined with increasing rates of N application. This was not the case for the Turbo site. However, the highest recovery of N varied from 28% at Turbo (60 kg N ha^{-1} application) to 38% at Illula (30 kg N ha^{-1} application). These recovery values are in line with those commonly reported in the literature (Sanchez, 1976), namely less than 50%.

Table 6.2 Total biomass nitrogen uptake and nitrogen recovery efficiency

	Total biomass nitrogen uptake (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
NR_0 0	18.20	36.40	18.60	24.60
NR_1 30	26.80	47.00	23.50	36.00
NR_1 60	34.16	53.87	35.44	41.26
$NR_1$120	44.20	58.30	41.32	51.33
	Nitrogen recovery efficiency (%)			
R_e 30	28.7	35.3	16.3	38.0
R_e 60	26.6	29.1	28.1	27.8
R_e 120	21.7	18.3	18.9	22.3
Mean R_e	25.7	27.6	21.1	29.4

6.3.1.3 Nitrogen physiological efficiency

The N physiological efficiency of sole-cropped maize (Table 6.3) showed a similar trend as was reported earlier for N yield efficiency. Highest values for Timboroa and Illula were estimated at a N rate of 60 kg ha^{-1}, and for Turbo and Illula at a N rate of 30 kg ha^{-1}. These values ranged from 53 kg grain kg N $uptake^{-1}$ at Timboroa to 133 kg grain kg N $uptake^{-1}$ at Turbo.

Table 6.3 Grain yield, total biomass nitrogen uptake and nitrogen physiological efficiency

	Grain yields (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	1450	1900	1600	1800
Y_1 30	1800	2650	2250	2500
Y_1 60	2300	3600	2300	2650
Y_1 120	2300	3200	2650	2700
	Total biomass nitrogen uptake (kg ha^{-1})			
NR_0 0	18.2	36.4	18.6	24.6
NR_1 30	26.8	47.0	23.5	36.0
NR_1 60	34.2	53.9	35.4	41.3
NR_1 120	44.2	58.3	41.3	51.3
	Nitrogen physiological efficiency (kg grain kg N $uptake^{-1}$)			
P_e 30	40.7	70.8	132.7	61.4
P_e 60	53.1	97.1	41.7	50.9
P_e 120	32.7	59.4	46.3	33.7
Mean P_e	42.2	75.8	73.6	48.7

6.3.2 Sole-cropped wheat

6.3.2.1 Nitrogen yield efficiency

The N yield efficiencies for sole-cropped wheat are displayed in Table 6.4. These values declined with higher N application rates at the Timboroa and Turbo sites. However, for the Kaprobu and Illula sites the highest N yield efficiencies were estimated at the 60 kg N ha^{-1} application rate. The highest N yield efficiencies varied from 32 kg grain kg N $applied^{-1}$ at Turbo to 47 kg grain kg N $applied^{-1}$ at Kaprobu.

Table 6.4 Grain yield and nitrogen yield efficiency of sole-cropped wheat

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	780	310	58	520
Y_1 20	1700	750	700	800
Y_1 40	2500	2200	1250	2200
Y_1 80	2500	2000	1550	2220
	Nitrogen yield efficiency (kg grain kg N applied^{-1})			
Ye 20	46.0	22.0	32.1	14.0
Y_e 40	43.0	47.3	29.8	42.0
Y_e 80	21.5	21.1	18.7	21.3
Mean Y_e	36.8	30.1	26.9	25.8

6.3.2.2 Nitrogen recovery efficiency

The N recovery efficiency of sole-cropped wheat (Table 6.5) followed a similar trend to the N yield efficiency, i.e. Timboroa site had the highest recovery efficiency, followed by the Kaprobu, Illula and Turbo sites respectively. These values were estimated at 38% and 25% at Timboroa and Kaprobu, respectively with a 40 kg N ha^{-1} application, and at 16 and 21% at Turbo and Illula, respectively with a 80 kg N ha^{-1} application.

Table 6.5 Total biomass nitrogen uptake and nitrogen recovery efficiency of sole-cropped wheat

	Total biomass nitrogen uptake (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
NR_0 0	160	150	105	148
NR_1 20	165	154	108	152
NR_1 40	175	160	110	155
NR_1 80	185	165	118	165
	Nitrogen recovery efficiency (%)			
R_e 20	25.0	20.0	15.0	20.0
Re 40	37.5	25.0	12.5	17.5
R_e 80	31.3	18.8	16.3	21.3
Mean R_e	31.3	21.3	14.6	19.6

6.3.2.3 Nitrogen physiological efficiency

The N physiological efficiencies of sole-cropped wheat are presented in Table 6.6. At

Timboroa the efficiency decreased from 184 kg grain kg N uptake^{-1} at a 20 kg N ha^{-1} rate to 69 kg grain kg N uptake^{-1} at a 80 kg N ha^{-1} rate. However, highest efficiencies were estimated for Kaprobu, Turbo and Illula at a 40 kg N ha^{-1} rate, namely 189, 238 and 240 kg grain kg N applied^{-1} respectively.

Table 6.6 Grain yield, total biomass nitrogen uptake and nitrogen physiological efficiency of sole-cropped wheat

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	780	310	58	520
Y_1 20	1700	750	700	800
Y_1 40	2500	2200	1250	2200
Y_1 80	2500	2000	1550	2220
	Total biomass nitrogen uptake (kg ha^{-1})			
NR_0 0	160	150	105	148
NR_1 20	165	154	108	152
NR_1 40	175	160	110	155
NR_1 80	185	165	118	165
	Nitrogen physiological efficiency (kg grain kg N uptake^{-1})			
P_e 20	184.0	110.0	214.0	70.0
P_e 40	114.7	189.0	238.4	240.0
P_e 80	68.8	112.7	114.8	100.0
Mean P_e	122.5	137.2	189.1	136.7

6.3.3 Sole-cropped beans

6.3.3.1 Nitrogen yield efficiency

The highest N yield efficiencies for sole-cropped beans realized with the 50 kg N ha^{-1} application rate at all four sites (Table 6.7). These values were 1.0, 1.2, 3.8 and 8.4 kg grain kg N applied^{-1} for the Illula, Timboroa, Turbo and Kaprobu sites, respectively.

Table 6.7 Grain yield and nitrogen yield efficiency of sole-cropped beans

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	90	100	80	100
Y_1 25	90	250	90	110
Y_1 50	150	520	270	150
Y_1 100	150	690	370	130
	Nitrogen yield efficiency (kg grain kg N $applied^{-1}$)			
Y_e 25	0.0	6.0	0.4	0.4
Y_e 50	1.2	8.4	3.8	1.0
Y_e 100	0.6	5.9	2.9	0.3
Mean Y_e	0.6	6.8	2.4	0.6

6.3.3.2 Nitrogen recovery efficiency

The N recovery efficiency of sole-cropped beans varied between the four sites as displayed in Table 6.8. Recovery of N declined with higher application rates at Timboroa. However, at Kaprobu, Turbo and Illula the highest recoveries were with 50 kg N ha^{-1} application. The highest recovery values ranged from 16% at Turbo to 30% at either Kaprobu and Illula.

Table 6.8 Total biomass nitrogen uptake and nitrogen recovery efficiency of sole-cropped beans

	Total biomass nitrogen uptake (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
NR_0 0	85	95	88	95
NR_1 25	90	102	91	102
NR_1 50	92	110	96	110
$NR_1$100	98	115	100	115
	Nitrogen recovery efficiency (%)			
R_e 25	20	28	12	28
R_e 50	14	30	16	30
R_e 100	13	20	12	20
Mean R_e	15.7	26.0	13.3	26.0

6.3.3.3 Nitrogen physiological efficiency

The N physiological N efficiencies of sole-cropped beans showed large variation (Table 6.9).

These efficiencies increased with higher N application rates at Kaprobu which was not the case for Timboroa, Turbo and Illula. For the latter three sites the highest N physiological efficiencies realized with a N application of 50 kg ha^{-1}. The highest efficiencies varied from 9 kg grain kg N $uptake^{-1}$ at the Timboroa site to 140 kg grain kg N $uptake^{-1}$ at the Kaprobu site.

Table 6.9. Grain yield, total biomass nitrogen uptake and nitrogen physiological efficiency of sole-cropped beans

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_o 0	90	100	80	100
Y_1 25	90	250	90	110
Y_1 50	150	520	270	150
Y_1 100	150	690	370	130
	Total biomass nitrogen uptake (kg ha^{-1})			
NR_0 0	85	95	88	95
NR_1 25	88	97	90	97
NR_1 50	92	98	92	99
NR_1 100	95	99	97	99
	Nitrogen physiological efficiency (kg grain kg N $uptake^{-1}$)			
P_e 25	0.0	75.0	5.0	5.0
P_e 50	8.6	140.0	47.5	12.5
P_e 100	6.0	147.5	32.2	7.5
Mean P_e	4.9	120.8	28.2	8.3

6.3.4 Intercropped maize

6.3.4.1 Nitrogen yield efficiency

The N yield efficiencies of intercropped maize are given in Table 6.10. These efficiencies decreased with higher N application rates at Timboroa, Kaprobu and Illula which was not the case at Turbo where the highest efficiency was at the 60 kg N ha^{-1} application rate.

Table 6.10 Grain yield and nitrogen yield efficiency of intercropped on maize

	Grain yield (kg ha^{-1})			
Rates(kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_0 0	850	1200	700	750
Y_1 30	1650	1850	1050	1650
Y_1 60	1850	2500	1850	2100
Y_1 120	3100	3300	2800	2900
	Nitrogen yield efficiency (kg grain kg applied^{-1})			
Y_e 30	26.67	21.67	11.67	30.0
Y_e 60	16.67	21.67	19.17	22.50
Y_e 120	18.8	17.5	17.5	17.9
Mean Y_e	20.7	20.3	16.1	23.5

6.3.4.2 Nitrogen recovery efficiency

The best N recovery efficiency for intercropped maize realized at a N application rate of 60 kg ha^{-1} at the Timboroa (21%), Turbo (20%) and Illula (33%) sites (Table 6.11). However, at the Kaprobu site the best N recovery efficiency was 27% with 30 kg N ha^{-1} application.

Table 6.11 Total biomass nitrogen uptake and nitrogen recovery efficiency of intercropped maize

	Total biomass nitrogen uptake (kg ha^{-1})			
Rates(kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
NR_0 0	35.0	60.0	26.0	38.0
NR_1 30	40.0	68.0	31.0	44.0
NR_1 60	47.4	75.0	38.0	58.0
NR_1 120	49.0	77.0	40.0	63.0
	Nitrogen recovery efficiency (%)			
R_e 30	16.7	26.7	16.7	20.0
R_e 60	20.7	25.0	20.0	33.3
R_e 120	11.7	14.2	11.7	20.8
Mean R_e	16.4	22.0	16.1	24.7

6.3.4.3 Nitrogen physiological efficiency

The N physiological efficiencies of intercropped maize are shown in Table 6.12. Efficiency values ranged from 71 kg grain kg N uptake^{-1} at Timboroa with a N application rate of 60 kg ha^{-1} to 169 kg grain kg N uptake^{-1} at Illula with a N application rate of 120 kg ha^{-1}. However, the best efficiencies for the four sites were estimated with the highest N application rate.

Table 6.12 Grain yield, total biomass nitrogen uptake and nitrogen physiological efficiency of intercropped maize

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_0 0	850	1200	700	750
Y_1 30	1650	1850	1050	1650
Y_1 60	1850	2500	1850	2100
Y_1 120	3100	3300	2800	2900
	Total biomass nitrogen uptake (kg ha^{-1})			
NR_0 0	18.0	34.0	16.8	30.5
NR_1 30	24.4	42.0	21.5	38.0
NR_1 60	32.0	47.3	31.4	41.6
NR_1 120	40.0	56.0	38.0	43.2
	Nitrogen physiological efficiency (kg grain kg N uptake^{-1})			
P_e 30	125	81.3	74.5	120.0
P_e 60	71.4	97.7	78.8	121.6
P_e 120	102.3	95.5	99.1	169.3
Mean P_e	99.6	91.5	84.1	137.0

6.3.5 Intercropped beans

6.3.5.1 Nitrogen yield efficiency

The estimated N yield efficiencies for intercropped beans were very low as displayed in Table 6.13. Regardless of experimental site or N application rates the efficiencies were less than 0.035 kg grain kg N applied^{-1}. A sound interpretation of these efficiency values is therefore almost impossible.

Table 6.13 Grain yield and nitrogen yield efficiency of intercropped on beans

	Grain yield (kg ha^{-1})			
	Sites			
Rates(kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_0 0	0.00	0.03	0.03	0.02
Y_1 25	0.00	0.20	0.06	0.08
Y_1 50	0.50	1.50	0.60	1.70
Y_1 100	0.50	0.80	0.50	1.50
	Nitrogen yield efficiency (kg grain kg applied^{-1})			
Y_e 25	0.0	0.007	0.001	0.002
Y_e 50	0.01	0.029	0.011	0.034
Y_e 100	0.005	0.008	0.005	0.015
Mean Y_e	0.005	0.015	0.006	0.017

6.3.5.2 Nitrogen recovery efficiency

At three of the four sites, namely Timboroa (16%), Turbo (16%) and Illula (32%) the best N recovery efficiencies for intercropped beans were estimated at the lowest application rate of 30 kg N ha^{-1} (Table 6.14). An application of 60 kg N ha^{-1} result at Kaprobu in the highest N recovery efficiency, viz. 28%

Table 6.14 Total biomass nitrogen uptake and nitrogen recovery efficiency of intercropped beans

	Total biomass nitrogen uptake (kg ha^{-1})			
Rates(kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
NR_0 0	85.0	95.0	88.0	95.0
NR_1 25	89.0	101.0	92.0	103.0
NR_1 50	93.0	109.0	95.0	108.0
NR_1 100	98.0	121.0	99.0	112.0
	Nitrogen recovery efficiency (%			
R_e 25	16.0	24.0	16.0	32.0
R_e 50	16.0	28.0	14.0	26.0
R_e 100	13.0	26.0	11.0	17.0
Mean R_e	15.0	26.0	13.7	25.0

6.3.5.3 Nitrogen physiological efficiency

The N physiological efficiencies (Table 6.15) of intercropped beans were like the N yield efficiencies (Table 6.13), very low. Physiological efficiency values were without exception lower than 0.60 kg grain kg N uptake^{-1}. These low values hindered proper interpretation to some extent. However, at all four sites the highest N physiological efficiencies were estimated with the 50 kg N ha^{-1} application, ranging from 0.07 kg grain kg N uptake^{-1} at Timboroa to 0.56 kg grain kg N uptake^{-1} at Illula.

Table 6.15 Grain yield, total biomass nitrogen uptake and nitrogen physiological efficiency of intercropped beans

	Grain yield (kg ha^{-1})			
Rates (kg N ha^{-1})	Timboroa	Kaprobu	Turbo	Illula
Y_0 0	0.00	0.03	0.03	0.02
Y_1 25	0.00	0.20	0.06	0.08
Y_1 50	0.50	1.50	0.60	1.70
Y_1 100	0.50	0.80	0.50	1.50
	Total biomass nitrogen uptake (kg ha^{-1})			
NR_0 0	85.0	95.0	88.0	95.0
NR_1 25	88.2	96.5	89.5	97.0
NR_1 50	92.0	98.0	92.0	98.0
NR_1 100	93.5	98.8	93.0	98.0
	Nitrogen physiological efficiency (kg grain kg N uptake^{-1})			
P_e 25	0.0	0.11	0.02	0.03
P_e 50	0.07	0.49	0.14	0.56
P_e 100	0.06	0.2	0.09	0.49
Mean P_e	0.04	0.27	0.08	0.36

6.4 Discussion

The yield, recovery and physiological use efficiency of nitrogen applied at different rates to sole-cropped maize, wheat and beans as well as intercropped maize and beans were investigated in 2007 at four distinct sites of Uasin Gishu District. They are Timboroa in sub-zone UH3 of the Upper Highland zone, Kaprobu in sub-zone LH3 of the Highland zone, Turbo in sub-zone UM4 of the Upper Midland zone, and Illula in sub-zone LH3 of the Lower Highland zone. Timboroa, Kaprobu, Turbo and Illula are located on a Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively. Crops typical cultivated are wheat-barley at Timboroa, wheat/maize-barley at Kaprobu, sunflower-maize at Turbo and wheat/maize at Illula.

The efficiency of fertilizer N use is expressed in several ways as mentioned earlier but the term ‘fertilizer use efficiency’ is commonly visualized as comprising uptake and utilization efficiencies (Bock, 1984). Efficiency in uptake and utilization of applied N in grain crop production requires that those processes associated with uptake, translocation, assimilation and redistribution of N by the crop operate effectively and efficiently (Beauchamp et al., 1976; Chevalier and Schrader, 1977). The N utilization efficiency varies with climate conditions, soil types, crop genotypes and management practices (Simonis, 1988; Rice and Rice, 2003). This was very clear from the yield, recovery and physiological efficiencies of fertilizer N that realized in this study.

6.4.1 Nitrogen yield efficiency

The N yield efficiency of sole-cropped maize, wheat and beans averaged over the N application rates for the four sites at 15.4 (Table 6.1), 21.7 (Table 6.4) and 2.6 (Table 6.7) kg grain kg N applied^{-1}, respectively. In comparison with the N yield efficiency for sole-cropped maize and beans, the intercropped maize and beans realized respectively a higher and lower average N yield efficiency of 20.2 (Table 6.10) and 0.01 (Table 6.13) kg grain kg N applied^{-1}.

However, for sole-cropped maize the best N yield efficiencies estimated per site ranged from 14 kg grain kg N applied^{-1} at Timboroa to 28 kg grain kg N applied^{-1} at Kaprobu (Table 6.1). In both instances 60 kg N ha^{-1} was applied. The equivalent kg grain kg N applied^{-1} ranges were 32 (Turbo with 30 kg N ha^{-1}) to 46 (Kaprobu with 60 kg N ha^{-1}) for sole-cropped wheat (Table 6.4), 1 (Illula with 60 kg N ha^{-1}) to 8.4 (Kaprobu with 60 kg N ha^{-1}) for sole-cropped beans (Table 6.7), 19 (Turbo with 60 kg N ha^{-1}) to 30 (Illula with 30 kg N ha^{-1}) for intercropped maize (Table 6.10) and 0.01 (Timboroa with 60 kg N ha^{-1}) to 0.03 (Illula with 60 kg N ha^{-1}) for intercropped beans (Tables 6.13).

A value of 24.2 kg grain kg N applied^{-1} for maize is globally accepted as a good N yield efficiency for maize (Prasad, 2009). The average N yield efficiency of 15.4 kg grain kg N applied^{-1} for sole-cropped maize and of 20.2 kg grain kg N applied^{-1} for intercropped maize in this study are therefore lower. However, the best N yield efficiency per site which ranged from 14 to 28 kg grain kg N applied^{-1} for sole-cropped maize and from 19 to 30 kg grain kg N applied^{-1} for intercropped maize is more representative of the global value.

Globally a value of 18.1 kg grain kg N applied^{-1} is regarded as a good N yield efficiency for wheat (Prasad, 2009). This value is lower than the average N yield efficiency of 21.7 kg grain kg N applied^{-1} in this study. The range for the best N yield efficiency per site, namely 32 to 46 kg grain kg N applied^{-1} exceeded the globally value also.

Unfortunately, in literature no value could be found for beans which is regarded as having a good N yield efficiency. This is probably due to the fact that this crop is supposed to fix sufficient symbiotically atmospheric N for its need. A comparison of the N yield efficiencies of beans in this study is therefore impossible.

6.4.2 Nitrogen recovery efficiency

Over the N application rates for the four sites the N recovery efficiency averaged 26% (Table 6.2), 22% (Table 6.5) and 20% (Table 6.8) for sole-cropped maize, wheat and beans, respectively. In comparison with the N recovery efficiency for sole-cropped maize and beans, the intercropped maize and beans had respectively a lower and higher average N recovery efficiency of 20% (Table 6.11) and 103% (Table 6.14).

The best N recovery efficiency per site varied from 28% (Turbo with 60 kg N ha^{-1}) to 38% (Illula with 30 kg N ha^{-1}) for sole-cropped maize (Table 6.2). Equivalent ranges were 16% (Turbo with 80 kg N ha^{-1}) to 38% (Timboroa with 40 kg N ha^{-1}) for sole-cropped wheat (Table 6.5), 16% (Turbo with 50 kg N ha^{-1}) to 30% (Kaprobu and Illula with 50 kg N ha^{-1}) for sole-cropped beans (Table 6.8), 20% (Turbo with 60 kg N ha^{-1}) to 33% (Illula with 60 kg N ha^{-1}) for intercropped maize (Table 6.11), and 16% (Timboroa and Turbo with 25 kg N ha^{-1}) to 32% (Illula with 25 kg N ha^{-1}) for intercropped beans (Table 6.14).

Concerning N recovery efficiency for maize values of 33% (Fox et al., 1974), 37% (Cassman et al., 2002) and 38% (Bekunda et al., 2007) were reported. However, Prasad (2009) is of opinion that globally a N recovery efficiency of 65% can be regarded as good for maize. The average N recovery efficiencies for sole-cropped (26%) and intercropped (20%) maize in this study are therefore very low. This is confirmed by the ranges of best N recovery efficiency per site that were 28 to 38% for sole-cropped maize and 20 to 33% for intercropped maize.

For wheat a N recovery efficiency of 57% is regarded as good by Prasad (2009). In this study the average N recovery efficiency was only 22%. This is in line with the range of 16 to 38% for best N recovery efficiency per site in this study.

Like for N yield efficiency for beans no values for N recovery efficiency for the crop could be found. Thus any discussion on the N recovery efficiency by beans in this study is not justified.

6.4.3 Nitrogen physiological efficiency

The N physiological efficiency for sole-cropped maize, wheat and beans averaged over the N application rates for the four sites 60 (Table 6.3), 146 (Table 6.6) and 40 (Table 6.9) kg grain kg N uptake^{-1}, respectively. In comparison with N physiological efficiency for sole-cropped maize and beans, intercropped maize and beans realized lower N physiological efficiencies, viz. 20 (Table 6.12) and 0.19 (Table 6.15) kg grain kg N uptake^{-1}, respectively.

For sole-cropped maize the best N physiological efficiency per site varied from 53 kg grain kg N uptake^{-1} at Timboroa with a rate of 60 kg N ha^{-1} to 133 kg grain kg N uptake^{-1} at Turbo with a rate of 30 kg N ha^{-1} (Table 6.3). The equivalent kg grain kg N uptake^{-1} ranges were 184 (Timboroa with 20 kg N ha^{-1}) to 240 (Illula with 40 kg N ha^{-1}) for sole-cropped wheat (Table 6.6), 9 (Timboroa with 50 kg N ha^{-1}) to 148 (Kaprobu with 100 kg N ha^{-1}) for sole-cropped beans (Table 6.9), 98 (Kaprobu with 60 kg N ha^{-1}) to 169 (Illula with 120 kg N ha^{-1}) for intercropped maize (Table 6.12), and 0.07 (Timboroa with 50 kg N ha^{-1}) to 0.56 (Illula with 50 kg N ha^{-1}) for intercropped beans (Table 6.15).

The average N physiological efficiency for sole-cropped maize in this study was 60 kg grain kg^{-1} N uptake^{-1} which is far higher than the global average of 36.7 kg grain kg N uptake^{-1} (Prasad, 2009). This is confirmed by the best N physiological efficiencies per site that ranged from 53 to 60 kg grain kg^{-1} N uptake^{-1}. However, the global average of 36.7 kg grain kg N uptake^{-1} (Prasad, 2009) exceeded the average N physiological efficiency of 20 kg grain kg N uptake^{-1} for intercropped maize in this study. In comparison the range of 98 to 169 kg grain kg N uptake^{-1} for best N physiological efficiency per site was extremely high.

Prasad (2009) regarded a N physiological efficiency of 28.9 kg grain kg N uptake^{-1} as good for wheat. The average N physiological efficiency for wheat in this study was thus extremely high, viz. 146 kg grain kg^{-1} N uptake^{-1}. Confirmation of this phenomenon manifested also in the range for best N physiological efficiency per site that was 184 to 240 kg grain kg N uptake^{-1}.

No comparison for the N physiological efficiencies for beans in this study was possible for the same reason(s) mentioned earlier concerning the yield and recovery efficiencies of applied nitrogen.

The variations in yield, recovery and physiological efficiencies of applied N between the three crops can be attributed to the genetic characteristics of maize, wheat and beans which are different (Ralph, 1976). However, the variations in the mentioned N efficiencies for a crop can be ascribed only to the climatic conditions, soil properties and management practices to which a crop was subjected to at each site. There were large differences in climatic conditions and soil properties between the Timboroa, Kaprobu, Turbo and Illula sites (See Section 3.1 for details). Further, management practices like sole-cropped and intercropping of maize and beans also influenced the three kinds of N use efficiencies that were estimated.

The estimated values for yield, recovery and physiologically efficient use of applied N confirmed that an effort should be made to establish guidelines for site-specific N recommendations taking into account differences in climatic conditions, soil properties, crop genetics and management practices. This will enhance the sustainability of cropping in the Uasin Gishu District in the long-term.

6.5 Conclusions

The estimated values for yield, recovery and physiologically efficient use of applied N in this study realized from experiments done without replications. Despite of this drawback the values gave a holistic view of nitrogen use efficiency in the Uasin Gishu District.

In comparison with global values that are regarded as good for maize, the values of N yield and recovery efficiencies in this study were lower while the values of N physiological efficiencies were higher. However, for wheat in this study the values of N yield and physiological efficiencies were higher and that of N recovery efficiencies were lower compared to global values regarded as good.

Despite these trends large variations in yield, recovery and physiological efficiencies of applied N were estimated for a crop between the four study sites. This confirmed that guidelines for N recommendations should be site-specific taking into account climatic conditions, soil properties, crop genetics and management practices. Such an approach could enhance the sustainability of cropping in the Uasin Gishu District of Kenya.

CHAPTER SEVEN

RATIONALE, SYNTHESIS AND RECOMMENDATIONS

7.1 Rationale of study

The motivation behind this study was an attempt to sustain current and if possible raise future crop yields in the Uasin Gishu District of Kenya. Crop yields although variable tended to decline year after year (Table 2.1). Farmers often report the yellowing of the staple maize crop just before tasseling as a visual N deficiency symptom, followed by overall low yields at harvest. This is likely due to low levels of N in soils as a result of leaching and other unexplained losses of N during crop growth, particularly from the rainy months of April to August.

However, the decreasing crop yields in Uasin Gishu District are theoretically attributed to a decline in soil fertility on account by continuous cropping of land with minimum to no land fallowing that coincide with inadequate nutrient inputs, neglible crop rotation practices, poor crop husbandry, leaching and denitrification of N, and surface runoff of N and P fertilizers. Above all, very few farmers can afford to buy fertilizers and related agricultural inputs. There are also unpalatable policies that discourage overall agricultural production.

Against this background the overall aim of this study was to quantify crop yields and some dynamic N parameters from N fertilizer applications under five cropping systems in four distinct agro-ecosystems of the Uasin Gishu District of Kenya for a better understanding of the factors contributing to the declining crop yields. The specific aims that were investigated are to:

- Determine yield and nitrogen response of annual crops grown with blanket N fertilizer recommendations.
- Establish spatial and temporal distribution of mineral N in soils under cropping systems with blanket N fertilizer recommendations.
- Quantify nitrogen use efficiency in sole and intercropping systems fertilized at different N rates.

These aims were addressed with field trials conducted at Timboroa in the Upper Highland zone, Kaprobu in the Lower Highland zone, Turbo in the Upper Midland zone and Illula in the Lower Highland zone. The soil at Timboroa, Kaprobu, Turbo and Illula was classified as a

Humic Nitisol, Rhodic Ferralsol, Orthic Acrisol and Mollic Gleysol, respectively. At each of the sites sole-cropped maize, wheat and beans as well as intercropped maize and beans were planted with minimum fallowing of land. The field trials were conducted in 2004 and 2005 with blanket N fertilizer recommendations, and in 2007 with variable N fertilizer rates.

7.2 Synthesis of results

The grain yield of sole-cropped maize, wheat and beans averaged for the four sites over the 2004 and 2005 seasons at 2.55 t ha^{-1} (Table 4.1), 1.25 t ha^{-1} (Table 4.4) and 0.48 t ha^{-1} Table 4.7), respectively. The respective intercropped maize and beans realized lower average grain yields of 2.20 t ha^{-1} (Table 4.10) and 0.10 t ha^{-1} (Table 4.13). Thus with the exception of sole-cropped beans, the other four crops' grain yields were lower than the reported mean grain yield of 2.9 t ha^{-1} for maize, 1.55 t ha^{-1} for wheat and 0.45 t ha^{-1} for beans from 1995 to 2004 in the Uasin Gishu District (Table 1.2).

Grain yields of the studied crops showed significant differences across sites and between seasons, but the interaction effects of sites and seasons were not significantly different. Compared to 2005, higher grain yields (from 8% with sole-cropped wheat to 55% with sole-cropped maize) realized in 2004 probably due to better distributed rainfall. The only exception was with intercropped beans which yielded the same in 2004 and 2005 (Table 4.1, 4.4, 4.7, 4.10 and 4.13).

The differences observed between sites with the grain yields of maize, wheat and beans also manifested to a large extent in their respective stover, straw and trash yields and hence the biomass yields of the crops. However, the low harvest indices calculated for all studied crops, indicated that they experienced some or other stress during the physiological ripening phase (Table 4.1, 4.4, 4.7, 4.10 and 4.13).

An explanation for the inconsistency in grain yields among sites is not obvious. In some instances grain yield differences between sites may be attributed to climate differences and in other instances to soil differences. For example the mean annual rainfall for the two seasons was 723 mm at Timboroa with a Humic Nitisol, 677 mm at Illula with a Mollic Gleysol, 535 mm at Kaprobu with a Rhodic Ferralsol, and 529 mm at Turbo with a Orthic Acrisol. The overall difference in rainfall between 2004 and 2005 was 83 mm in favour of 2004.

Nonetheless, it is apparent that Kaprobu is suitable for maize production, but average in wheat and bean production. On the other hand, Timboroa is suitable for wheat production, but poor in maize and bean production. Illula and Turbo can be regarded as respectively average and poor for maize, wheat and bean production. A golden thread is therefore lacking, implying that other factors than climate conditions and soil types should be considered.

For the two seasons, mean grain N content of sole and intercropped maize was 2.1% at Timboroa and ranged from 2.8 to 2.9% at Kaprobu, Turbo and Illula. Sole-cropped wheat realized over the two seasons the highest mean grain N content at Timboroa (3.7%), followed by either Turbo and Illula (3.6%) and then Kaprobu (3.4%). The mean grain N content of sole and intercropped beans ranged from 6.0 to 6.1% at Timboroa, Kaprobu and Turbo with a lower value of 5.5% at Illula. Observations between sites for the N content of maize stover, wheat straw and bean trash showed similar trends as the crops' grain N content, although the values were lower. Across sites, neither the mean grain N content of maize, wheat and beans nor their respective mean stover, straw and trash N content differed significantly between seasons (Table 4.2, 4.5, 4.8, 4.11 and 4.14).

Only the crops' mean biomass N uptake for the two seasons will be dealt with as it mirrors to a large extent the N uptake by the grain of maize, wheat and beans and their respective stover, straw and trash over this period (Table 4.3, 4.6, 4.9, 4.12 and 4.15). The biomass N uptake of sole-cropped maize ranged from 93 kg ha^{-1} at Timboroa to 141 kg ha^{-1} at Kaprobu. For intercropped maize the biomass N uptake was slightly lower and varied between 88 kg ha^{-1} at Turbo to 113 kg ha^{-1} at Kaprobu. Thus at all four sites the biomass N uptake by sole and intercropped maize exceeded the blanket N application of 60 kg ha^{-1} (Table 3.5).

Compared to either sole or intercropped maize, sole-cropped wheat realized a larger range of N uptake, namely 15 kg ha^{-1} at Turbo, 37 kg ha^{-1} at Kaprobu, 69 kg ha^{-1} at Illula and 102 kg ha^{-1} at Timboroa. The blanket N application of 40 kg N ha^{-1} was exceeded therefore at Timboroa and Illula but not at Kaprobu and Turbo. Biomass N uptake of intercropped beans (6 kg ha^{-1} at both Timboroa and Turbo to 15 kg ha^{-1} at Kaprobu) was distinctly lower than the biomass N uptake of sole-cropped beans (23 kg ha^{-1} at Timboroa to 60 kg ha^{-1} at Kaprobu). Only the biomass N uptake of sole-cropped beans at Illula and Kaprobu exceeded the blanket N application of 50 kg N ha^{-1}.

Thus biomass N uptake exceeded the blanket N application in many instances implying that especially maize and to a lesser extent wheat and beans rely on the supply of N from soil through mineralization of organic reserves. This may ultimately lead to an exhaustion of the organic reserves, viz. a viz. organic matter which plays an important role in soil quality (Kapkiyai *et al*., 1999). Organic matter is often regarded as the key determinant of soil quality due to the vital influence it has on soil physical, chemical and biological conditions (Weil and Magdoff, 2004).

Further evidence of stress during the physiological ripening phase of the crops manifested also in the N uptake by biomass per ton of grain produced. In this study the averages were 45.4, 44.6 and 89.3 kg for sole-cropped maize, wheat and beans, and 44.8 and 66.0 kg for intercropped maize and beans, respectively. These values exceeded the reported values in literature (Bergmann, 1992; Voss, 1993; FSSA, 2008) which are respectively 27, 30 and 45 kg N t grain^{-1} for maize, wheat and beans.

The exceedance of blanket N application by biomass N uptake in many instances may be the result of excessive leaching of nitrate during the rainy months from April to August. Thus the distribution of mineral N in the soils under sole and intercropping systems with blanket N fertilizer application was followed in 2004 from early April before any application of fertilizer until harvesting was completed late December, thus for six sampling intervals (day 0, day 15, day 30, day 60, day 90 and day 270) in five depth intervals (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm).

The mean nitrate content across cropping systems and depth intervals in the Humic Nitisol of Timboroa site, Rhodic Ferralsol of Kaprobu site and Orthic Acrisol of Turbo site exceeded the mean ammonium content at most sampling intervals (Figure 5.1, 5.4 and 5.7). This was not true for the Mollic Gleysol of Illula site probably because nitrification was retarded due to poor aeration which was not the case in the other three soils that were better drained (Sanchez, 1976; Karlen *et al*., 2001).

Despite this dissimilarity either ammonium or nitrate build-up in all four soil types from day 0 before any fertilizer was applied until they peaked after some time before a decline started to day 270 at harvesting. Levels of 4 to 9 mg kg^{-1} for ammonium and 5 to 16 mg kg^{-1} for nitrate were recorded when they peaked. In most instances ammonium (day 15 to day 30) peaked sooner and shorter than nitrate (day 15 to day 90) probably on account of mineralization that preceded nitrification (Semb and Robinson, 1969; Sanchez, 1976; Tiessen *et al*., 1994).

The four soil types differed with respect to the rate at which either ammonium or nitrate increased or decreased in them. In this regard climatic conditions and soil characteristics may have played an important role. Over the nine months study period rainfall amounted to 654 mm at Timboroa, 538 mm at Kaprobu, 502 mm at Turbo and 625 mm at Illula. This resulted in a mean monthly rainfall of 73 mm, 60 mm, 42 mm and 70 mm at Timboroa, Kaprobu, Turbo and Illula, respectively, which may manifested in different soil water contents at the sites. Temperature was not recorded at the four sites, however, reported mean annual temperatures over the long term are 14.5°C for Timboroa, 16.5°C for Kaprobu, 19.3°C for Turbo and 16.5°C for Illula. The chance is good that soil temperature varied accordingly. Both soil water content and soil temperature could influence microbial N transformations in the experimental soils. Other contributing factors may be the soils' organic matter and clay contents (Table 3.8). In the upper 30 cm soil of Timboroa, Kaprobu, Turbo and Illula clay contents of 14%, 31%, 25% and 32% were measured, respectively. The organic C in this soil layer of Timboroa (4%) was twice that of Kaprobu, Turbo and Illula (2%). Microbial N transformations are usually enhanced by higher contents of organic matter and clay in soils.

These trends in mean ammonium and nitrate contents across cropping systems and depth intervals also manifested to a large extent in each of the five depth intervals that were sampled at six intervals over the nine months. The content of ammonium remained relatively constant over depth for most sampling intervals at the four sites (Figure 5.2, 5.5, 5.8 and 5.11). Exceptions were at either the day 15 and day 30 sampling intervals where ammonium content declined from the first to the third or fourth depth interval. A similar trend evolved for nitrate for day 15 and day 30 sampling intervals, namely a decline from the first to third or fourth depth interval where after it stabilized to a large extent (Figure 5.3, 5.6, 5.9 and 5.12). The fact that ammonium and nitrate both decreased both with depth may be an indication that leaching probably played a minor role since the mobility of the two ions differ (John and Hollocher, 1977). However, this decline of either ammonium or nitrate may be ascribed rather to the crops' high demand for N due to their strong vegetative growth in this period (Terry and McCants, 1970).

Across sampling intervals neither ammonium content (Table 5.1, 5.3, 5.5 and 5.7) nor the mean nitrate content (Table 5.2, 5.4, 5.6 and 5.8) to 100 cm depth was affected by the cropping systems employed at the four sites. However, the content of ammonium and nitrate both differed significantly between sampling intervals, indicating that cropping systems were inferior to sampling intervals concerning this interaction. Similarly, sampling intervals were superior to experimental sites concerning their interaction effects on the mean ammonium content to 100 cm soil depth (Table 5.9). This was not true for the mean nitrate content to 100 cm soil depth since both experimental sites and sampling intervals influenced this parameter significantly (Table 5.10).

There are thus several similarities and dissimilarities regarding the distribution of mineral N in the different soils of Uasin Gishu District in Kenia when various cropping systems are employed. This knowledge together with those evolved from crop yields and coinciding biomass N uptake is a clear confirmation that blanket N fertilizer recommendations for cropping in the district will not be sustainable in the long term. An effort should be made to establish guidelines for site-specific N recommendations taking into account differences in climate, soil and crops.

A small step in this direction was taken in 2007 by quantifying the N use efficiency of sole and intercropping systems in the Uasin Gishu District. The same experimental sites and cropping systems were used with a range of N fertilizer rates. This enables the estimation of yield, recovery and physiological efficiencies in the cropping systems.

For sole-cropped maize the best N yield efficiencies estimated per site ranged from 14 kg grain kg N applied^{-1} at Timboroa to 28 kg grain kg N applied^{-1} at Kaprobu (Table 6.1). In both instances 60 kg N ha^{-1} was applied. The equivalent kg grain kg N applied^{-1} ranges were 32 (Turbo with 30 kg N ha^{-1}) to 46 (Kaprobu with 60 kg N ha^{-1}) for sole-cropped wheat (Table 6.4), 1 (Illula with 60 kg N ha^{-1}) to 8.4 (Kaprobu with 60 kg N ha^{-1} for sole-cropped beans (Table 6.7), 19 (Turbo with 60 kg N ha^{-1}) to 30 (Illula with 30 kg N ha^{-1}) for intercropped maize (Table 6.10) and 0.01 (Timboroa with 60 kg N ha^{-1}) to 0.30 (Illula with 60 kg N ha^{-1}) for intercropped beans (Table 6.13).

A value of 24.2 kg grain kg N applied^{-1} for maize is globally accepted as a good N yield efficiency for maize (Prasad, 2009). The best N yield efficiency per site which ranged from 14 to 28 kg grain kg N applied^{-1} for sole-cropped maize and from 19 to 30 kg grain kg N applied^{-1} for intercropped maize is therefore largely representative of the global value.

Globally a value of 18.1 kg grain kg N applied^{-1} is regarded as a good N yield efficiency for wheat (Prasad, 2009). The range for the best N yield efficiency per site, namely 32 to 46 kg grain kg N applied^{-1} exceeded the global value.

In literature no value could be found for beans which is regarded as having a good N yield efficiency.

The best N recovery efficiency per site varied from 28% (Turbo with 60 kg N ha^{-1}) to 38% (Illula with 30 kg N ha^{-1}) for sole-cropped maize (Table 6.2). Equivalent ranges were 16% (Turbo with 80 kg N ha^{-1}) to 38% (Timboroa with 40 kg N ha^{-1}) for sole-cropped wheat (Table 6.5), 16% (Turbo with 50 kg N ha^{-1}) to 30% (Kaprobu and Illula with 50 kg N ha^{-1}) for sole-cropped beans (Table 6.8), 20% (Turbo with 60 kg N ha^{-1}) to 33% (Illula with 60 kg N ha^{-1}) for intercropped maize (Table 6.11), and 16% (Timboroa and Turbo with 25 kg N ha^{-1}) to 32% (Illula with 25 kg N ha^{-1}) for intercropped beans (Table 6.14).

Prasad (2009) is of the opinion that globally a N recovery efficiency of 65% and 57% can be regarded as good for maize and wheat, respectively. Thus the ranges of best N recovery efficiency per site were very low, viz. 20 to 38% for maize and 16 to 38% for wheat. No values for N recovery efficiency for beans could be found in the literature.

For sole-cropped maize the best physiological efficiency per site varied from 53 kg grain kg N uptake^{-1} at Timboroa with a rate of 60 kg N ha^{-1} to 133 kg grain kg N uptake^{-1} at Turbo with a rate of 30 kg N ha^{-1} (Table 6.3). The equivalent kg grain kg N uptake^{-1} ranges were 184 (Timboroa with 20 kg N ha^{-1}) to 240 (Illula with 40 kg N ha^{-1}) for sole-cropped wheat (Table 6.6), 9 (Timboroa with 50 kg N ha^{-1}) to 148 (Kaprobu with 100 kg N ha^{-1}) for sole-cropped beans (Table 6.9), 98 (Kaprobu with 60 kg N ha^{-1}) to 169 (Illula with 120 kg N ha^{-1}) for intercropped maize (Table 6.12), and 0.07 (Timboroa with 50 kg N ha^{-1}) to 0.56 (Illula with 50 kg N ha^{-1}) for intercropped beans (Table 6.15).

The ranges of best N physiological efficiency per site given above for either maize or wheat exceeded the global average values by far which are regarded as good by Prasad (2009), namely 36.7 kg grain kg N uptake^{-1} for maize and 28.9 kg grain kg N uptake^{-1} for wheat. No comparison for the N physiological efficiencies for beans in this study was possible for the same reason mentioned earlier.

The variation in yield, recovery and physiological efficiencies of applied N between the three crops can be ascribed to their distinct genetic characteristics. However, the variations in the mentioned N efficiencies for a crop can be attributed only to the climatic conditions, soil properties and management practices to which a crop was subjected to at each site. This is a further confirmation that an effort should be made to establish guidelines for site-specific N recommendations in the particular district.

In the development of guidelines for site-specific N recommendations in the Uasin Gishu District it must be kept in mind that there are almost no policies governing the use of N fertilizers apart from the N concentration in the manufactured compounds. Farmers have a choice from eight nitrogenous fertilizers depending on their availability. The fertilizers in decreasing order of their N concentration are: anhydrous ammonia (82%), urea (46%), calcium ammonium nitrate (28%), aqua ammonia (25%), ammonium sulphate (21%), diammonium phosphate (18%), calcium nitrate (15%) and mono-ammonium phosphate (11). However, the fertilizers commonly used by the majority of farmers in the district are calcium ammonium nitrate and/or diammonium phosphate on account of their availability. It is noteworthy that the fertilizer acquisition policy in Kenya is currently liberalized, hence the use of the mentioned fertilizers should depend on farmers' demands and ability to purchase them.

The inherent physical and chemical characteristics of the nitrogenous fertilizers should also be considered in the development of site-specific recommendation guidelines since their efficiency depends on proper management, e.g. rate, method and time of application. In this study on account of the field experiments conducted calcium ammonium nitrate and triple superphosphate were used as N and P sources, respectively.

7.3 Recommendations for consideration

Based on the synthesis of the results that evolved from this study the following recommendations could be considered for implementation by the agriculture industry of Uasin Gishu District in Kenya to improve productivity of annual crops and prevent degradation of natural resources over the long term:

- Propagate the production of crops that are best adapted to a particular agro-ecological zone in the district. From this study it was apparent that climatic conditions and/or soil properties had a large influence on crops' productivity.
- Preference should be given to sole-cropping instead of intercropping. In this study intercropping was inferior to sole-cropping with respect to yields.
- Rectify the fertility status of soils with regard to acidity and other essential plant nutrients like P, K, Ca and Mg which seems low in many instances. This should increase the efficient use of applied N even if rely on blanket recommendations.
- Avoid blanket recommendation of N fertilizer application for any of the three crops. The large variation in yield of a crop between sites does not justify this simple approach.

- Develop guidelines for site-specific N recommendations for a crop which taken into account climatic and soil differences and hence N demand by the specific crop. An approach like this should be beneficial for crops to realize their full potential at a site.
- Increase the rates of N application based on proper experimental data to meet the N demand of especially for maize and wheat crops. In many instances the biomass N uptake exceeded the blanket N application implying possible exhaustion of organic N reserves in the soils.
- Consider the use of ammonium-containing fertilizers rather than nitrate-containing fertilizers. The latter fertilizers are more susceptible to leaching.
- Introduce split application of N to avoid potential deficiency of this nutrient during strong vegetative growth of the crops. A remarkable decline in either ammonium and nitrate was detected in the upper 60 to 80 cm soil during this period.
- Research is warranted to quantify losses of fertilizer N as a result of leaching and denitrification properly. This will bring a better understanding of the dynamics and utilization of mineral N in the various agro-ecological zones of the district.

The Uasin Gishu District in Kenya has a high potential for cropping. This potential will not be realized without proper attention to the aspects that were raised above.

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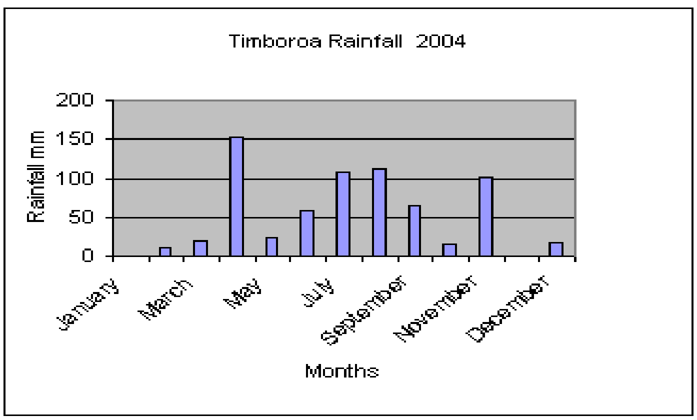
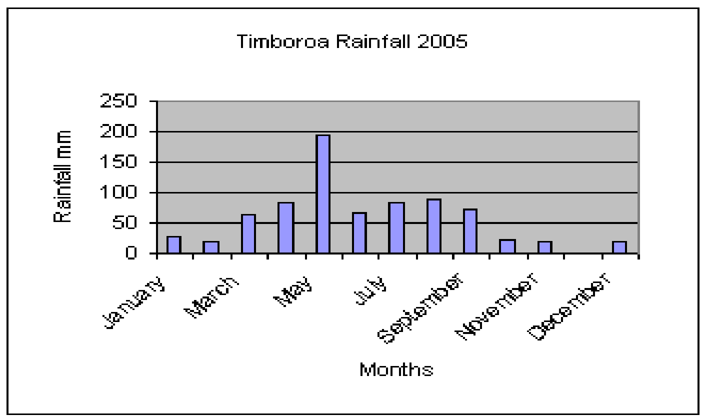
APPENDICES

Appendix 1: Rainfall recorded at the Timboroa, Kaprobu, Turbo and Illula sites for the years 2004 and 2005

Timboroa site

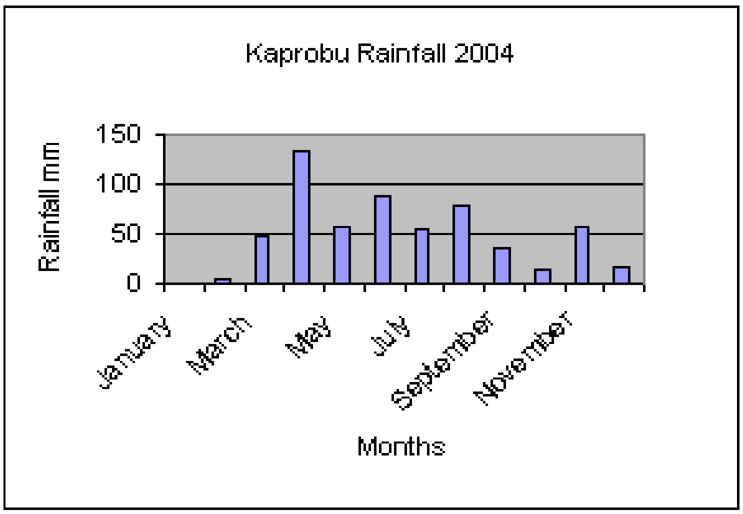
2004	mm	2005	mm
January	0	January	28.6
February	10.55	February	18.4
March	20.1	March	64
April	153.2	April	84.1
May	24.5	May	194.1
June	58.4	June	66.25
July	106.85	July	82.95
August	111.5	August	87.74
September	65.1	September	72.25
October	15.55	October	23.2
November	101.9	November	19.33
December	16.95	December	20.15
Total	684.33	Total	761.07
Mean	57.03	Mean	63.42

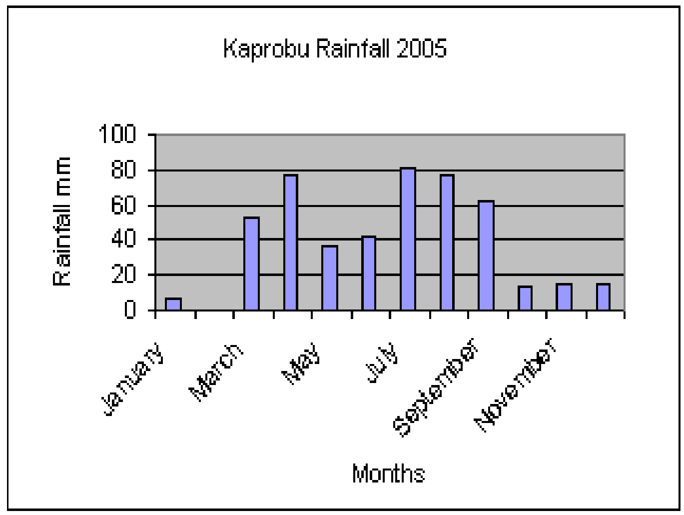




Kaprobu site

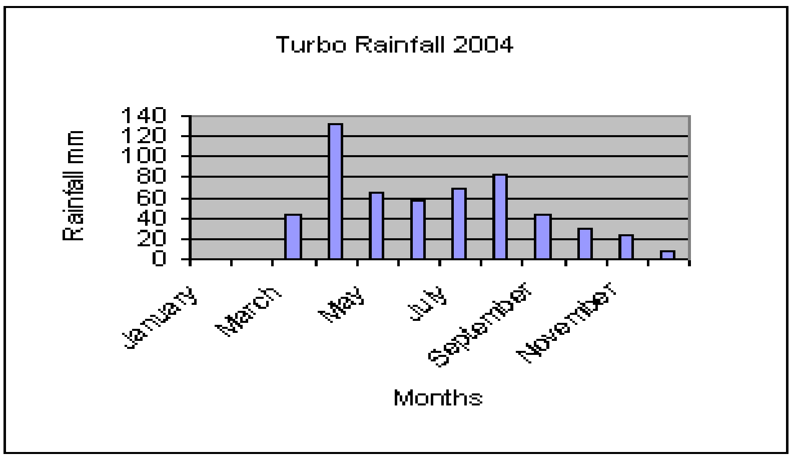
2004	mm	2005	mm
January	0	January	6.85
February	3.9	February	0
March	48.5	March	52.2
April	134.5	April	76.85
May	57.5	May	36.65
June	88.3	June	42.24
July	55.75	July	81.11
August	77.43	August	77.7
September	35.35	September	62.3
October	15.25	October	13.5
November	56.85	November	15.5
December	16.9	December	15.2
Total	590.23	Total	480.1
Mean	49.19	Mean	40.1

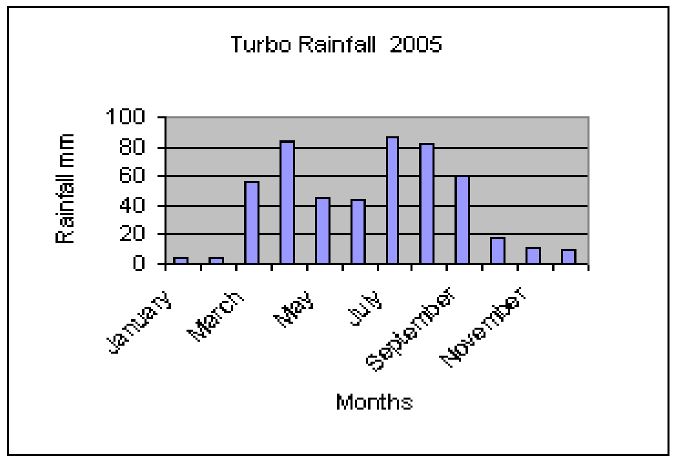




Turbo site

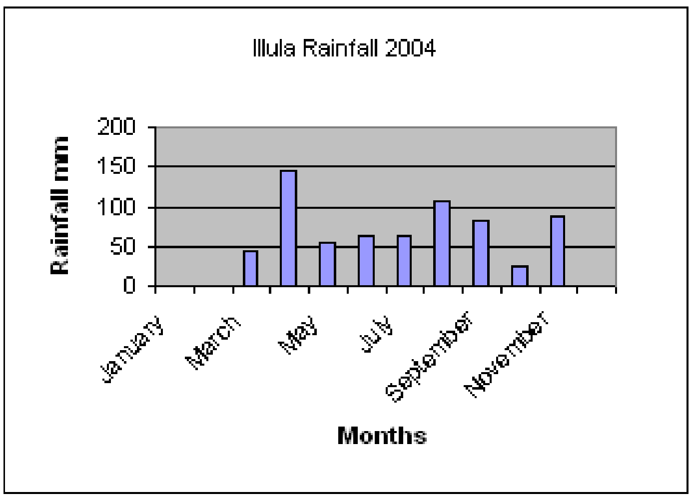
2004	mm	2005	mm
January	0	January	3.6
February	0	February	3.8
March	43	March	56.6
April	132.2	April	83
May	64.5	May	45.5
June	57.7	June	43.2
July	68.5	July	86.9
August	82.4	August	82.2
September	44.1	September	60
October	30.1	October	17.3
November	24.4	November	11
December	8.6	December	9.3
Total	555.5	Total	502.4
Mean	46.29	Mean	41.87

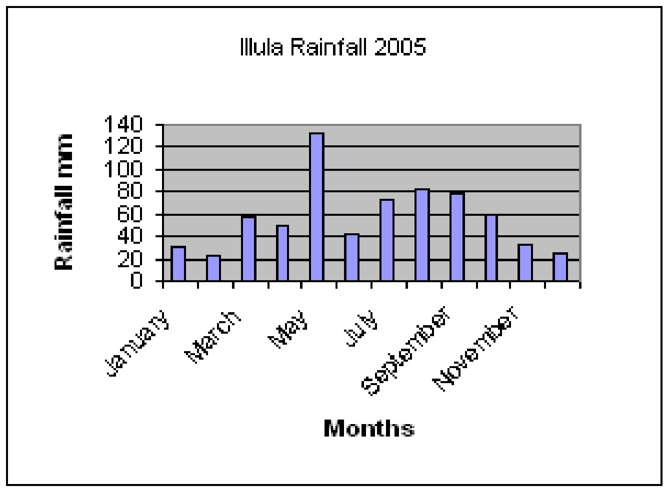




Illula site

2004	mm	2005	mm
January	0	January	30.15
February	1.3	February	23.65
March	44	March	58.4
April	145.4	April	49.1
May	54.45	May	132.4
June	64.25	June	41.65
July	62.8	July	73.3
August	107.65	August	82
September	82.4	September	79.3
October	23.65	October	58.6
November	88.05	November	32
December	0	December	25.6
Total	673.95	Total	677.15
Mean	56.16	Mean	56.43





Appendix 2: Nitrate and ammonium nitrogen contents measured under different cropping systems (M = sole-cropped maize; B = sole-cropped beans; I = intercropped maize and beans; W = sole-cropped wheat; and F = fallow) in the Humic Nitisol of Timboroa site, Rhodic Ferralsol of Kaprobu site, Orthic Acrisol of Turbo site and Mollic Gleysol of Illula site in 2004.

		Nitrate - N (mg kg^{-1})						Ammonium - N (mg kg^{-1})					
Sample	Depth (cm)	Day 0	Day 15	Day 30	Day 60	Day 90	Day 270	Day 0	Day 15	Day 30	Day 60	Day 90	Day 270
Timboroa site													
M-1	0-20	4.24	8.06	9.16	11.27	3.41	0.51	3.17	9.23	6.65	4.30	1.46	1.25
"	20-40	4.12	7.06	8.74	12.33	6.29	0.41	3.06	6.70	5.37	2.80	0.73	1.25
"	40-60	3.10	5.80	6.74	18.47	5.32	0.22	2.64	3.74	5.47	1.50	0.34	3.13
"	60-80	3.11	8.43	11.89	21.64	3.22	0.18	2.34	4.51	4.19	1.21	0.45	4.58
"	80-100	2.16	12.36	23.77	22.91	8.63	0.15	1.64	3.86	3.30	0.84	0.34	2.71
M-2	0-20	5.34	11.15	19.75	35.13	12.34	0.56	3.15	9.23	7.24	4.58	1.29	1.67
"	20-40	4.28	9.32	12.40	19.42	9.32	0.17	3.07	6.70	6.16	3.36	0.73	1.67
"	40-60	4.19	9.84	9.61	15.34	9.51	0.17	2.55	3.74	4.29	1.78	0.50	1.52
"	60-80	3.17	15.88	17.33	21.22	9.27	0.13	2.42	4.51	4.48	1.40	0.17	1.42
"	80-100	2.20	14.09	19.89	29.47	21.12	0.11	1.31	2.86	3.69	0.75	0.45	1.04
M-3	0-20	5.24	14.67	10.66	13.86	11.85	0.52	3.12	9.23	5.76	2.43	1.06	3.21
"	20-40	5.19	7.90	7.01	8.41	8.34	0.34	3.04	6.70	4.38	2.06	0.78	3.24
"	40-60	4.18	3.02	8.38	7.04	7.37	0.30	2.45	3.74	4.98	1.03	0.22	2.92
"	60-80	3.17	6.54	15.37	9.74	5.90	0.22	2.24	4.51	3.10	0.93	0.50	2.29
"	80-100	3.18	11.84	12.85	14.23	8.63	0.17	1.45	2.86	3.69	0.84	0.62	0.63
B-1	0-20	4.35	9.79	9.14	8.62	16.59	1.18	3.07	2.35	3.69	2.90	0.73	1.67
"	20-40	4.27	8.06	6.19	6.46	8.73	0.45	3.10	2.20	4.29	2.62	0.56	1.52
"	40-60	4.19	3.75	4.59	5.66	3.41	0.42	2.55	1.87	4.09	1.96	0.73	1.88
"	60-80	3.19	3.54	5.50	14.97	5.56	0.35	1.47	1.32	3.69	1.31	0.45	1.56
"	80-100	2.18	14.78	11.71	16.19	7.46	0.38	1.23	0.88	3.60	0.84	0.62	1.59
B-2	0-20	5.27	13.32	16.37	18.20	12.88	0.26	3.66	3.08	5.96	2.90	1.23	3.42
"	20-40	5.20	7.59	16.74	10.58	14.00	0.17	3.31	2.42	4.78	2.62	0.45	3.41
"	40-60	4.17	7.17	16.23	9.52	8.78	0.17	2.40	1.54	3.40	1.68	0.39	3.35
"	60-80	4.22	14.72	17.10	20.63	13.46	0.15	2.14	1.21	4.09	1.40	0.17	3.33
"	80-100	2.34	19.19	17.05	16.14	13.12	0.18	1.53	1.10	2.71	1.21	0.28	2.21
B-3	0-20	4.31	6.12	12.44	15.98	12.93	0.30	3.70	7.58	3.89	2.43	1.06	2.29
"	20-40	4.32	6.90	8.70	12.01	8.98	0.28	3.54	3.30	3.60	2.24	0.56	3.54
"	40-60	3.22	3.28	10.62	6.08	8.73	0.23	2.23	2.09	3.30	1.96	0.56	2.42
"	60-80	2.28	12.05	12.23	12.43	11.76	0.22	1.85	1.87	4.88	1.87	0.22	1.46
"	80-100	2.21	12.68	12.81	14.02	11.32	0.24	1.45	1.43	5.17	0.93	0.28	0.83
I-1	0-20	4.41	8.53	14.73	13.33	7.61	1.01	3.22	4.07	5.57	3.46	0.90	1.88
"	20-40	3.58	7.85	10.34	9.26	4.20	0.22	2.78	2.64	4.19	1.68	0.62	2.92
"	40-60	3.29	4.65	6.23	9.26	6.63	0.20	2.41	2.09	4.68	1.78	0.28	2.92
"	60-80	3.11	7.27	13.95	15.93	6.10	0.18	1.39	1.98	2.71	1.50	0.62	3.75
"	80-100	3.06	11.10	16.32	12.70	7.76	0.16	2.65	1.21	3.50	1.40	0.45	1.67
I-2	0-20	4.19	8.53	10.16	8.68	5.49	1.74	2.31	4.07	6.95	2.71	1.40	1.88
"	20-40	4.06	7.85	8.65	9.79	8.68	0.33	2.06	2.64	5.96	1.96	0.95	2.17
"	40-60	3.87	4.65	5.50	6.98	6.95	0.31	1.59	2.09	3.30	1.21	0.45	0.63
"	60-80	3.17	7.27	9.47	6.67	4.41	0.29	1.04	1.98	2.91	1.12	0.62	0.23
"	80-100	3.03	11.10	13.68	14.76	12.22	0.25	3.25	1.21	3.50	0.93	0.56	0.14
I-3	0-20	4.23	9.58	10.48	21.16	12.63	0.75	3.17	9.89	5.76	3.08	2.07	2.92
"	20-40	4.09	8.41	12.44	13.97	11.76	0.79	2.62	9.34	5.67	1.78	1.57	2.67
"	40-60	3.65	7.06	6.23	6.19	7.80	0.65	2.44	5.93	7.64	1.50	1.46	1.88

"	60-80	3.27	4.96	3.77	7.51	3.61	0.68	2.23	4.51	3.40	1.12	1.01	1.52
"	80-100	2.21	13.78	8.33	8.15	7.17	0.67	3.34	2.75	3.60	0.84	0.73	1.04
W-1	0-20	5.47	16.51	14.86	29.05	22.29	3.26	3.25	4.51	6.55	3.46	1.57	3.45
"	20-40	4.63	11.73	16.14	18.41	19.61	2.87	2.58	2.75	6.85	2.62	1.40	3.33
"	40-60	4.48	6.38	9.20	18.41	15.95	0.73	2.38	2.42	4.98	2.52	0.73	0.21
"	60-80	3.35	12.20	20.48	18.68	15.90	0.60	1.49	1.76	3.10	1.87	0.90	0.63
"	80-100	2.20	18.14	24.13	18.73	16.59	0.55	3.51	1.54	3.69	0.84	0.73	2.92
W-2	0-20	4.42	17.14	19.61	21.16	15.12	1.29	3.47	5.82	5.37	2.34	0.90	2.08
"	20-40	4.65	7.85	7.37	18.73	8.78	1.24	2.66	3.08	4.88	1.68	0.50	2.29
"	40-60	3.96	9.58	11.76	13.39	16.83	1.22	2.48	2.31	5.27	1.40	0.84	1.88
"	60-80	3.55	12.15	12.49	21.80	21.32	1.18	1.56	2.20	3.00	1.31	0.78	0.83
"	80-100	3.58	12.94	17.47	23.65	21.76	1.19	3.35	1.98	4.78	1.21	0.50	0.42
W-3	0-20	5.67	11.15	11.39	20.63	22.10	1.12	3.04	3.85	7.93	3.18	1.79	2.71
"	20-40	4.82	7.06	12.53	13.92	17.07	1.12	2.74	3.08	7.64	2.71	1.01	2.51
"	40-60	4.42	6.59	9.20	7.83	8.00	0.67	2.34	2.53	4.09	2.15	1.06	0.63
"	60-80	2.58	14.93	14.86	7.09	10.15	0.60	1.46	2.42	3.40	1.21	0.95	1.25
"	80-100	2.55	18.92	21.16	11.53	15.27	0.56	3.56	9.12	3.69	0.84	0.95	0.21
F-1	0-20	4.85	8.22	10.71	27.99	14.73	1.81	3.47	4.95	5.17	3.74	1.51	3.96
"	20-40	4.38	7.32	12.03	11.11	14.54	1.67	2.63	3.30	4.19	1.78	1.06	3.54
"	40-60	4.56	7.22	11.58	13.17	18.78	1.24	2.77	2.42	4.48	1.59	1.12	2.71
"	60-80	3.78	17.03	13.81	24.02	28.20	1.18	2.08	2.75	3.10	1.12	0.84	2.29
"	80-100	2.15	18.71	19.25	32.12	27.21	1.12	3.73	2.42	3.99	0.93	0.62	0.21
F-2	0-20	4.93	10.21	15.91	22.28	19.17	0.94	3.41	4.29	6.65	2.61	1.90	3.79
"	20-40	4.31	11.10	12.26	16.08	14.34	0.81	2.56	8.02	6.55	1.96	1.06	1.46
"	40-60	3.64	6.17	11.30	15.87	17.41	0.56	2.33	6.37	4.88	1.21	0.73	0.63
"	60-80	3.22	18.35	13.31	16.77	19.37	0.58	1.58	6.26	3.50	1.03	0.62	0.42
"	80-100	2.66	22.81	12.12	15.87	24.24	0.37	3.56	4.73	5.17	0.93	0.84	1.25
F-3	0-20	4.08	9.84	13.17	12.22	17.32	0.51	3.41	6.59	8.13	2.62	1.62	3.13
"	20-40	4.15	9.53	12.21	17.41	14.24	0.40	2.68	7.47	5.96	2.06	1.29	2.92
"	40-60	3.75	6.48	12.40	9.42	7.71	0.28	2.48	6.15	3.30	1.68	0.95	1.04
"	60-80	2.43	6.69	13.81	12.01	6.54	0.23	1.78	8.13	2.61	1.59	0.78	1.88
"	80-100	2.13	13.31	15.73	22.54	15.02	1.01	1.53	6.92	3.40	1.12	0.95	0.42
Kaprobu site													
M-1	0-20	4.41	11.26	15.31	11.20	5.38	0.66	3.45	10.51	2.57	6.86	3.27	3.23
"	20-40	4.40	7.89	14.13	10.37	5.04	0.63	3.12	7.58	2.94	7.81	4.59	3.64
"	40-60	3.36	4.79	16.53	9.15	3.87	0.53	3.02	5.22	2.48	5.24	3.06	3.03
"	60-80	3.33	3.53	13.01	8.28	4.03	0.71	2.88	4.21	1.93	4.38	2.76	2.22
"	80-100	2.31	3.37	12.85	7.93	4.37	0.78	1.75	1.74	1.56	3.14	2.65	1.21
M-2	0-20	5.42	13.16	5.15	7.53	5.63	0.76	3.43	12.42	1.38	2.19	3.16	2.42
"	20-40	4.39	4.84	4.08	7.14	4.45	0.73	3.39	8.71	2.84	1.43	5.31	3.64
"	40-60	4.37	4.26	3.65	6.57	5.38	0.66	2.64	6.01	1.74	1.71	3.98	3.85
"	60-80	3.31	4.00	4.08	5.26	5.00	0.66	2.28	3.09	1.10	1.62	2.55	2.42
"	80-100	3.27	4.37	3.68	5.61	4.12	2.03	1.23	2.87	1.01	1.10	3.47	1.82
M-3	0-20	4.40	15.68	5.85	3.86	5.13	1.71	3.37	8.03	2.39	2.29	4.18	1.41
"	20-40	4.34	14.21	8.13	5.31	3.28	1.66	3.22	4.33	3.03	0.86	3.88	1.01
"	40-60	4.29	9.05	4.93	5.61	3.87	0.93	2.44	1.97	2.39	0.76	3.78	1.12
"	60-80	3.23	4.26	2.27	3.56	5.04	0.66	2.14	1.52	1.83	0.57	3.47	2.42
"	80-100	2.21	3.74	2.27	2.99	4.71	1.53	1.75	1.74	1.74	0.29	2.86	3.64
B-1	0-20	4.44	12.11	7.23	7.23	8.99	1.23	3.46	12.08	2.48	1.71	3.88	3.64
"	20-40	4.39	17.63	8.03	6.79	8.92	0.73	3.26	11.29	2.66	1.52	4.90	2.02
"	40-60	3.38	11.95	8.56	6.97	8.50	0.72	2.68	7.58	1.93	0.67	3.88	1.82
"	60-80	3.28	7.74	5.20	7.10	7.65	0.47	2.34	4.78	1.19	0.48	3.88	1.01

"	80-100	3.19	6.84	5.25	11.77	15.21	1.44	1.58	2.19	1.74	0.38	3.06	2.04
B-2	0-20	5.44	9.58	4.83	4.78	9.66	1.23	3.55	6.12	2.29	2.00	3.27	2.83
"	20-40	4.41	13.26	5.69	6.40	5.13	0.84	3.25	7.92	2.48	1.33	3.88	3.23
"	40-60	4.38	7.47	6.05	5.92	5.87	0.74	2.48	9.49	2.20	0.86	4.69	2.02
"	60-80	3.33	4.37	3.97	4.25	5.46	0.47	2.31	4.10	1.38	0.67	2.76	2.85
"	80-100	3.21	3.74	3.52	4.52	4.71	0.28	1.67	3.99	1.19	0.57	2.96	2.05
B-3	0-20	4.37	7.00	4.59	6.48	4.20	1.78	3.56	15.11	1.56	1.33	3.47	3.18
"	20-40	4.40	9.42	4.20	5.17	7.90	0.82	3.44	10.62	1.93	1.05	4.18	2.73
"	40-60	4.35	4.00	3.96	8.67	9.24	0.53	2.20	11.07	1.47	0.76	2.76	2.43
"	60-80	3.28	3.00	3.64	8.06	9.11	0.41	1.85	7.47	1.10	0.48	2.55	1.25
"	80-100	2.14	2.79	11.15	14.39	11.43	0.41	1.46	12.30	0.92	0.29	2.86	2.63
I-1	0-20	5.38	12.11	3.28	7.53	6.64	2.87	3.38	14.33	1.38	1.24	3.06	1.41
"	20-40	5.23	16.58	3.23	7.93	4.03	2.84	3.07	12.64	1.19	1.43	3.98	3.06
"	40-60	4.48	7.05	2.85	8.36	3.19	1.61	2.58	10.39	1.38	0.95	4.69	3.45
"	60-80	3.11	4.11	2.00	5.00	2.44	1.53	2.21	3.20	1.28	0.19	3.47	2.63
"	80-100	3.08	3.11	2.48	8.62	3.87	0.53	1.54	1.74	1.38	0.10	2.04	2.83
I-2	0-20	4.41	9.42	1.73	7.53	5.63	2.78	3.50	7.64	1.01	1.05	1.94	2.22
"	20-40	4.04	6.16	2.96	6.57	3.95	1.84	3.35	5.45	1.38	1.14	3.27	3.43
"	40-60	3.28	6.74	7.92	7.10	1.26	0.59	2.71	2.53	1.38	1.43	3.47	1.41
"	60-80	3.30	4.63	4.47	3.78	1.93	0.53	2.34	2.08	1.01	0.19	3.27	2.83
"	80-100	3.25	4.95	0.72	3.21	2.94	0.22	1.58	2.42	0.92	0.57	1.02	0.61
I-3	0-20	4.67	9.53	2.21	4.61	1.84	2.87	3.61	6.16	1.28	1.90	1.84	1.72
"	20-40	4.54	10.42	1.57	4.17	1.60	1.34	2.64	5.90	1.28	1.43	4.90	1.41
"	40-60	3.58	6.95	1.36	5.09	3.78	0.79	2.47	6.69	1.10	0.95	2.65	3.64
"	60-80	3.23	4.47	3.33	5.48	4.12	0.56	2.03	4.89	0.64	0.76	2.14	3.03
"	80-100	3.00	3.63	2.67	3.25	1.85	0.55	1.55	3.09	0.83	0.57	1.94	1.41
W-1	0-20	5.40	11.74	4.72	9.06	6.22	2.53	3.52	7.58	1.19	1.43	3.78	2.05
"	20-40	5.29	9.74	3.44	10.56	7.31	2.28	3.22	5.00	3.21	0.86	4.18	2.25
"	40-60	4.92	6.05	5.31	14.56	7.90	1.22	2.58	3.09	1.38	0.67	2.86	1.46
"	60-80	3.52	4.63	2.05	10.90	4.45	1.13	2.43	2.75	0.92	0.48	2.96	3.27
"	80-100	2.31	6.95	2.59	10.72	4.03	1.11	1.30	2.87	0.83	0.29	2.35	3.84
W-2	0-20	4.95	11.79	5.79	9.89	3.95	2.39	3.77	8.82	2.20	2.10	1.84	2.83
"	20-40	4.75	12.05	6.59	7.53	4.29	1.42	3.54	6.35	1.10	1.52	3.06	3.84
"	40-60	3.77	5.00	4.03	5.96	5.63	1.12	2.51	4.87	1.01	0.95	2.76	3.84
"	60-80	3.31	4.11	5.09	8.84	8.07	1.03	2.38	2.53	0.55	0.95	2.45	2.04
"	80-100	5.20	3.95	2.64	5.92	7.56	0.66	1.84	2.42	0.64	0.76	3.37	2.42
W-3	0-20	4.82	12.68	4.24	9.54	5.38	2.97	3.53	7.25	3.69	0.95	3.78	3.03
"	20-40	3.72	14.11	7.01	6.53	10.92	1.88	3.27	4.78	2.66	0.76	2.76	1.21
"	40-60	3.29	6.84	7.07	7.31	7.39	1.56	2.58	3.31	1.19	0.67	4.08	1.18
"	60-80	3.15	6.11	7.87	6.14	8.10	1.52	2.23	2.75	0.92	0.48	3.27	2.83
"	80-100	2.72	3.63	3.44	6.66	7.56	0.69	1.65	1.63	0.37	0.38	3.27	2.42
F-1	0-20	4.37	13.16	12.00	12.90	12.02	0.88	3.52	12.08	0.55	3.05	3.88	2.85
"	20-40	4.28	13.58	11.67	13.21	14.32	0.64	3.21	9.16	1.65	2.19	3.57	1.62
"	40-60	3.79	7.68	17.89	17.97	14.52	0.53	2.76	5.45	0.92	2.10	3.27	1.61
"	60-80	3.21	6.32	13.41	15.22	17.73	0.53	2.33	4.10	0.46	0.86	3.67	1.01
"	80-100	2.55	6.05	9.04	13.52	13.53	0.33	1.81	5.11	0.28	0.48	1.73	1.82
F-2	0-20	4.46	7.79	5.47	10.11	5.46	0.65	3.49	2.98	1.74	2.48	3.67	2.63
"	20-40	4.39	5.37	4.61	11.11	9.34	0.59	3.29	4.94	0.55	1.81	2.55	1.62
"	40-60	4.32	3.58	3.07	10.76	10.00	0.34	2.75	6.35	0.37	1.52	2.35	1.82
"	60-80	3.28	1.89	4.67	8.76	6.64	0.31	2.34	5.00	0.46	1.14	3.98	2.22
"	80-100	2.78	1.84	3.60	4.91	4.20	0.28	1.74	2.98	0.64	0.76	2.45	2.02
F-3	0-20	5.40	8.95	4.19	7.05	7.82	0.34	3.55	12.98	1.01	2.57	3.67	1.62
"	20-40	4.33	9.26	4.67	12.07	11.18	0.32	3.28	8.60	2.57	2.29	3.37	1.82

"	40-60	4.27	6.84	7.23	12.29	10.76	0.16	2.74	9.83	2.75	1.24	3.78	1.61
"	60-80	3.21	5.32	3.65	11.11	11.76	0.18	2.28	5.45	2.75	0.86	3.57	1.67
"	80-100	3.18	0.58	2.53	8.71	7.56	0.15	1.56	4.10	2.57	0.67	3.67	1.21
Turbo site													
M-1	0-20	4.05	7.75	4.01	5.04	1.45	0.65	2.56	2.75	4.64	5.21	3.01	1.08
"	20-40	3.64	7.25	7.05	5.14	1.23	0.47	2.32	3.40	4.28	4.28	1.97	2.12
"	40-60	3.23	6.98	9.11	5.19	0.94	0.48	2.14	4.31	4.10	3.04	1.73	2.32
"	60-80	2.27	5.11	10.17	5.35	0.56	0.44	1.44	3.01	3.29	3.19	2.13	2.12
"	80-100	1.46	3.74	6.79	6.17	0.98	0.27	1.04	4.18	2.57	1.48	0.44	1.16
M-2	0-20	4.08	6.87	5.13	4.22	0.89	0.26	2.46	2.48	3.56	4.36	1.65	1.12
"	20-40	3.52	10.49	6.79	6.02	0.88	0.65	2.34	2.75	3.85	4.12	2.05	1.32
"	40-60	3.47	8.96	8.31	6.48	0.73	0.43	2.25	4.05	4.46	2.57	2.37	2.44
"	60-80	2.45	3.52	10.63	7.76	3.09	0.32	1.56	3.92	5.27	2.26	1.33	2.55
"	80-100	2.08	5.11	11.09	9.20	3.09	0.66	1.07	3.27	5.00	2.41	1.65	1.82
M-3	0-20	3.85	8.24	4.34	2.67	0.75	0.72	2.57	5.10	6.08	2.60	1.73	1.22
"	20-40	3.55	9.67	8.05	6.58	0.56	0.61	2.47	3.27	4.91	2.57	2.69	1.26
"	40-60	2.70	8.46	9.64	7.40	4.31	0.78	2.32	3.66	4.73	1.71	2.05	3.32
"	60-80	2.65	6.81	5.66	7.51	6.32	0.64	2.05	2.88	3.11	1.56	1.08	2.22
"	80-100	1.35	5.66	4.21	5.55	0.66	0.44	1.58	2.48	2.84	1.63	1.65	1.46
B-1	0-20	4.24	5.60	5.93	5.19	3.65	2.63	2.56	3.40	4.01	2.02	2.29	1.51
"	20-40	3.62	9.07	4.27	8.79	3.00	2.57	2.41	3.40	5.27	3.66	2.93	2.08
"	40-60	3.23	9.78	7.12	10.90	5.90	2.14	2.21	4.05	4.64	1.32	1.33	2.57
"	60-80	2.55	6.98	9.50	8.48	2.67	1.55	1.66	3.01	3.74	2.02	1.73	2.38
"	80-100	2.14	4.45	9.17	7.40	4.82	0.69	1.41	2.75	2.57	2.02	2.05	2.36
B-2	0-20	3.22	4.95	5.00	2.52	5.29	2.05	2.86	2.75	3.56	3.35	2.53	2.57
"	20-40	3.19	7.31	5.20	2.31	4.82	2.13	2.56	3.92	5.09	3.11	3.17	2.56
"	40-60	2.18	7.25	6.46	3.55	7.03	1.91	2.12	3.27	4.82	2.18	2.53	1.36
"	60-80	2.05	7.42	10.89	3.91	6.70	1.82	1.74	3.27	2.48	1.48	2.13	1.18
"	80-100	1.68	6.37	8.11	3.24	4.42	1.78	2.66	3.27	3.11	1.79	1.65	1.26
B-3	0-20	4.22	6.70	4.93	3.55	3.65	2.74	2.46	3.01	4.46	3.58	2.62	1.24
"	20-40	4.12	7.33	5.26	5.50	3.19	2.48	2.35	4.97	4.19	3.27	2.85	1.06
"	40-60	3.82	8.35	6.26	8.84	3.14	1.66	1.70	3.92	4.01	1.25	1.65	2.71
"	60-80	3.17	5.05	5.93	8.12	2.30	1.43	1.34	2.35	5.00	1.71	1.73	2.28
"	80-100	2.73	4.45	4.01	5.04	0.66	0.71	2.55	3.01	3.56	1.17	1.33	2.14
I-1	0-20	4.51	11.48	4.54	1.59	2.01	1.94	2.36	3.84	5.27	2.88	1.65	1.15
"	20-40	4.41	11.12	8.38	2.21	1.73	1.93	2.25	4.05	4.37	3.04	1.73	1.12
"	40-60	3.34	7.86	9.76	5.55	4.22	1.92	2.05	3.01	4.28	2.02	2.21	1.08
"	60-80	2.85	4.40	9.64	5.81	5.15	1.85	1.45	3.53	3.20	1.32	1.73	2.16
"	80-100	2.20	5.38	9.50	4.22	3.84	1.56	2.56	3.58	3.56	1.09	1.16	2.23
I-2	0-20	4.45	13.19	4.74	5.86	1.69	2.23	2.32	3.92	4.46	2.65	3.57	2.12
"	20-40	4.23	11.98	7.12	6.63	1.41	2.21	2.12	3.53	4.37	2.80	3.33	2.14
"	40-60	3.61	11.04	5.60	9.20	1.87	1.16	1.58	5.10	3.11	2.33	1.24	3.16
"	60-80	3.32	9.54	7.19	6.68	3.84	1.05	1.44	5.20	2.30	1.32	2.29	3.16
"	80-100	2.21	4.95	9.24	3.44	3.14	1.05	2.52	5.49	4.10	1.32	2.53	2.23
I-3	0-20	4.34	9.56	4.21	2.87	0.74	2.22	2.43	4.84	4.28	4.12	4.30	2.34
"	20-40	3.77	12.20	6.92	3.55	0.52	2.17	2.28	6.01	4.10	1.25	2.37	1.67
"	40-60	3.36	10.22	7.05	7.66	1.08	1.89	2.06	4.84	3.56	2.65	2.29	1.78
"	60-80	2.56	6.37	6.19	6.99	0.89	1.77	1.64	3.66	2.93	2.02	2.61	1.77
"	80-100	2.30	5.16	4.14	8.07	4.36	1.59	3.04	5.10	4.91	2.33	2.69	2.22
W-1	0-20	4.54	7.03	8.31	5.76	7.26	2.13	2.64	3.14	5.18	3.11	2.53	2.12
"	20-40	3.73	5.93	3.87	4.68	5.57	2.05	2.35	4.58	3.83	3.19	3.01	2.12
"	40-60	3.73	5.93	3.87	4.68	5.57	2.05	2.35	4.58	3.83	3.19	3.01	2.12
"	60-80	3.35	3.46	4.07	6.43	4.54	1.64	2.13	2.88	4.91	2.65	2.69	3.02

"	80-100	2.28	2.92	5.07	5.86	3.89	1.53	1.48	4.71	3.38	1.63	2.29	3.02
W-2	0-20	4.33	8.79	6.85	5.81	3.23	3.67	2.56	3.40	2.75	3.81	5.02	3.12
"	20-40	3.86	11.92	10.03	6.58	3.14	3.65	2.33	6.01	4.46	3.89	3.41	1.12
"	40-60	3.61	10.22	7.85	8.17	2.86	1.44	2.21	3.92	4.55	1.56	2.93	2.33
"	60-80	3.22	7.03	7.91	7.56	3.57	1.32	1.48	2.88	3.20	2.33	2.93	2.22
"	80-100	2.03	5.88	6.79	5.96	4.02	1.27	3.28	4.71	3.56	1.56	2.37	1.34
W-3	0-20	4.56	18.35	6.85	13.11	3.56	2.42	2.58	3.40	3.83	1.95	3.17	1.75
"	20-40	4.34	19.29	6.79	12.34	3.50	2.22	2.36	4.18	6.08	3.42	2.93	2.25
"	40-60	3.56	11.70	5.20	9.82	4.12	0.71	2.25	3.40	4.46	3.04	3.25	2.18
"	60-80	3.38	5.38	6.06	4.99	2.62	0.59	1.65	3.53	5.00	2.57	2.69	2.38
"	80-100	2.30	4.29	6.66	4.83	2.15	0.56	2.66	4.18	3.56	1.79	3.17	2.26
F-1	0-20	4.21	5.55	6.13	1.13	2.67	3.34	2.48	4.97	4.64	2.33	3.33	3.04
"	20-40	3.69	5.93	6.19	1.89	2.10	3.23	2.32	3.92	2.75	1.17	2.69	3.04
"	40-60	3.42	6.10	5.00	1.75	2.15	2.65	1.68	3.53	3.29	1.01	3.09	2.34
"	60-80	2.52	5.82	6.32	2.57	2.28	1.84	1.45	2.61	3.74	0.78	2.37	2.36
"	80-100	2.05	7.53	6.06	2.72	3.56	1.57	2.58	3.14	2.75	0.47	2.45	2.24
F-2	0-20	4.23	9.01	7.12	2.78	1.93	2.47	2.47	4.44	5.18	2.72	3.98	3.02
"	20-40	4.15	12.91	6.19	6.22	1.55	2.43	2.31	4.31	4.46	2.49	3.17	3.04
"	40-60	3.79	11.37	7.58	5.81	1.55	1.27	1.60	4.58	6.08	2.26	2.93	2.57
"	60-80	3.35	7.58	6.46	5.40	2.70	1.27	1.32	5.10	4.10	1.25	3.49	2.51
"	80-100	2.24	5.71	6.39	4.78	0.33	0.75	3.21	3.66	4.10	1.25	3.25	2.53
F-3	0-20	5.02	17.91	4.27	3.34	1.03	3.89	2.75	5.36	3.65	0.47	3.73	3.04
"	20-40	4.67	14.78	5.13	7.35	1.73	1.48	2.46	4.84	4.64	3.19	3.33	1.57
"	40-60	4.22	11.37	5.20	9.82	2.62	0.71	2.43	4.44	5.00	2.65	3.25	1.57
"	60-80	3.55	9.56	7.12	7.10	4.40	0.71	1.81	3.79	3.47	2.10	2.69	1.65
"	80-100	3.35	7.09	8.18	5.60	8.76	0.67	1.42	6.01	4.01	3.97	2.61	1.65
Illula site													
M-1	0-20	5.22	8.62	7.03	4.42	7.21	3.35	3.23	10.05	10.60	5.63	3.14	1.43
"	20-40	3.21	5.66	4.27	3.14	8.06	2.81	2.34	8.91	7.47	3.57	2.62	3.47
"	40-60	2.32	4.58	2.05	2.65	10.85	1.99	1.45	6.15	1.57	2.54	4.29	2.14
"	60-80	1.45	2.17	1.38	6.14	2.34	1.82	1.25	8.45	1.11	3.65	5.97	1.57
"	80-100	0.85	1.51	0.76	2.95	1.89	0.52	0.56	4.66	1.01	1.75	9.11	1.57
M-2	0-20	4.33	7.80	0.93	4.37	2.79	2.64	3.44	13.51	8.39	5.63	11.20	1.75
"	20-40	3.36	5.14	0.93	2.85	2.19	1.64	2.35	12.70	5.32	2.38	6.39	2.95
"	40-60	0.45	0.90	1.10	3.54	2.49	1.06	1.35	6.26	3.50	2.78	5.24	3.26
"	60-80	0.34	0.74	1.78	3.69	2.04	0.23	1.14	3.16	3.04	1.75	4.82	3.24
"	80-100	0.21	0.54	1.21	2.80	2.64	0.21	0.46	3.74	1.75	0.63	3.98	2.19
M-3	0-20	4.58	10.56	6.58	3.83	3.73	1.62	3.36	16.03	8.94	8.65	4.50	2.14
"	20-40	2.30	3.71	5.73	2.46	1.79	1.55	2.23	8.79	8.11	5.33	3.25	1.81
"	40-60	0.53	0.79	1.10	2.06	1.79	1.15	1.48	5.06	4.06	2.06	5.65	1.76
"	60-80	0.22	0.59	0.82	2.36	2.14	0.65	0.85	4.89	3.04	2.06	6.07	2.29
"	80-100	0.12	0.43	1.95	2.26	1.94	0.45	0.34	4.43	2.76	1.75	7.85	2.29
B-1	0-20	4.33	8.82	5.40	3.19	10.55	3.88	3.66	14.89	5.66	3.41	6.18	2.61
"	20-40	2.24	4.07	0.37	1.72	2.29	2.96	2.46	6.84	3.69	2.78	6.60	1.33
"	40-60	0.56	1.51	0.48	1.92	1.84	1.62	1.49	4.66	3.50	2.62	6.49	1.36
"	60-80	0.46	2.43	0.37	1.72	1.59	1.57	0.67	5.92	2.86	1.90	6.49	2.52
"	80-100	0.32	1.20	0.82	2.01	1.79	1.23	0.45	7.41	3.69	1.75	5.13	3.05
B-2	0-20	3.35	7.95	2.85	4.37	15.12	3.34	3.68	16.95	7.93	5.71	4.50	3.43
"	20-40	1.62	4.17	1.21	2.46	2.64	2.48	2.34	10.75	6.82	3.10	5.03	3.05
"	40-60	0.54	2.79	0.54	2.26	1.94	2.05	1.23	5.34	4.24	2.86	4.08	2.48

"	60-80	0.37	0.23	0.82	2.95	1.59	1.29	0.70	6.15	3.23	2.62	3.73	3.62
"	80-100	0.24	0.13	0.88	2.31	1.79	0.15	0.31	6.49	2.95	2.59	3.46	3.81
B-3	0-20	2.34	3.35	8.73	3.73	5.27	1.44	3.54	19.14	12.53	5.71	5.65	3.76
"	20-40	0.45	0.38	1.78	1.67	3.48	1.37	2.15	9.37	6.73	3.25	4.19	3.24
"	40-60	0.32	0.33	1.16	2.21	2.64	1.33	1.15	6.15	3.13	2.14	4.40	3.05
"	60-80	0.21	0.33	0.59	1.87	2.94	0.75	0.72	5.11	2.21	1.87	4.19	2.67
"	80-100	0.22	0.23	1.95	2.51	2.64	0.61	0.42	5.80	2.12	1.67	4.82	3.62
I-1	0-20	2.24	3.35	8.20	2.46	3.13	1.81	3.63	19.14	5.71	4.76	2.72	3.14
"	20-40	2.03	0.38	7.77	1.47	3.18	0.91	2.15	9.37	8.48	1.67	4.08	2.93
"	40-60	0.44	0.33	0.71	2.11	3.08	0.83	1.22	6.15	3.04	1.35	4.71	2.29
"	60-80	0.23	0.33	1.16	2.80	3.88	0.58	0.65	5.11	2.30	1.75	2.62	1.93
"	80-100	0.15	0.23	1.33	2.75	4.03	0.38	0.42	5.80	1.66	1.67	3.04	1.71
I-2	0-20	4.56	17.52	2.85	4.28	3.63	2.51	3.45	15.23	9.12	9.21	2.51	1.59
"	20-40	3.55	5.70	0.37	2.31	2.69	2.13	2.34	7.07	5.35	1.67	4.92	2.19
"	40-60	0.06	1.51	0.25	1.92	2.79	0.84	1.46	5.69	1.84	1.51	3.46	3.24
"	60-80	0.04	0.59	0.48	2.56	2.49	0.38	0.82	5.00	2.58	0.95	0.84	1.71
"	80-100	0.04	0.23	0.99	2.51	3.28	0.38	0.55	4.54	1.75	0.48	0.72	1.57
I-3	0-20	4.45	10.05	0.42	2.90	3.83	3.52	3.58	17.87	7.74	2.37	1.26	1.75
"	20-40	2.28	2.28	0.39	2.26	2.14	2.37	2.38	10.75	7.28	3.81	1.15	2.59
"	40-60	1.04	1.36	0.59	2.70	1.14	1.49	1.43	6.15	4.24	3.02	0.63	2.29
"	60-80	0.60	1.25	0.42	2.31	2.49	0.46	0.62	5.57	3.13	1.51	0.52	1.52
"	80-100	0.33	0.90	0.59	3.00	3.38	0.38	0.44	5.46	2.95	1.19	0.21	1.33
W-1	0-20	4.59	18.08	1.67	6.19	11.29	3.08	3.55	15.34	12.67	2.86	2.62	3.24
"	20-40	2.44	6.57	1.72	2.11	2.79	2.05	2.25	12.82	5.71	1.90	4.29	3.81
"	40-60	1.32	4.37	0.54	2.21	1.49	0.76	1.45	10.06	4.42	1.67	0.52	3.24
"	60-80	0.66	0.79	1.33	2.46	1.59	0.66	0.65	6.84	3.23	1.43	0.31	1.57
"	80-100	0.32	0.38	0.93	2.80	1.49	0.46	0.46	5.57	2.40	0.95	0.10	1.55
W-2	0-20	4.04	8.01	1.50	9.19	16.27	0.91	3.48	15.23	10.14	3.33	0.42	2.38
"	20-40	2.31	5.91	1.89	3.98	2.94	0.89	2.68	11.21	3.78	2.78	0.48	2.67
"	40-60	1.22	5.14	0.65	1.87	2.69	0.84	2.04	4.43	3.13	2.22	0.52	3.05
"	60-80	0.45	1.92	0.71	2.70	2.34	0.46	1.40	6.38	2.49	1.98	0.42	2.76
"	80-100	0.36	1.71	2.97	2.06	2.29	0.26	0.62	5.23	2.21	0.87	3.14	2.57
W-3	0-20	3.45	5.09	6.58	12.78	25.67	3.14	3.56	13.62	12.72	4.76	4.19	3.14
"	20-40	1.57	3.04	3.98	3.98	3.58	2.28	2.42	8.22	7.28	2.38	4.61	3.11
"	40-60	1.12	2.07	2.40	2.51	2.69	1.67	1.17	14.43	3.41	1.75	4.61	2.67
"	60-80	0.44	1.76	0.65	2.26	2.94	0.83	0.56	11.44	2.76	1.35	3.56	1.95
"	80-100	0.26	1.61	0.88	1.25	3.43	0.49	0.32	8.33	2.40	1.11	2.93	1.76
F-1	0-20	4.41	11.43	6.02	6.49	30.95	1.66	3.48	16.84	10.69	4.37	4.29	1.62
"	20-40	2.29	9.39	0.88	1.82	7.61	1.23	2.38	12.70	4.88	1.75	5.86	2.52
"	40-60	1.66	3.96	0.48	1.87	4.38	0.85	1.49	10.52	3.50	1.27	4.19	2.29
"	60-80	0.62	3.20	0.71	2.36	4.33	0.76	0.65	7.41	3.23	1.27	4.61	2.67
"	80-100	0.42	5.53	1.10	1.72	5.32	0.67	0.42	6.49	2.86	0.95	5.03	3.05
F-2	0-20	2.56	5.24	7.15	3.34	29.65	1.86	3.37	17.41	3.23	5.79	18.01	3.07
"	20-40	2.21	3.15	0.99	1.33	8.71	1.46	2.58	9.83	3.59	1.59	4.61	2.95
"	40-60	1.45	2.48	1.50	1.62	4.88	1.14	1.62	9.37	2.40	1.35	3.25	2.92

"	60-80	0.45	2.79	0.37	1.23	5.07	1.06	1.02	9.25	2.03	1.43	4.92	2.13
"	80-100	0.23	2.99	0.82	1.97	5.97	0.38	0.48	8.33	1.66	1.11	4.92	1.52
F-3	0-20	2.83	7.70	7.54	6.54	29.45	3.05	3.57	18.45	7.93	3.25	4.71	1.67
"	20-40	1.53	3.61	1.78	1.77	8.76	2.66	2.48	8.91	3.69	3.02	7.43	3.18
"	40-60	0.64	3.25	1.27	2.36	2.34	1.72	1.44	5.69	3.13	1.51	5.13	3.62
"	60-80	0.44	2.28	1.10	2.26	2.74	0.58	0.63	5.57	1.20	1.27	3.98	1.33
"	80-100	0.20	1.92	4.66	2.46	3.33	0.23	0.42	4.54	1.11	0.95	4.61	3.24