Sustainability of Crop Residues and Manure Management in Smallholder CerealLegume-Livestock Systems in the Savannas of West Africa

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In

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DECLARATION

I declare that I have personally, under supervision, undertaken the study herein submitted.

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We declare that we have supervised the student in undertaking the study submitted herein and confirm that the student has our permission to present it for assessment.

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LIST OF ACRONYMS

Acronym	Meaning
ADF	Acid detergent fibre-N
ADG	Average daily gain
AfNET	African Network for Soil Biology and Fertility
AM	Arbuscular mycorrhizal
AMSC	Arbuscular mycorrhiza spore count
ARI	Animal Research Institute
ATO	Apparent tradeoffs
ATP	Adenosine triphosphate
BD	Bulk density
BNF	Biological nitrogen fixation
CEC	Cation exchange capacity
CP	Crude protein
CPU	Crop production unit
CR	Crop residue
DAC	Days after composting
DM	Dry matter
DMD	Dry matter digestibility
DMI	Dry matter intake
FAO	Food and Agriculture Organisation of the United Nations
FOM	Faecal organic matter excretion
FYM	Farm yard manure
GI	Germination index
IITA	International Institute of Tropical Agriculture
INRAN	National de Recherche Agronomique du Niger
IOM	Organic matter intake

LF	Livestock feeding
LPU	Livestock production unit
LSD	Least significant difference
LW	Live weight
LWG	Live weight gained
MBC	Microbial biomass carbon
MDS	Minimum data set
NAPRI	National Animal Production Research Institute
NDF	Neutral detergent fibre
NFB	Net farm benefit
NFI	Net farm income
NGS	Northern guinea savanna
NPV	Net present value
NS:NB	Nutrient stock to nutrient balance ratio
NUTMON	Nutrient monitoring
OC	Organic carbon
OM	Organic matter
PGD	Plant growing days
PRQI	Plant residue quality index
SA	Soil application
SI	Sustainability index
SLP	Systemwide livestock project
SOC	Soil organic carbon
SQS	Soil quality score
SSI	Sustainability sub index
SSP	Single super phosphate
TLU	Tropical livestock unit
TN	Total nitrogen
TTO	True tradeoff
UNESCO	United Nations Educational and Scientific Cooperations

VAM	Vesicular-arbuscular mycorrhizal
VCR	Value cost ratio
WAP	Weeks after planting

ABSTRACT

The integration of crops and livestock is an effective means of harnessing and recycling nutrients in manure and crop residues to improve crop yields. However, the competing demands for crop residues within the farm present a tradeoff between increasing crop yields and sustaining livestock productivity. The effectiveness of manure as fertiliser on the other hand is constrained by poor handling and storage techniques. This thesis addresses the challenges associated with crop residues and manure management in five studies: i) assessment of nutrient balances, ii) quantification of tradeoffs, iii) appraisal of the sustainability of crop residue uses, iv) evaluation of manure management options and v) quantification of added benefits from integrated use of mineral fertiliser and manure. The NUTMON framework was used to assess the N and P balances in cereal-legumelivestock farms at Cheyohi, Ghana (Ferric Luvisols), Sarauniya, Nigeria (Regosols) and Garin Labo, Niger (Eutric Gleysols). Nitrogen balances ranged from -7 to -22 kg ha^{-1} with the application of the recommended N rate and -34 to -82 kg ha^{-1} in the absence of fertiliser use. The application of the recommended rate of P led to the P accumulation in the order of 3 to 7 kg ha^{-1}. However, without the application of fertiliser, P depleted at rate of 2 to 7 kg ha^{-1} annually.

The tradeoffs for allocating crop residues between the crop and livestock units of the farm were evaluated by incorporating 0, 25, 50, 75, and 100 % of haulm and stover yield of the farm into the soil and feeding the remaining amount to small ruminants. The tradeoffs estimates favoured the incorporation of 75 % haulm and 25 % stover at

Cheyohi, 25 % haulm and 75 % stover at Sarauniya, and 0 % haulm and 0 % stover at Garin Labo.

An agricultural sustainability index was used to appraise the sustainability of the five management scenarios. The use of 75 % of haulm and 25 % of stover as soil amendment was found to be the most sustainable option in Farm 1 at Cheyohi. Other sustainable options were, the total removal of crop residues in Farm 1 at Sarauniya and Garin Labo, and the use of 75 % of haulm and 25% of stover as soil amendment in Farm 2 at Sarauniya. The effects of oil cakes and manure storage methods on nutrient losses during composting were evaluated at Nyankpala, Zaria and Maradi. The storage of manure in heaps or pits and fortification with oil cake had no effect on N and P losses during composting at all locations. The use of plastic sheets to cover heaps or line pits significantly reduced N losses from 29 – 67 % to 5 – 30 % and P losses from 25 – 37 % to 2 – 20 % at Nyankpala and Zaria but had no effect on nutrient losses at Maradi.

The added benefits and economic returns from the combined application of mineral fertiliser and manure were evaluated at Nyankpala, Sarauniya and Maradi. Added benefits in grain yield ranged from -68 to 470 kg ha^{-1} at Nyankpala and -514 to 684 kg ha^{-1} at Sarauniya. No added benefits were found at Maradi. The most cost effective application rates were 2.5 t ha^{-1} of manure complemented with either 25 % of the fertiliser recommendation at Nyankpala or 50 % of the fertiliser recommendation at Sarauniya.

CHAPTER ONE

1.0 INTRODUCTION

Agriculture is the basis of West African economies and contributes about 35 % of their gross domestic product (World Bank, 2001). Despite the unremitting efforts made by governments to attain food security, hunger remains widespread (World Bank, 2006). A revolution in the farming systems with strong emphasis on ―input efficient management practices‖ has been identified as an appropriate strategy for addressing the deficits in food production and increase incomes (World Bank, 2007).

A major setback to this agricultural transformation is the alarming rate of nutrient mining in these crop(s) – livestock systems (Smaling *et al*., 1996; Sanchez *et al*., 1996).

However, a thorough audit of nutrient flows in these farming systems (Budelman and Defoer, 2000) and judicious manipulation of the flows to redress the nutrient imbalances could lead to the identification of some input efficient technologies.

Crop residues and manure are major organic inputs at the disposal of smallholder farmers which when managed proactively, could improve the productivity of these farms. Crop residues have enormous potential to improve soil fertility (Bationo *et al*., 1995) but their use have been limited by keen competition for them as fodder and the large amounts needed to achieve optimum crop yields. Currently there are conflicting reports on the partition of crop residues for either crop or livestock production (Delve *et al*., 2001 and Larbi *et al*., 2002). Until now, no study has been conducted to quantify the benefits a crop–livestock farmer may gain or forfeit (tradeoffs) for using crop residues as either fodder or mulch so as to recommend optimum supply rates.

Notwithstanding the pivotal role played by manure in crop production (Harris, 2002), its effectiveness as fertiliser is largely constrained by its low nutrient concentrations and poor storage methods (Harris and Yusuf, 2001). The FAO (2006) proposed the cocomposting of oilcake and manure as one of the feasible options for improving the quality of manure. Although the contributions of materials such as rock phosphate (Bado, 1985), coal fly ash and lime (Wong *et al*., 2009) and olive cake (Hachicha *et al*., 2006) to manure quality have been widely explored, no study has been done to evaluate the potential of locally available oilcakes on manure quality. In addition, as about 70 % of N in manure may be lost during storage (Rufino *et al*., 2006), it is imperative to develop appropriate measures to check nutrient losses from manure during storage.

The use of manure alone cannot sustain crop production. A credible option for optimizing the crop productivity is to ascertain the best combinations of manure and mineral fertilisers that allow substantial savings on fertilisers while improving crop yields.

Conventionally, the evaluation of many agricultural technologies has been based on agronomic effectiveness, yet agronomic effectiveness alone does not determine the actual usefulness of a technology to a farmer. Certainly, to motivate farmers to inculcate emerging ‗best-fit' technologies into their practices, it is necessary to evaluate the sustainability of these technologies in terms of their agronomic superiority, economic viability, environmental friendliness and social acceptability.

The study therefore aims at increasing the productivity of smallholder farmers and conserving the soil resource base by identifying sustainable management options for manure and crop residue use in crop–livestock systems.

The specific objectives were to:

i. quantify the nutrient balances in cereal–legume–livestock systems; ii. quantify the tradeoffs in using crop residues as fodder or soil amendments; iii. evaluate the sustainability of using crop residues as fodder or soil amendment; iv. evaluate the effect of storage methods and fortification of manure with oilcakes on nutrient losses during composting;

v. assess the added benefits in cereal yields derived from the combined application of manure and mineral fertiliser.

Hypotheses

The above specific objectives were formulated to test the following null hypotheses:

i. The amount of nutrients supplied into a cereal–legume–livestock system does not differ from the amount of nutrients lost from the system; ii. Re-allocation of crop residues from crop production into livestock production does not affect the quantity of crop produce a farmer forgoes to gain more livestock produce; iii. The use of crop residue as fodder or soil amendment does not affect the ecological benignity, economic viability and social acceptability of crop residue management; iv. The amount of nutrients lost during composting of manure is not influenced by the method of storage and addition of oil cake;

v. The grain yield from the combined application of mineral fertilisers and manure does not differ from the sum of their grain yields when applied separately.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Cereal-legume-livestock systems in West Africa

Farming system refers to a population of farms that have similar resource bases, enterprise patterns, household livelihoods, production constraints, and for which similar development strategies and interventions would be applicable (Dixon *et al.,* 2001). An integrated crop-livestock system is a system of farming in which crop and livestock production activities are managed by the same economic entity, such as a household, with animal inputs (manure or draft power) being used in crop production and crop inputs (residues or forage) being used in livestock production (Williams *et al*., 2000).

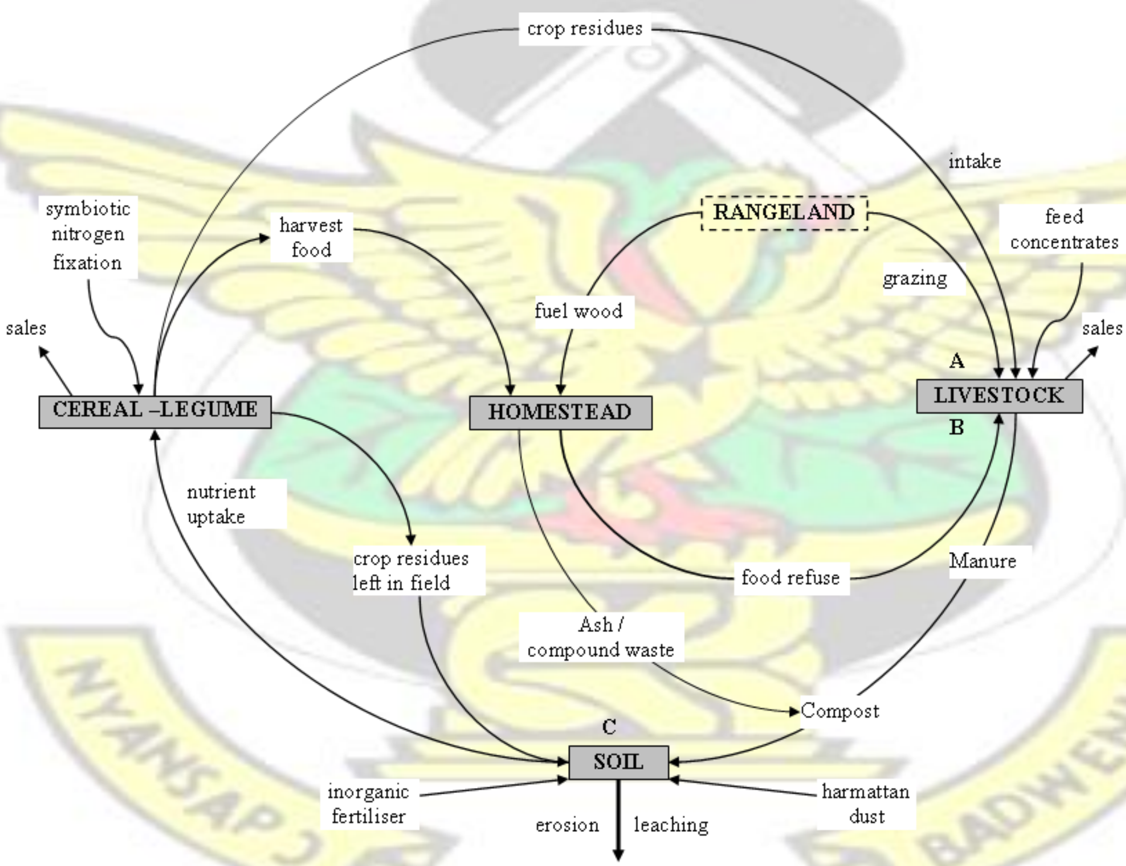
Manyong (2002) identified ten specific crop-livestock systems in West Africa. The dominant crops in these systems are pearl millet (*Pennisetum americanum* (L.) Leeke), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) rice (*Oryza sativa* L.), cowpea (*Vigna unguiculata* (L.) Walp). Ruminant livestock kept were cattle *(Bos primigenius L.)*, sheep (*Ovis aries* L.) and goats (*Capra aegagrus* L.).

Among the ten crop-livestock systems, millet-cowpea-livestock, and maize / sorghumcowpea-livestock were the most common systems in the dry savannas of West Africa.

The millet-cowpea-livestock system stretches across much of West Africa from northern Nigeria, through south-western Niger and Burkina Faso, to the southern parts of Mali. It is the largest crop-livestock system in West Africa covering about 0.64 million km^2 of the land area. Lastly, the maize/sorghum-cowpea-livestock system is found in several locations in West Africa and covers an area of 0.23 million km^2.

2.2 Nutrient cycling in cereal-legume-livestock systems

A cereal-legume-livestock system is conceptualized as a farming system comprising of a cereal-legume production unit, a livestock production unit and a homestead through which nutrient transfers take place (Fig. 2-1). Nutrients may be imported into the farm primarily through feed concentrate, mineral fertilisers, and biological N_2 fixation while export occurs through the sales of livestock and crop products (Watson *et al*., 2005).



A = Feed degradation, B = Partitioning of nutrients by ruminants, C = Mineralization of nutrients

Figure 2-1: Conceptual framework for nutrient cycling in smallholder cereal-legumelivestock systems.

In the savannas of West Africa, deposition of harmattan dust is another important nutrient input into the farming system (Harris, 1999). Additional nutrient losses may occur through leaching, erosion and denitrification (de Jager *et al*., 1998).

Nutrients in crop-livestock systems are cycled in several stages, and losses at each stage may decrease the amount of useful output. For example, crop residues may be fed to livestock and the manure generated returned to the cropland. Turner and Hiernaux (2002) found rangeland to be an integral component of the daily grazing orbit of livestock in the dry savannas as animals are typically kept on a free range. As a result, livestock grazing on rangelands may import nutrients onto croplands when the manure deposited in confinement either through kraaling or night parking is used in crop production (Harris, 2002). Alternatively, nutrients in crop residues may be taken up by the subsequent crop to produce biomass and grain when left on the field after harvest (Powell *et al*., 2004). Nonetheless, in the dry savannas a substantial amount of crop residues left on the field may be lost as a result of bush fires, strong winds, termites, free roaming animals, or transhumant cattle.

2.2.1 Recycling of nutrients in livestock production unit

2.2.1.1 Feed degradation in the ruminants

Ruminants are capable of utilizing energy from cellulose because they maintain large populations of cellulose-degrading microorganisms in their rumens (Rufino *et al*., 2006). The nutritional availability of cellulose depends largely on its degree of lignification. Lignin protects cell wall structural polysaccharides from microbial attack and so limits the availability of feed nutrients to livestock (Chesson, 1997). The C:N ratio of the feed is also a key factor, since rumen microorganisms require N for growth and efficient fermentation. Proteins consumed in the diet by ruminants are subject to hydrolysis in the rumen, releasing small peptides and amino acids, which are absorbed into the bloodstream (Webb and Bergman, 1991). These amino acids and peptides are then utilised for the synthesis of milk protein and body protein. Undigested protein passes into the large intestine, where there is a small amount of further digestion, but most is excreted in the faeces (Rufino *et al.*, 2006). Much of the ammonia liberated, together with some free amino acids is used by rumen microorganisms for further protein synthesis (Ørskov, 1992).

2.2.1.2 Partitioning of dietary nutrients into animal products and by-products

Dietary N, P and K that is not used by the animal for metabolic or productive activities is excreted in faeces and urine. Williams and Haynes (2000) estimated that grazing animals generally use only 10 – 35 % of the ingested nutrients for maintenance and productive purposes. A study by Agboola and Kintomo (1995) on the recycling of nutrients in extensive livestock production systems found the recovery of dietary P and K in manure to be more efficient than that of dietary N. The susceptibility of urinary N to losses (Powell and Williams, 1993) largely accounted for the poor recovery of dietary N. The concentration of nutrients in animal tissues is maintained relatively constant by homeostatic mechanisms, irrespective of the diet composition (Rufino *et al.*, 2006). Thus, whereas the intake of high N diet leads to high urinary N, low N intake is associated with low amount of N in excreta (Delve *et al.*, 2001). In general, livestock in tropical smallholder systems retain less than 20 % of ingested N for productive purposes

(Reynolds and de Leeuw, 1995).

2.2.2 Recycling of nutrients in cereal-legume production unit

2.2.2.1 Symbiotic N fixation

Biological nitrogen fixation (BNF) is a biochemical reduction of atmospheric nitrogen to ammonia in the presence of nitrogenase (Robertson and Lyttletonm, 1984).

Nitrogenase is an enzyme complex found in microorganisms, such as the symbiotic Rhizobium and Frankia, or the free-living Azospirillum and Azotobacter. It consists of an iron-containing protein called azoferredoxin and a second protein; molybdoferredoxin, which contains both iron and molybdenum (Chen *et al*., 2003).

2.2.2.2 Mineralization of nutrients from crop residues and manure

2.2.2.2.1 Nitrogen

In crop residues, N exists in compounds such as protein, amino sugars and nucleic acids (Stevenson, 1994). Nitrogen released from manure is derived from proteins and non-protein N in undigested feed. Endogenous N substances such as bile salt, mucus, keratinized tissues and microbial debris excreted in the faeces of ruminants also contribute substantially to manure N (Rufino *et al*., 2006).

The N in these organic compounds is transformed into plant available forms by complex biochemical processes involving ammonification and nitrification.

2.2.2.2.2 Phosphorus

Inositol phosphates constitute more than 50 % of organic phosphates in plant debris while

1-5 % are phosopholipids and 0.2 – 0.5 % nucleic acids (Turner *et al*., 2002). In legumes, cereals and oil seeds, for instance, Kasim and Edwards (1998) found that all the inositol phosphates existed mainly as myo-inositol 1,2,3,4,5,6-hexakisphosphate (myo-IP6), commonly referred to as phytic acid.

Dephosphorylation of myo-IP6 is the biochemical hydrolysis of myo-IP6 into inositol and orthophosphates by phytases and phosphatases. The enzymes 3-phytase and 6phytase are known to initiate dephosphorylation. The final dephosphorylation is achieved by an acid or alkaline phosphatase.

2.2.3 Quantification of nutrient flows using the NUTMON approach

A quantitative knowledge on nutrient flows in agriculture production system facilitates the identification of the pathways through which nutrients are lost. A nutrient balance for a system is calculated as the sum of nutrient inputs minus the sum of nutrient outputs. Nutrient monitoring (NUTMON) model is an integrated, multidisciplinary methodology that targets different stakeholders in the process of managing natural resources in general and soil nutrients in particular (Smaling *et al*., 1996; Van den Bosch *et al*., 1998). The NUTMON concept considers six nutrient flows into the farm (inflows) and six nutrient flows out of the farm system (outflows).

2.2.3.1 Nutrient inflows

Mineral fertiliser (IN 1) use in SSA is low and constitutes one of the most serious constraints to sustainable agricultural production and intensification. FAO (2006) estimated the national average of mineral fertiliser consumption in Ghana to be 4 kg ha^{-1}, whereas average fertiliser consumption in Egypt was found to be 383 kg ha^{-1}.

Organic nutrient inputs (IN 2) include pen manure, manure deposited by grazing, compost, and household waste. Elias *et al.* (1998) found that rich farmers with a herd size of 11.5 TLU applied 21.6 kg N ha^{-1} from manure while poor farmers with a herd size of 1.1 TLU could only access 6.6 kg N ha^{-1} from manure.

The process of atmospheric deposition (IN 3) supplies considerable amounts of nutrients to soils. In Africa, Stoorvogel and Smaling (1990) estimated about 3 – 15 kg N ha^{-1}, 0.2 – 2 kg P ha^{-1}, and 2 – 15 kg K ha^{-1} accumulate in the soils annually through atmospheric deposition.

Biological nitrogen fixation (IN 4) in production systems results from both symbiotic and non-symbiotic N_2 fixation. Studies conducted in various parts of the tropics found the percentages of total N uptake through symbiotic N fixation for groundnut, soybean, pulses and surgar cane to be 65, 67, 55 and 17 % respectively (Giller and Wilson, 1991; Danso, 1992; Giller, 2001; Hartemink, 2001).

Sedimentation (IN 5) relates to input of nutrients by irrigation water and input of nutrients by deposition of sediments as a result of erosion. Stoorvogel and Smaling (1990) found 3.3 mg N l^{-1}, 0.43 mg P l^{-1} and 1.4 mg K l^{-1} in irrigation water. The FAO (2003) fixed the annual sedimentation rate in natural floodplains at 1 mm yr^{-1}.

Subsoil exploitation or deep capture (IN 6) is usually ignored because of the difficulties in determining this flow and its marginal contribution to the total nutrient balance.

2.2.3.2 Nutrient outflows

Outflow via farm products (OUT 1) relates to the removal of nutrients through harvested farm products for human or animal consumption or further industrial processing.

Outflow through crop residues (OUT 2) relates to the loss of nutrients from the soil through the removal of crop residues. Elias *et al*. (1998) reported that 1.6 – 50 kg N ha^{-1} and 0.2 – 5.6 kg P ha^{-1} were lost from crop production systems, depending on the amount of crop residues removed from the field.

Leaching (OUT 3) is a significant loss mechanism for soil nutrients. In tropical soils, P is bound tightly to soil particles and so P loss due to leaching is negligible (Van den Bosch *et al*., 1998). The amount of N lost through leaching, measured in a wide range of rainfed agricultural systems, varied from 9 to 123 kg N ha^{-1} (Van den Bosch *et al*., 1998). The emission of gaseous N (OUT 4) in agricultural systems occurs through denitrification and volatilization. Smaling *et al*. (1993) identified emissions from soil and stored organic inputs to be the two major types of gaseous losses from agricultural systems.

Nutrients exported by water erosion (OUT 5) relate to the annual soil loss, nutrient concentration of the soil and an enrichment factor (FAO, 2003). Enrichment factors for N, P and K vary between 1.5 (Smaling *et al*., 1993) and 2.0 (FAO, 2003).

Nutrient loss through human faeces (OUT 6) is calculated as a user-defined amount per consumer unit. These nutrients are however often lost since many households use deep latrines (FAO, 2003).

2.2.4 Knowledge gaps

Much of the debate on nutrient cycling and flows in crop-livestock systems ignores the socio-economic factors influencing farmers‘ decision on the use of nutrient inputs and misses many of the key driving forces influencing the nutrient balances. Secondly, the nutrient balances are not related to nutrient stocks in most of the studies. Consequently, whereas the conclusions from those studies point to severe nutrient mining annually, smallholder farmers continue to produce crops with little or no inputs of mineral fertilisers and yet, there are only marginal fluctuations in their crop yields (0.9 and 1.0 t ha^{-1}, according to FAOSTAT, 2009). Lastly, although a substantial amount of dietary N is partitioned into livestock urine, the models for estimating nutrient balances failed to account for nutrient inputs and outputs from urine.,

Redressing the nutrient deficits in crop-livestock systems necessitates the pragmatic management of key nutrient carriers such as crop residues, manure and mineral fertilisers.

2.3 Impact of crop residues on cereal-legume-livestock systems

2.3.1 Effects of crop residue application on crop growth and yield

In the Sahelian zone of Niger, Bationo *et al*. (1993) found that the application of crop residues without mineral fertiliser for four successive years increased pearl millet yields from 400 to 745 kg ha^{-1} while the yields of control plots declined from 280 to 75 kg ha^{-1}. In a related study, Franzluebbers *et al*. (1994) also showed that the application of 2000 kg ha^{-1} of either cowpea haulms or millet stover led to significant increases in the grain yield of millet (1400, 1050 and 700 kg ha^{-1} for cowpea haulms, millet stover and no residue application respectively). In the Sudanian zone, however, the application of crop residues decreased yields of millet from 751 kg ha^{-1} in the first year to 140 kg ha^{-1} in the fourth year. Along the transect from the humid forest to the northern Guinea savanna, Larbi *et al*. (2002)

reported that the grain yield of maize increased with increasing proportions of the crop residues applied.

In a study to explore the mechanisms governing crop residue-induced growth in the major agroecological zones of West Africa, Buerkert *et al*. (2000) confirmed that crop residue mulch produced higher dry matter yields of cereal (73 %, relative to the control) in Sahel than in the wetter Sudanian and Guinean zones (16 %, relative to the control). Mobilization of soil P through the release of organic acids from the decomposing residue, as asserted by Hue (1991), was found to be the most important mechanism for increasing P availability in all the agroecological zones. The enhanced crop growth in the Sahel was attributed to increased root length density as a result of increases in soil moisture (Tian *et al*., 1993), reduced physical resistance to root elongation (Buerkert and Stern, 1995) and a hormone driven feed-back mechanism which stimulates root growth (Hafner *et al*., 1993). At the moment, the mechanisms governing the poor response of cereals to crop residue application in the Sudan savanna are not clearly understood.

2.3.2 Effect of crop residue application on soil quality

2.3.2.1 Soil organic carbon

The decomposition of plant residues contributes greatly to the turnover of soil organic carbon (SOC). Mubarak *et al*. (1999) asserted that due to rapid decomposition rates of OM in the tropics, continued application of crop residues for periods exceeding 30 months may be required to accumulate significant amounts of OM. Indeed, Kelly and Sweeney (1998) observed only marginal changes in soil OM after incorporating residues for 12–14 years. Even in another study, there was a decrease in OC of the topsoil after incorporating crop residues for 5 seasons (Mubarak *et al*., 2003). In contrast, some studies have found positive effects of crop residue application on SOC within shorter periods. Buerkert *et al*. (2000) reported that the application of 2000 kg of millet stover for 3 successive years increased OC significantly on mulched plots (2.32 g kg^{-1}) and was comparable to the OC concentration measured on land fallowed for 8 years (2.26 g kg^{-1}).

2.3.2.2 Soil nitrogen

Availability of N from crop residues to the subsequent crops is dependent on the application rate, residue quality, and environmental conditions. At Nyankpala in the northern Guinea savanna of Ghana, Larbi *et al*. (2002) observed that the total N in the upper 10 cm of the soil increased steadily from 3.41 to 4.01 g kg^{-1} when the crop residue application rate was increased from 25 % (1.8 t ha^{-1}) to 75 % (5.07 t ha^{-1}) of total crop residue yield. However, due to immobilization, the total N decreased to 3.63 g kg^{-1} when 100 % (6.91 t ha^{-1}) of the crop residue yield was used as mulch.

Studies by several scientists have shown that the subsequent crop derives proportionately more N from legume haulms than from cereal stover. In the Sahelian zone of Niger, Franzluebbers *et al*. (1994) observed that the incorporation of 2 t ha^{-1} of cowpea haulms increased the mineral N concentration in the upper 10 cm of the soil by 20 mg kg^{-1} while the application of 3 t ha^{-1} of millet stover increased the mineral N by only 9 mg kg^{-1}. Mubarak *et al*. (2002) also found the rate of N release from groundnut haulms (0.20% wk^{-1}) during 13 weeks of decomposition was significantly higher than that from maize residue (0.12 % wk^{-1}). In an incubation study involving the common plant species native to the interior savanna of Ghana, Fening *et al*. (2005) also reported that *Crotolaria spectabilis* (a legume) released the highest amount of mineral N and *Andropogon gayanus* (a grass) released the lowest. The observation by Tian *et al*. (2007) that the release of N from high quality residues such as Gliricidia decreased from the humid zones to the arid zones of West Africa illustrates the influence of climate on N transformation in the soils.

2.3.2.3 Soil microbial community size

Many studies have found both short-term and long-term effects of crop residue application on biomass and the activity of various micro-organisms in the soil. Doran (1980) reported that the addition of maize stover to the soil surface dramatically increased the microbial biomass in the top 15 cm of the soil compared with the unmulched soil. Changes in microbial biomass correlate with the amount of residues added. Karlen *et al*. (1994), for instance, found that the application of crop residues at 8 t ha^{-1} increased microbial biomass C from 330 to 696 mg kg^{-1}. Furthermore, the microbial biomass C surged to 1060 mg kg^{-1} with a doubling of the application rate.

2.3.2.4 Bulk density

The incorporation of rice and wheat straw significantly reduced the bulk density of the upper 10 cm of the soil from 1.72 to 1.65 Mg m^{-3} (Singh *et al*., 2007). Kladivko (1994) explained that residues have a lower density than soil and so their incorporation into the soil lowers the overall density. Even in cases where the residue is applied to the soil surface, the bulk density decreases as evident from the results of Lal (1980) where the surface application of rice straw mulch to a newly cleared tropical Alfisol in Nigeria decreased the bulk density of the top soil (0 – 5 cm) from 1.22 to 1.05 Mg m^{-3}. Kladviko (1994) asserted that the amounts of crop residues added or removed from the soil may not be large enough to cause detectable differences in bulk density within a short period of time. This assertion is supported by the observation of Biederbeck *et al*. (1980) that mulching with straw caused a measurable improvement in bulk density only after 20 years of continuous application.

2.3.3 Effect of cereal-legume fodder on live weights of livestock

The growth rate of livestock is a function of voluntary dry matter intake (DMI), dry matter digestibility (DMD), and the nutritive value of the feed (Coleman and Moore, 2003). Voluntary intake is the consumption of feed when there is no limitation on the amount available. Digestibility is the difference between the amount of a nutrient eaten and the amount voided in faeces. The nutritive value, on the other hand, relates to the amount of protein, carbohydrates, vitamins, and minerals in the feed. Bliimmel *et al*. (1997) examined the effect of DMI and DMD of 54 cereal and legume residues on the live weight gained (LWG) by livestock and concluded that DMI was best correlated with animal performance (LWG) as it accounted for approximately 68 % of the variations in LWG. In studies where decreases in the DMI of herbage were observed (Kaitho *et al*., 1998; Sangare *et al*., 2003; Ayantunde *et al*., 2007), low palatability due to high levels of the anti-nutritional factors such as polyphenolics, cyanogens, saponins, alkaloids, triterpenes, and oxalic acids (Kumar, 1992) were cited as the major cause.

Supplementation of cereal stover or straw with legume haulms has been shown to increase feed digestibility (Devendra, 1982) or intake (Hiernaux and Ayantunde, 2004) or both (Moran *et al*., 1983; McMeniman *et al*., 1988) and consequently LWG. Faftine *et al*. (1998) found that supplementing goats with groundnut or cowpea haulms increased the average daily gain (ADG) in live weight by 38.1 or 29.6 g d^{-1}, respectively over the unsupplemented animals. Similarly, Osuji and Odenyo (1997) observed a gain as high as 367 % in the live weight of calves fed with teff straw supplemented with herbaceous legume lablab or cowpea hay. In other studies, however, the degree of response to residues varied from maintenance to slight increases in LW when cowpea haulms were fed with maize stover (Warambwa and Ndlovu, 1992), millet stover (Kouame *et al*., 1992) and rice straw (Ngwa and Tawah, 1992). The variation in the quality of the crop residues and its mode of administration, namely whether it is offered as green foliage or dried and/or treated in some way (Bonsi *et al*., 1995; Ahn *et al*., 1997) may account for the differences in the results reported by these studies.

The growth rate of livestock increases with increasing amount of crop residues offered to it. Ayantunde *et al*. (2007) reported that sheep fed with only bush hay lost 18.4 g LW d^{-1}, while those offered 150, 300 and 450 g of groundnut haulms in addition to the bush hay significantly gained 1.4, 19.3 and 40.2 g LW d^{-1} respectively. Tanner *et al*. (2001) also found that DMI of forage and growth rate of sheep increased with the offer-rate but the incremental improvement from 50 to 75 g DM kg^{-1} LW d^{-1} was not significant ($P > 0.05$) and was less than that observed from 25 to 50 g DM kg^{-1} LW d^{-1}. The observed increases in growth rate at high feeding rates confirmed the assertion by Wahed *et al*. (1990) that excess feeding provides greater opportunity for selective feeding, which leads to improvements in the quality of the diet ingested.

2.3.4 Tradeoffs in alternative uses of crop residues

In allocating a scarce resource between two competing production activities, an entrepreneur sacrifices an amount of one product to achieve more of the other product.

The quantity of a product sacrificed by the entrepreneur is the opportunity cost for producing more of the other product. Tradeoff refers to the opportunity costs of selecting one production alternative rather than the other. Thus, in general, a tradeoff analysis indicates that for a given set of resources and technology, to obtain more of a desirable outcome of a system, less of another desirable outcome is obtained (Stoorvogel *et al*., 2004a). Smallholder farmers face multiple tradeoffs when deciding on the allocation of their available financial, labour and nutrient resources to competing production activities within their farms (Tittonell *et al*., 2007). Such tradeoffs are reinforced by their limited access to production resources (Giller *et al*., 2006) and poor development of markets for the resources (Ruben and Pender, 2004). Crissman *et al*. (1998) proposed tradeoff analysis as a tool for providing quantitative information to support decision making about agricultural production systems. Indeed, tradeoff analysis has been used to streamline resource allocation in peri-urban vegetable production (Francisco and Ali, 2006), resource and labour allocation by smallholder farmers (Tittonell *et al*., 2007), investments in nitrogen fertilization and weed control (Dimes *et al*., 2001), and potato productivity and environmental quality (Stoorvogel *et al*., 2004b).

The allocation of the limited crop residues between competing uses is a difficult task confronting smallholder crop-livestock farmers in the savannas of West Africa. Albeit, a choice is constantly made by farmers between the allocation of crop residues for livestock production and crop production. Powell and Unger (1998) opined that returning crop residues to soils may not be a viable strategy for many farmers owning livestock as huge losses would occur in the livestock production if crop residues are not used to supplement dry season feeding. Delve *et al*. (2001) also observed that returning cereal residues to soil had delayed benefits and these were less attractive to farmers. In contrast, legume residues provided immediate benefits to a cereal crop, but farmers preferred to feed such high quality residues to livestock.

Efforts to quantify the impact of crop residues usage on agricultural productivity have focused on either crop production (e.g., Mubarak *et al*., 2002; Larbi *et al*., 2002; Tanimu *et al*., 2007) or livestock production (e.g., Ngwa and Tawah, 2002; Sangare *et al*., 2003; Ayantunde *et al*., 2007; Bogale *et al*., 2008) but seldom on both. Delve *et al*. (2001) investigated the notion that farmers could maintain the fertility of their soils by feeding crop residues to livestock and applying the farmyard manure produced to their cropped lands. It was evident from their results that the application of faeces from low quality crop residues released more N than the direct incorporation of the crop residues, while high quality plant materials released more N than the faeces derived from them. They proposed that low quality plant materials should be first fed to livestock and the faeces collected used as a fertiliser. High quality plant materials, on the other hand, should be used directly as soil amendments. Considering that farmers are inclined to feed high quality crop residues to livestock, it is unlikely that such a recommendation could influence the pattern of the crop residue allocation. In order to recommend specific mulching and fodder supplementation rates, Larbi *et al*. (2002) applied five levels (0, 25, 50, 75, and 100 %) of crop residues produced per unit area of cereal-legume intercrop as mulch. The remaining crop residues were removed and fed to livestock. These authors concluded that 25 – 50 % of the crop residue yield could be used as feed for livestock without any adverse effect on grain yield. Whereas the study monitored the impact of crop residue use on grain yield, no data were presented on the changes in live weight of livestock. Consequently, it is uncertain whether the proposed fodder supplementation rate of 25 – 50 % increased or reduced the growth of livestock. To enable farmers to make informed decisions on the allocation of crop residues, it is imperative to provide them with information on the quantities of crop or livestock products they give away for allocating more crop residues into livestock or crop production.

2.3.5 Knowledge gaps

Although knowledge on the mechanisms for crop residue-induced growth in Sahel savanna has advanced considerably in recent years, the mechanisms for poor response of crops to crop residue application in the Sudan and Guinea savannas are yet to be elucidated. Secondly, a major missing link in the use of crop residue as soil amendment is the lack of site-specific application rates. Lastly, the lack of consensus on the allocation of crop residues between the crop and the livestock production units of the farm warrants both short and long term studies to obtain accurate estimates of the tradeoffs for the alternative uses of crop residues.

The major organic inputs accessible to smallholder farmers are crop residues and manure. Therefore, improvement in the management of crop residues should be coupled with efficient handling, storage and application of manure to boost the productivity of these farms.

2.4 Management of manure in cereal-legume-livestock systems

2.4.1 Acquisition and handling of manure in the savannas of West Africa

Manure refers to the bulk organic material resulting from the faecal matter of farm animals with or without urine, bedding materials, orts and household waste. Farmers in the savannas of West Africa use strategies such as the grazing of crop residues, night parking, dynamic kraaling, and zero-grazing to acquire manure for their croplands (Harris, 2002). Animals deposit manure as they graze the crop residues on a farmer‘s field. Night parking relates to a contractual agreement between herders and farmers, which allows a specific herd to consume the crop residues on a farmer‘s field in return, the herd is tethered on the field overnight for several nights. As ruminants deposit 43 % of their daily faecal excretion during the night (Fernandez-Rivera *et al*., 1995), this system provides a better return of manure to the cropland. Night parking a herd of 50 cattle for 3 nights provided 41 – 104 kg ha^{-1} of N and 10 – 15 kg ha^{-1} of P (Powell and Mohammed-Saleem, 1987). In dynamic kraaling, the position of the kraal is rotated yearby-year and cultivation is done on the area fertilized by the previous year's kraaling (Harris, 2002). During the cropping season animals are tethered in the compound and fed daily on a zero-grazing basis. Annual manure production by zero-grazing cattle has been estimated as 1 – 1.5 t $head^{-1}$ (Strobel, 1987). Two to eight animals would be needed to supply enough manure to grow a 2 t ha^{-1} maize crop depending on the quality (Bationo *et al*., 2004). Yet the mean livestock holding of a smallholder farm in Niger is 0.23 cattle and 4.16 sheep and goats (Seo and Mendelsohn, 2006). Clearly, there are insufficient animals and feed resources to provide the 5 – 20 t ha^{-1} of manure needed for crop production (Bationo *et al*., 2004).

On a typical smallholder crop-livestock farm in the savannas of West Africa, manure accumulates in the kraal and may be collected at variable intervals to be composted or applied directly to cropland (Harris, 1996). Manure collected by farmers and stored is usually not protected from rain or sun, but may be mixed once or twice during the storage period of about 6 months (Rufino *et al*., 2006). The existing manure management regimes result in either losses or dilution of nutrient concentration in the manure (Harris and Yusuf, 2001).

In sum, the methods used by farmers to acquire and store manure limit the quantity and reduce the quality of the material. Nonetheless, considering that the quantity of manure produced cannot be increased without substantial capital investment, it has been recommended (Harris and Yusuf, 2001; Tarawali, 2002) that research focuses on improving the quality rather than the quantity.

2.4.2 Quality of manure

2.4.2.1 Indicators of manure quality

Manure quality refers to the value of manure in improving soil properties and enhancing crop yields. The initial concentration of N or the C:N ratio of manure is the most widely accepted indicator of the quality of manure (Kimani and Lekasi, 2004). Regardless of the frequent use of the C:N ratio to evaluate the quality of manure, evidence for and against this ratio as a responsive indicator of manure quality has been reported. While Kristensen (1996) and Delve *et al*. (2001) observed a strong negative correlation between C:N and N release from manure, Nyamangara *et al*. (1999) found that manure with a C:N ratio of 9 immobilised N, whereas manure with a C:N ratio of 18 released N.

Other quality parameters such as lignin, polyphenol, condensed tannins, and soluble C, have been highlighted as important modifiers of nutrient release patterns from manure (Palm *et al*., 2001; Handayanto *et al*., 1997). Palm *et al*. (2001) classified the quality of manures acquired by farmers as either medium, i.e. contained high N (>2.5 %), high lignin (>15 %) and high polyphenol (>4 %) or low, i.e. contained low N (<2.5 %) and low lignin (<15 %) and recommended them to be applied in combination with mineral fertilisers. However, to a larger extent, these quality parameters have not provided a credible explanation for the mineralization or immobilization of manure N (Kihanda and Gichuru, 2000; Vanlauwe *et al*., 2002a). Rufino *et al*. (2006) indicated that the large differences between the biochemical composition of manure and plant materials may account for the failure of plant quality indicators to justify nutrient release from manure.

2.4.2.2 Processes affecting manure quality

Loss of nutrients from manure following its excretion, collection, storage and field application is a key factor affecting the quality of manure. As illustrated in Fig. 2-2, the major mechanisms by which N in faecal matter may be lost are NH_3 volatilisation, denitrification, and leaching (King, 1990). Losses of nutrients may also occur through runoff (Murwira *et al*., 1995).

As NH_4^+-N is the predominant form of mineral N in manure deposits, NH_3 volatilisation may occur when the pH and temperature of the manure are high (Dewes, 1996). Nitrate is formed in the more aerobic surface layers and is susceptible to losses by denitrification or leaching (Fig. 2-2). Denitrifying bacteria require anaerobic conditions and, as such, denitrification occurs only when oxygen becomes depleted in layers where nitrate-N is present (Rufino *et al*., 2006). King (1990) attributed the source of anaerobic conditions in the centre of manure deposits to the high moisture content of cattle dung. Among the few trials on the relative importance of different pathways of N loss (Murwira *et al*., 1995; Thomsen, 2000; Kulling *et al*., 2001), volatilisation of NH_3 appears to cause the largest N losses during composting as only 4 –17 % of N was lost through leaching or denitrification in these studies.

Losses of N through runoff can occur as dissolved salts or as components of particles washed away in suspension (Murwira *et al*., 1995). The total loss of N from manure during storage may vary from 10 % (Eghball *et al*., 1997) to 70 % (Rufino *et al*., 2006) of the total N initially present.

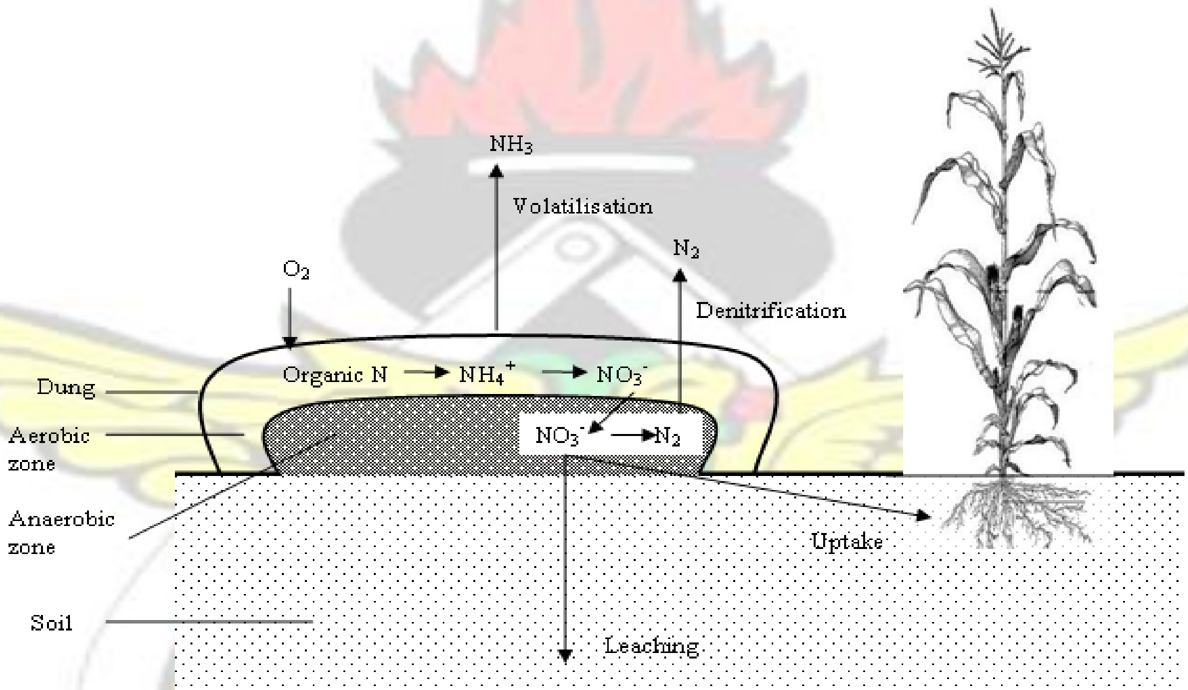


Figure 2-2: Pathways of N losses from faecal matter (adapted from King, 1990).

2.4.2.3 Strategies for improving manure quality

2.4.2.3.1 Manipulation of feed quality

Animals fed on high quality supplements produce high quality manures. These high quality supplements may range from feeds concentrates (Odongo, 1999; Lekasi, 2000) to legume fodder (Delve *et al*., 1999). As the scarcity of feed compels smallholder farmers to feed their livestock opportunistically, a strategy for improving manure quality premised on feed manipulations would not be a viable option.

2.4.2.3.2 Improved storage of manure

The conditions under which manure is stored largely affect the rates of nutrient losses. Rufino *et al*. (2007) enumerated roof type, floor type, and the type of material used to cover manure as major attributes of the storage facility which affect the quality of manure during storage. Lekasi *et al*. (1999) reported that manure removed from grazing units with a soil floor had much lower N and P and higher ash contents than manure removed from barns with concrete floors. A study by Rufino *et al*. (2007) showed that covering manure heaps with polythene film effectively controlled 30 % of total N losses. However, towards the end of 7-month storage period, roof type had no effect on N losses. Manures composted in pits are often of a better quality than those composted in heaps (Murwira *et al*., 1995). Thomsen (2000) reported that manure composted aerobically (heap) lost 46 % of its total N while only 18 % of total N was lost from anaerobically (pit) composted manure during 86 days of storage. In a 3-month storage study, Kwakye (1980) also found higher N (108 %), P (20 %), and K (62 %) contents when manure was stored in pits than when manure was loosely heaped in the open air.

Improving a manure storage facility may not significantly affect the nutrient concentration in the manure if large losses occurred before storage. Several authors (e.g., Murwira, 1995; Thomsen, 2000) have reported that the largest C and N losses from manure occurred 7 – 10 days after excretion. Frequent removal of manure from the kraal may therefore be a useful practice for conserving the quality of manure.

2.4.2.3.3 Co-composting of manure

Co-composting of manure and materials with complementary characteristics is another management practice that has been used to improve the quality of manure (Young *et al*., 2000; Tognetti *et al*., 2007). The quality of the final product of co-composting is largely influenced by the nutrient concentration of the material added to the manure. In a recent study by Wong *et al*. (2009) where coal fly ash and lime (containing no N) were cocomposted with food waste in a thermophilic composter, the composting period was shortened by 35 % but no effect on the total N was observed. Similarly, Kihanda and Gichuru (2000) found no changes in the P concentration of manure by composting it with different proportions of *Tithonia diversifolia* (3.5 N % and 0.37 P %), yet the N content of the manure increased by 10 to 40 %. Likewise, in studies where manure was composted with rock phosphate changes in the water soluble P fraction ranging from 64 to 740 % relative to the control were reported (Lompo, 1984; Bado, 1985).

The added material may also exert an indirect effect on the manure quality. Kwakye (1980) observed that the co-composting of manure and single super phosphate (SSP) conserved 73 % of the total N content of manure relative to the control. The enhanced effect of the SSP on N content was attributed to the conversion of the liberated NH_3 into soluble $(NH_4)_2SO_4$ by the $CaSO_4$ contained in the SSP.

Oilcakes have higher nutrient concentrations (mean of 5.2 % N and 1.8 % P_2O_5) than manure (mean of 0.5 % N and 0.15 % P_2O_5). Consequently, co-composting of locally available oilcake with manure may be an innovative means of improving the quality of the manure (FAO, 2006). Evidence by Hachicha *et al*. (2006) confirmed the feasibility of making high quality compost from olive cake, olive mill wastewater, and poultry manure. In the savannas of West Africa, groundnut cake, decorticated or undecorticated cotton seed cake, and shea nut cake are some of the oil cakes commonly available. Groundnut cake is mainly used as a protein supplement in livestock feeding (Bedingar and Degefa, 1990). Cotton seed cake is also an excellent protein supplement but contains the anti- nutritional factor; gossypol, which restricts its use in monogastric rations (Bedingar and Degefa, 1990). Sheanut cake is derived from sheanut (*Vitellaria paradoxa*, Gaertn.) and contains moderate amounts of crude protein and fat (Morgan and Trinder, 1980). Of the three, sheanut cake is the only oilcake that is not used for livestock feeding. Presumably, the high levels of saponins and theobromine (Atuahene *et al*., 1998) make it unpalatable and deleterious to livestock growth. Although these and other non edible oil cakes have high nutrient concentrations (Boateng and Dennis, 2001; Atuahene *et al*., 1998) there is a dearth of information on their capacity to improve the quality of manure.

2.4.3 Effect of manure application on crop yield

Many scientists have reported substantial yield increases from manure application in West Africa (Bationo *et al*., 1995; Ikpe and Powell, 2002; Mando *et al*., 2005; Agbede and Ojeniyi, 2009). As crop responses varied widely even between different seasons within the same study, the conclusions from these studies were highly site and season specific. In a study to evaluate the effect of nutrient cycling practices in western Niger on the yield of millet, Ikpe and Powell (2002) reported that grain yield was highest (1600 kg ha^{-1}) in plots where the kraaling of sheep directly on the cropland for the application of dung and urine was simulated. Yields on manured (dung only) and non-manured plots were 1400 and 1000 kg ha^{-1}, respectively. The enhanced yield as a result of kraaling was attributed to immediate incorporation of manure and thus minimum loss of N through volatilization as well as the additional N supplied by the application of urine.

Agbede and Ojeniyi (2009) reported that the application of manure at 7.5 t ha^{-1} in the forest-savanna transition zone of Nigeria for 3 years significantly increased sorghum yields from 1.24 t ha^{-1} (on control plots) to 1.72 t ha^{-1}. In the Sudano-Sahelian zone of Burkina Faso, Mando *et al*. (2005) found that the continuous application of manure of 10 t ha^{-1} for a decade also increased sorghum grain yield from 460 to 2618 kg ha^{-1}.

The application of adequate amounts of manure may sufficiently replace the use of chemical fertiliser. In the Sahelian zone of West Africa, Bationo and Mokwunye (1991) established that the application of 20 t FYM ha^{-1} produced as much millet as the yields obtained by the recommended chemical fertiliser rate. In a recent study, Shisanya *et al*. (2008) also reported that the application of cattle manure at rates equivalent to 60 kg N ha^{-1} gave significantly higher yield (4.1 t ha^{-1}), which was comparable to yields (4.2 t ha^{1}) obtained from mineral fertiliser applied at the same rate.

2.4.4 Knowledge gaps

The inconsistency in the relationship between the release of nutrients from manure and established quality parameters for organic inputs highlights the need for further studies to ascertain the quality parameters governing manure mineralisation. In addition, data on the loss of nutrients through the current farmer practice of acquiring and storing manure is lacking. Studies are therefore needed to obtain accurate estimates of nutrients lost from manure during collection, storage and after its application on the field. Furthermore, the technologies associated with composting and nutrient fortification should be explored to improve the fertiliser value of manures.

The low fertiliser value and amounts of manure acquired by farmers imply that balanced crop nutrition in crop-livestock systems may only be achieved through judicious application of manure and mineral fertiliser. It is therefore imperative to examine and quantify the various interactive effects of combined manure and mineral fertiliser application.

2.5 Interactive effects of combined application of organic and mineral fertilisers

The combined application of organic and mineral nutrient sources may lead to synergistic, antagonistic or additive effects on crop production (FAO, 2003). Where an interaction is synergistic (positive), the combined effect of the nutrient sources on crop production is greater than the sum of their individual effects used singly. In an antagonistic (negative) interaction, their combined impact on crop production is lower than the sum of their individual effects. An additive (no interaction) effect is found where the combined effect of the nutrient sources on crop production is directly equivalent to the sum of their individual effects when applied separately. Considering the diverse meanings of the word _interaction‘, Palm *et al*. (1997) proposed the term _added benefit (or disadvantages)‘ as a better phrase for interactive effects. In general, the effect of nutrients supplied by organics are additive to those supplied by mineral sources (Jones *et al*., 1996; Giller, 2002). The added benefits or disadvantages of combined nutrient applications may therefore be due to the decomposition rate, the availability of C for microbial growth and hence the quality of the organic manures (Palm *et al*., 1997). Although evidence of added benefits from the combined use of organic and mineral fertiliser have been presented by several studies (Vanlauwe *et al*., 2001a, Iwuafor *et al*., 2002, Sakala *et al*., 2000) the mechanisms by which these added benefits occur is not precisely understood (Gentile *et al*., 2008). Giller (2002) suggested the stimulation (priming effect) of decomposition and nutrient release by the addition of a labile C or N as a possible mechanism. He, however, admitted that there was scanty evidence to support true priming effect of agronomic significance. Studies to unravel the mechanisms governing the improved N efficiency from the combined application of nutrient sources led Vanlauwe *et al*. (2001a) to formulate and test two hypotheses. The first hypothesis related to the direct benefits on N supply and stated that _the temporary immobilization of mineral fertiliser-N after the application of organic manure can reduce N loss to the environment and delay N release until later in the season, thereby improving N synchrony between soil supply and plant demand'. The second hypothesis related to indirect benefits on soil properties and stated that _any OM related improvement in soil conditions following the combined application of nutrient resources may improve plant growth and the efficiency of the applied N'. The observation by Vanlauwe *et al*. (2002a) that incorporation of maize residues with urea fertiliser reduced the leaching of urea-N while the incorporation of urea with *Mucuna pruriens* residues led to greater leaching of urea N supports the direct hypothesis of immobilization reducing N losses. In support of the indirect hypothesis, Vanlauwe *et al*. (2001b) found greater maize yields at two out of four sites with combined residue and fertiliser use than could be explained by the application of either resource alone. The improved yields were attributed to improved soil moisture conditions under the combined treatment. In another study (Okalebo *et al*., 2004) the application of wheat straw and soybean haulms with urea on an acidic Ferralsol (pH– water of 4.9) yielded added benefits of 684 kg grain ha^{-1} which could be explained by the increase in soil pH (to 5.4, on average) following the addition of organic residues.

Gentile *et al*. (2008) studied the interactive effect of ^{15}N-enriched crop residues and ^{15}N labeled urea on N transformation in a 545 day microcosm experiment. Their results indicated that mixing ^{15}N-enriched maize stover and unlabeled urea or ^{15}N urea and unlabeled maize stover immobilized urea-applied N and stimulated the release of maize stover-N. However, the retention of fertiliser-N (35 to 57 %) was greater than the release of residue-N, resulting in an overall negative interactive effect on an extractable mineral N. This initial immobilization and slow release of fertiliser-N provided further support for the direct hypothesis of Vanlauwe *et al*. (2001a) on the interactive benefits of combining fertiliser and organic inputs. In addition, their observation that the interactive effects switched from negative to positive when high quality residues were mixed with urea corroborates the assertion of Palm *et al*. (1997) that residue quality controls the interactive relationship of combined organic and mineral fertiliser use.

2.5.1 Knowledge gaps

Many studies have confirmed the existence of synergistic or antagonistic effect of combined application of manure and mineral fertiliser on grain yields. However, there is a dearth of information on the magnitude of the grain yields derived from this synergism or antagonism. Furthermore, the key mechanisms for the synergistic or antagonistic effects of combined manure and mineral fertiliser application are uncertain.

Also, there are no site-specific recommendations for combined application of manure and mineral fertiliser in the savannas of West Africa. A series of long term multi-locational studies are required to evaluate the impact of continuous application of manure and mineral fertiliser on soil quality, crop yields and livelihoods of farmers.

2.6 Framework for evaluating the sustainability of crop residue management

2.6.1 Concept of agricultural sustainability

Dalal *et al*. (2003) defined agricultural sustainability as management of an agricultural ecosystem in such a way that its capacity to meet the economic, environmental and social needs of present and future generations does not diminish. Despite the diversity in conceptualizing sustainable agriculture, there is a consensus that agricultural sustainability should be assessed from the perspectives of economic viability, environmental stability and social responsiveness (Rasul and Thapa, 2004; Doran, 2002; von Wiren-Lehr, 2001 and Van Cauwenbergh *et al*., 2007).

The efforts to empirically evaluate the sustainability of agricultural systems (FAO, 1993; De Jager *et al*., 2001; Wijnhoud *et al*., 2003; Lo´pez-Ridaura *et al*., 2005; Kang *et al*., 2005; Herrero *et al*., 2007; Van Cauwenbergh *et al*., 2007) have led to the identification of several indicators and indices of sustainability. Indicators are composite set of measurable attributes which are derived from functional relationships and can be monitored through field observation, field sampling, or compilation of existing information (Walker and Reuter, 1996). Indices, on the other hand, are decision tools intended to simplify complex information for decision makers (Andrews *et al*., 2003).

2.6.2 Farm-level indicators of agricultural sustainability

2.6.2.1 Ecological indicators

Maintenance of the natural resource base is fundamental to achieving a sustainable farming system (Dalal *et al*., 1999). Inevitably, the use of land and water for agriculture alters the quality and quantity of the natural resource base. Soil quality, crop, and livestock performance parameters are the key indicators of ecological sustainability in crop-livestock agriculture.

2.6.2.1.1 Soil quality indicators

Soil quality is defined as the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al*., 1997; Doran and Zeiss, 2000). Soil quality may be evaluated by using a number of chemical, physical and biological parameters.

Soil pH has widely been used as a key indicator, which provides trends in land resource quality in terms of surface and subsurface acidification, salinisation and structural stability (Andrews *et al*., 2003; Masto *et al*., 2008), nutrient availability (FAO, 1993), pesticide retention or breakdown (Dalal *et al*., 2003).

Bulk density is a common measure of the degree of compaction or total porosity of a soil. Stepniewski *et al*. (1994) observed that, at constant water content, compaction increases the proportion of soil pores filled with water as average pore size decreases. This may lead to aeration stress, lower soil temperature and changes in biological processes (Brussaard and Van Faassen, 1994), increased denitrificaton (Linn and Doran, 1984), and loss of mycorrhizal fungi (Ellis, 1998). For these reasons, bulk density is frequently used as an indicator of soil quality.

The trend in soil organic matter content has been widely promoted as a key indicator of sustainable farming systems (Karlen *et al*., 1997; Doran and Parkin, 1994; Gregorich *et al*., 1994). Even though it is well acknowledged that the organic matter content of a soil as measured by the OC concentration changes slowly and many years may be required to detect changes resulting from agricultural practices.

Soil nutrient stock is defined as the total amount of plant nutrients present in the upper 30 cm of the soil profile (De Jager *et al*., 1998). As trends in available plant nutrients indicate the capacity of soils to support crop growth, potential crop yield and environmental hazards associated with eutrophication (Dalal *et al*., 1999), nutrient stocks have been used frequently as sustainability indicators (Nambiar *et al*., 2001; Kang *et al*., 2005; Masto *et al*., 2008).

The soil microbial biomass refers to the organisms living in soil that are generally smaller than 10 µm (Schloter *et al*., 2003). Dalal (1998) asserted that nutrient fluxes through microbial biomass are faster, compared to the remaining part of organic matter. In line with this assertion, microbial biomass has been found to be a sensitive indicator for conservation tillage (Rolda´n *et al*., 2007), organic and mineral fertiliser application (Karlen *et al*., 1997; Ndiaye *et al*., 2000; Bloem *et al*., 2003), pesticide application (Yang *et al*., 2000) and soil fumigation (Ibekwe *et al*., 2001).

Mycorrhizal symbioses and their propagules are fundamental for ecosystem stability and sustainability (Van der Heijden *et al*., 1998; Jeffries *et al*., 2003). The external mycelium of AM fungi acts as an extension of host plant roots and serves as a direct link between roots and soil nutrient reserves. These effects of soil management practices on spore population and root colonization of AM make AM a sensitive indicator of soil quality. Soil enzymes play a pivotal role in catalysing the processes of depolymerization, hydrolysis and oxidation of larger organic compounds into forms that are readily assimilable by plants and microorganisms (Bunemann, 2008). Soil enzymes intimately linked with nutrient transformations includes dehydrogenases, β-glucosidase, proteases, urease, and phosphatases. Dehydrogenases fulfill a significant role in the oxidation of soil organic matter by transferring H from the substrate to acceptors (Tabatabai, 1994). The activity of β-glucosidase is a sensitive indicator of biomass turnover in the soil as it catalyses the rate limiting step in the hydrolysis of cellulose into glucose (Garcia *et al*., 1994).

2.6.2.1.2 Crop performance indicators

Although crop yield is not robust as an indicator of crop productivity because of annual climatic variability (Dalal *et al*., 1999), long-term trends in crop yields provide information on the ability of agricultural practices to sustain production capacity and manage production risks (Nambiar *et al*., 2001).

The amount of crop residues produced per unit area per unit time is paramount in sustaining productivity of crop-livestock systems in semi-arid agro-ecological zones (Fernandez-Rivera *et al*., 2004). Trends in crop residue yields could be a useful indicator of the capacity of a cropping system to maintain soil quality and support livestock production.

2.6.2.1.3 Livestock performance indicators

Livestock feed balance relates to the difference between annual dry matter requirement of livestock and annual dry matter availability for the livestock production (Kassa *et al*., 2003). Given that inadequate supply of fodder is major constraint to livestock production in West Africa (Bayu *et al*., 2004), the livestock feed balance may be a useful indicator for assessing the reliability and resilience of a livestock system to maintain its productivity all year round. In a study to appraise the sustainability of dairy goat systems, Nahed *et al*. (2006) used pasture area head^{-1} and stubble area head^{-1} as surrogate indicator of feed availability. Other indicators used to appraise the performance of livestock systems relate to the reproductive or production trait of the animals. The reproductive traits may include herd size, calving to conception interval, prevalence of abortion and % cows calving (Chapman *et al*., 2008). Some of the production traits monitored in evaluating livestock performance are milk yield, calf growth rate (Ogle, 2001) and mortality rate (Ogle, 2001; Nahed *et al*., 2006).

2.6.2.2 Economic indicators

Economic indicators measure the productivity and profitability of a farm enterprise. Sydorovych and Wossink (2008) contented that a sustainable farming system should be able to maintain its productivity and profitability indefinitely by relying more on its own inputs and capital. Lynam and Herdt (1989) proposed net present value (NPV) from cost–benefit analysis as indicator of economic productivity. This indicator is estimated as the value of outputs divided by the value of inputs. They observed that a farming enterprise is productive and would not operate at an economic loss if NPV is greater than or equal to one. However, Tisdell (1996) challenged the responsiveness of this indicator to economic sustainability of a farming system as it did not reflect profit accrued. He therefore proposed a parallel indicator: the ratio of output value less input value and divided by the input value. This indicator must satisfy the condition that it be equal to or greater than zero, otherwise it is meaningless.

Net farm income (NFI) and value cost ratio (VCR) are other frequently used indicators of profitability (Williams *et al*., 1995; de Jager *et al*., 1998; Zhen and Routray, 2003). The NFI is the difference between gross income of production and the total variable costs per unit of land area while the VCR relates agronomic efficiency to the prices of inputs and outputs. A farming enterprise satisfies conditions for economic sustainability when the NFI is greater than zero and the VCR is greater than one (Zhen and Routray, 2003).

To incorporate environmental issues into traditional economic analysis, van der Pol (1993) developed the farmer income sustainability quotient which relates the cost of replacing depleted nutrients to the net farm income.

2.6.2.3 Social indicators

The social dimension of agricultural sustainability still lacks broad recognition by scientists and decision makers. Currently, it is at best dealt with as the social implications of adopting an agricultural technology, rather than as an integral component of the technology, which governs the appropriateness of the technology to the target group.

Indicators such as input-sufficiency, employment generation and food security (Rasul and Thapa, 2004), access to education and physical well being (Van Cauwenbergh *et al*., 2007) have been used to evaluate the social sustainability of some agricultural innovations.

Whereas these indicators may be useful in the ex-post evaluation of an innovation, they give no indications of the likelihood of acceptance and adoption of the innovation. Assefa and Frostell (2007) approached the ex-ante assessment of the social dimension of agricultural sustainability from the angle of social acceptance and argued that, for an innovation to be deemed socially sustainable, it should at a minimum enjoy wider social acceptance. Knowledge, perception, and fear were the key indicators used by these authors to quantify social acceptance. In a related study, Zhen and Routray (2003) also found knowledge and awareness of innovation under focus among farmers to be an important factor, which motivates farmers to adopt emerging innovations in agriculture. Equal access to the requisite input for operating the innovation and supporting services have been identified by Zhen and Routray (2003) as equally important factors ensuring sustainability. In a recent study, Sydorovych and Wossink (2008) found mental and physical stress associated with the innovation to be yet another factor driving its social acceptability.

2.6.3 Knowledge gaps

Most of the frameworks for assessing agricultural sustainability presented partial coverage of sustainability with a stronger emphasis on environmental aspects. In addition, accurate and consistent assessment of agricultural sustainability requires a systematic method for selecting the relevant indicators, scoring and integrating them into an index. Currently, there is no standardized protocol for evaluating agricultural sustainability. Furthermore, as the negative effects of some agricultural technologies may only be observed after several years of practice, the sustainability of agricultural technology ought to be evaluated on both short and long-term bases. On the contrary, most of the reported studies (Dalal *et al*., 1999; Nambiar *et al*., 2001; Kang *et al*., 2005) focused on a short time-frame evaluation without much emphasis on the long term implications of the technology.

The practical significance of evaluating the sustainability of management practices in cereal-legume-livestock systems is how to use the concept to identify improved crop residue and manure management options, which resonate with the aspirations of farmers and may be widely adopted.

2.7 Conclusion

The benefits and processes governing nutrient cycling in crop-livestock systems have been well studied, yet crop-livestock integration in West Africa is still weak as a result of low yields of crop residues, unbalance competition for crop residues, low livestock holdings, low manure production, and poor handling of manure. Optimizing and sustaining the productivities of smallholder crop-livestock systems warrant:

- Research into crop-livestock tradeoffs to develop new strategies for balancing the conflicting demands of crop residues for feed and soil fertility maintenance.
- Studies to maximize the fertiliser value of manure by streamlining its collection, improving storage facilities, and fortifying manure with high quality nutrient inputs
- Studies to model the relationship between manure quality and livestock feed quality, composting techniques, manure handling, and storage methods.

In addition, most manures are characterised as intermediate-low quality resources and hence are prescribed to be used in combination with mineral fertilisers. The challenge for research presently is to identify the _best-fit' manure–mineral fertiliser combinations in a given agro-ecological zone that can satisfy the short-term goal of nutrient availability and the long-term goal of building soil OM.

Lastly, a chronic problem, which can undermine the sustainability of crop-livestock systems, is the low adoption rate of improved agricultural innovations. The poor scalingout (diffusion among farmers) of these innovations is largely due to the inappropriateness of these innovations to the economic and social conditions of the farmers. The imperative for research in this study is to develop a holistic framework to screen and recommend technologies that are agronomically superior, economically viable, environmentally benign, and socially acceptable to smallholder farmers.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experimental Sites

The studies were conducted in the northern Guinea savanna of Ghana, Sudan savanna of Nigeria and Sahel savanna of Niger. The villages selected for the studies were Cheyohi in Ghana, Sarauniya in Nigeria, and Garin Labo in Niger as shown in Fig. 3-1.

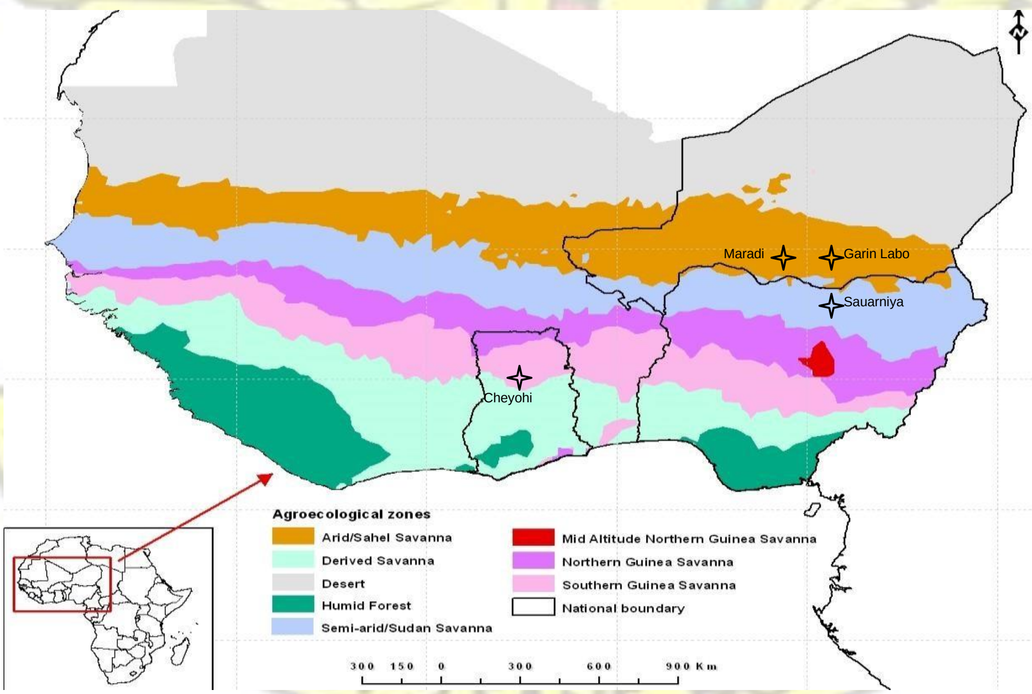


Figure 3-1: Locations of study Sites (Source: Geographical Information Systems unit, IITA, Ibadan, Nigeria).

Cheyohi is on latitude 9 º 43´N and longitude 0º 98´W in the Tolon-Kumbungu district of the northern region of Ghana. The soils are Ferric Luvisols (FAO and UNESCO, 1994). Saurauniya is on latitude 12 º 09´N and longitude 8º 38´E in the Dawakin Tofa Local Government of Kano State, Nigeria. The soils are Regosols (FAO and UNESCO, 1994). Garin Labo is on latitude 13 º 35´N and longitude 7º 07´E in the Maradi region of the Republic of Niger. The soils are Eutric Gleysols (FAO and UNESCO, 1994). The selected physical and chemical properties of the soils are shown in Table 3-1.

Table 3-1: Physical and chemical properties of soils (0 – 15 cm) in the study areas

Site (Soil)	Sand	Silt	Clay	OC[1]	T N*	NH_4^+ – N	NO_3^- – N	Avail P	pH H_2O 1:1
	%					mg kg^{-1}			
Cheyohi (Ferric Luvisol)									
Farmer 1	49	36	15	0.62	0.05	3.32	3.36	2.50	5.85
Farmer 2	49	38	13	0.52	0.04	3.79	1.37	5.62	5.75
Farmer 3	49	38	13	0.51	0.04	3.67	1.21	7.64	6.35
Sarauniya (Regosol)									
Farmer 1	79	10	11	0.42	0.03	5.64	1.00	9.72	6.15
Farmer 2	79	10	11	0.48	0.03	5.36	0.81	9.04	6.00
Farmer 3	73	14	13	0.52	0.03	5.66	1.26	20.42	6.35
Garin Labo (Eutric Gleysol)									

[1] OC = organic carbon, TN = total N

Farmer 1	87	4	9	0.27	0.01	3.75	0.12	1.34	6.40
Farmer 2	89	2	9	0.27	0.01	3.55	0.12	1.74	6.30
Farmer 3	89	4	7	0.27	0.01	5.61	0.17	1.61	6.00
Farmer 4	89	4	7	0.26	0.01	3.58	0.12	1.35	6.40
Farmer 5	88	4	8	0.26	0.01	3.94	0.17	2.18	6.40
Farmer 6	90	2	8	0.25	0.01	4.70	0.28	1.42	6.30
Farmer 7	90	2	8	0.21	0.01	4.02	0.17	2.33	6.20
Farmer 8	90	2	8	0.23	0.01	4.32	0.49	4.03	6.10
Farmer 9	90	2	8	0.24	0.01	4.32	0.65	1.04	6.20

3.2 Study 1: Nutrient balance and resource flow analysis

3.2.1 Characterization of households

At Garin Labo, nine case study farms were selected to represent three socio-economic groups of farmers namely, resource rich, medium, and poor. Three farmers from each socio-economic group were used to appraise the effect of resource endowment on nutrient balance at the farm level. However, at Saurniya and Cheyohi, nutrient balance assessments were conducted on a village scale with one farmer from each socioeconomic group.

Categorization of households into socio-economic groups was based on a local wealth ranking exercise centred on ownership of draught oxen, donkeys, livestock herds and cultivated crop land. Differentiation of households into the socio-economic group or farm typologies was undertaken before data collection, and the three groups were defined as follows:

Rich: This refers to a crop-livestock farmer who is equipped with draught animals and tillage implements.

Medium: This refers to a crop-livestock farmer who owns neither draught animals nor tillage implements but has a sizeable number of other livestock exceeding one Tropical livestock unit (TLU).

Poor: This refers to a farmer who is essentially into crop production but may keep a number of livestock not exceeding one TLU.

The various wealth ranking indicators used for the characterization of households at the selected sites are shown in Table 3-2.

Table 3-2: Resource profile of household's categories

Criteria	Rich	Medium	Poor
Draught oxen (number)	2	0	0
Cattle (number)	>1	0-1	0
Donkeys (number)	≥1	0	0
Small ruminants (number)	>20	11-20	0-10
Total herd size (TLU)	>2	1-2	<1
Ploughs (number)	≥1	0	0
Carts (number)	≥ 1	0	0
Total land holding (ha)	≥ 2	0.9-2	0.1-0.8

Source: SLP - IITA baseline report (2007) (unpublished).

3.2.2 Quantification of nutrient flows

3.2.2.1 Nutrient flows managed by farmers

A survey was conducted from March to October 2007 in the 15 selected households to collect information on nutrient flows managed by farmers. The inflows investigated were the quantities and types of mineral fertilisers (IN 1) and manure (IN 2) entering the farm annually. The outflows were crop products (OUT 1) and residues (OUT 2) leaving the farm annually for the homestead use or sold. Farmers generally gave quantities in their own units, such as sacks, bags and buckets, which were converted to standard metric amounts. Samples of the different inputs and products were collected and analysed for their total N, P, K contents.

3.2.2.2 Environmental nutrient inflows

Atmospheric deposition was estimated as nutrient inputs through rainfall and harmattan dust (FAO, 2004). Biological nitrogen fixation (IN 4) in the crop production systems was estimated from the general equation:

$$IN\ 4\ (N) = IN\ 4a + IN\ 4b$$

Where IN 4a is the symbiotically fixed N and IN 4b the non-symbiotically fixed N. Symbiotic nitrogen fixation was calculated with the function of Stoorvogel and Smaling (1990).

$$IN\ 4a = \left(\left(N_G \times Y_G\right) + \left(N_H \times Y_H\right)\right) \times 0.6$$

Non-symbiotic nitrogen fixation was estimated from the function (Smaling *et al.*, 1993):

$$IN\ 4b = \left(2 + \left(p - 1350\right) \times 0.005\right)$$

Where p is preciptation, N_G and N_H are quantities of N accumulated in grain and haulm, respectively with Y_G and Y_H being grain yield and haulm yield respectively.

3.2.2.3 Estimation of environmental nutrient outflows

The quantities of N lost annually through leaching (kg ha^{-1} yr^{-1}) were estimated from the transfer function developed by De Willigen (2000) as follows:

$$OUT\ 3N = 21.37 + \frac{p}{C \times L} \times (0.0037 \times Nf + 0.0000601 \times Oc - 0.00362 \times Nu)$$

Where p is annual precipitation (mm yr^{-1}), C is the clay content (%) of the topsoil, L is rooting depth (m), Nf is N derived from the application of mineral and organic fertiliser

(kg ha^{-1}), Oc is organic carbon content (%) of the top soil and Nu = N uptake by the crop (kg ha^{-1} yr^{-1}).

The amount of K lost annually through leaching (kg ha^{-1} yr^{-1}) was calculated using the transfer function developed by Smaling (1993) as follows:

$$OUT\ 3K = (Ke + Kf) \times (0.00029 \times p + 0.41)$$

Where Ke is the exchangeable K ($cmol_c$ kg^{-1}) in the top soil and Kf is the amount of K derived from mineral fertiliser.

The loss of gaseous N (kg ha^{-1} yr^{-1}) from the soil (OUT 4) was calculated by multiplying the percentage of N lost through denitrification (DN) by the amount of N supplied through fertiliser application and soil mineralization as follows:

$$OUT\ 4 = (Ns + Nf) \times DN$$

$$Ns = 20 \times Ntot \times M$$

Where Ns is mineralized N (kg ha^{-1}) in the rootable zone, Nf is N applied with mineral and organic fertiliser (kg ha^{-1}). Ns is determined from soil total N and the annual relative mineralization rate (M) estimated at 3 % (Nye and Greenland, 1960). DN is a function of clay content C (%) of the top soil, and the annual rainfall p (mm yr^{-1}), through the transfer function (Smaling *et al*., 1993):

$$DN = -9.4 + 0.13 \times C + 0.01p$$

The nutrient balance was therefore estimated as:

Nutrient balance = IN 1 + IN 2 + IN 3 + IN 4 – OUT 1 + OU T2 + OUT 3 + OUT 4

3.3 Study 2: Quantification of tradeoffs in alternative uses of crop residue

Two researcher-managed on-farm experiments (Study 2a and 2b) were conducted to quantify the benefits from crop production that a farmer sacrifices for a unit benefit in livestock produce by feeding more crop residues to livestock rather than incorporating them into the soil. Five scenarios of allocating legume haulms (H) and cereal stover (S) for soil application (SA) and livestock feeding (LF) were evaluated as:

Scenario 1: 0 % SA (0 % H, 0 % S) versus 100 % LF (100 % H, 100 % S)

Scenario 2: 50 % SA (25 % H, 75 % S) versus 50 % LF (75 % H, 25 % S)

Scenario 3: 50 % SA (50 % H, 50 % S) versus 50 % LF (50 % H, 50% S)

Scenario 4: 50 % SA (75 % H, 25 % S) versus 50 % LF (25 % H, 75 % S)

Scenario 5: 100 % SA (100 % H, 100 % S) versus 0% LF (0 % H, 0% S)

Study 2a monitored the impact of incorporating crop residues into the soil on the productivity of the cropping system and Study 2b assessed the effect of feeding crop residues to livestock on the productivity of the livestock unit of the farm.

3.3.1 Study 2a: Effect of crop residue incorporation on productivity of cereal-legume cropping system

3.3.1.1 Sites

The study was conducted on two farms each at Cheyohi, Sarauniya, and Garin Labo. The soils at Cheyohi, were Ferric Luvisols (FAO and UNESCO, 1994) with loamy texture. At

Sarauniya, however, the soils were Regosols (FAO and UNESCO, 1994) with sandy loam texture. The study in Garin Labo on the other hand was conducted on Eutric Gleysols (FAO and UNESCO, 1994) with sandy texture. The selected physical, chemical and microbiological properties of the soils (0 – 15 cm) at the beginning of the study are given in Table (3-3).

Table 3-3: Physical, chemical and microbiological properties of soils at the study sites

Soil parameters	Location (Soil)					
	Cheyohi (Ferric Luvisols)		Sarauniya (Regosols)		Garin Labo (Eutric Gleysols)	
	Farmer 1	Farmer 2	Farmer 1	Farmer 2	Farmer 1	Farmer 2
BD (g cm^{-3})	1.27	1.29	.36	1.35	1.45	1.52
pH (H_2O 1:1)	5.95	6.43	6.14	5.9	6.46	6.13
OM (%)	0.87	0.85	0.64	0.63	0.47	0.45
Total N (kg ha^{-1})	600.0	600.0	450.0	450.0	150.0	150.0
NO_3^- - N (mg kg^{-1})	4.74	4.69	4.34	5.23	3.28	7.65
NH_4^+ - N (mg kg^{-1})	0.69	0.74	1.66	1.45	0.68	0.62
Avial P (mg kg^{-1})	4.41	6.88	12.9	10.03	1.83	3.74
Ca ($cmol_c$ kg^{-1})	2.25	2.29	2.04	2.22	1.96	2.01
Mg ($cmol_c$ kg^{-1})	1.01	1.04	0.79	0.67	0.47	0.54
K ($cmol_c$ kg^{-1})	0.35	0.35	0.32	0.34	0.20	0.20
Na ($cmol_c$ kg^{-1})	0.21	0.22	0.21	0.21	0.18	0.19
ECEC ($cmol_c$ kg^{-1})	3.82	3.9	3.36	3.44	2.81	2.94
MBC (mg kg^{-1})	859	923	264	253	527	287
AMSC*	75.3	92.1	45.2	74.8	167.2	87.2
β-glu*	65.8	59.6	71.2	90.7	15.8	22.7

*AMSC: Arbuscular mycorrhiza spore count (spore $100g^{-1}$), β-glu: β-glucosidase activity (mg PN kg^{-1} h^{-1}), 3.3.1.2 Experimental design

Five treatments of legume haulms and cereal stover mix were incorporated into the soil as follows: 0% H 0% S (T1), 25% H 75% S (T2), 50% H 50% S (T3), 75% H 25% S (T4), and 100% H 100% S (T5). The design was a randomized complete block design with three replications. Plot sizes were 20 m x 10 m at Cheyohi, 30 m x 4 m at Sarauniya, and 20 m x 6 m at Garin Labo. Adjacent plots within the blocks were separated by 1 m wide access while blocks were separated by 2 m wide access.

3.3.1.3 Soil sampling

Soil samples for physical and chemical analyses were collected before the incorporation of crop residues, and after harvest. Five soil cores (0 – 15 cm) were taken randomly from each plot with 3 cm diameter soil auger and bulked to give a composite. The soil samples were air dried, sieved through 2 mm and 0.5 mm screens for analyses. A metallic core (5.0 cm internal diameter and 5.0 cm high) was used to sample soils for bulk density determination. Two of such samples were taken from the surface soil (0 – 5 cm) of each plot. Soil samples from the rhizosphere of cereal crops were collected before the incorporation of crop residues and also after harvest for microbial analysis.

3.3.1.4 Crop residue incorporation

Crop residues used for the study were obtained from the selected farms, at the end of the cropping season in 2007. Crop residues were weighed into the appropriate proportions, spread evenly on the designated plots, and incorporated manually into the soil. The chemical characteristics and plant residue quality index (PRQI) of the crop residues incorporated into the soils are shown in Table 3-4. Appendix (3) shows the amount of crop residues incorporated at various locations.

3.3.1.5 Land preparation and planting

Animal-drawn mould board ploughs and tine harrows were used to prepare plots for seeding during the major rainy season of 2008. At Cheyohi, maize seeds (variety Obaatanpa) were planted at a spacing of 75 cm x 40 cm. An extra-early maize genotype, 2004 TZEE-W POP STR C4 obtained from IITA was planted at a spacing of 75 cm x 25 cm at Sauarniya. At Garin Labo, pearl millet variety (Zatib) was planted at a spacing of 150 cm x 100 cm.

Table 3-4 Chemical characteristics of crop residues incorporated into soil

Location	Crop Residue	Quality parameter (%)						C:N ratio	PRQI
		OC	Total N	Total P	Total K	Lig*	Phenol		
Sarauniya									
Farmer 2	Groundnut haulms	47.6	2.2	0.14	2.4	12.4	5.7	21.6	6.5
	Maize stover	48.6	0.6	0.03	2.3	7.5	5.1	81.0	2.6
Farmer 3	Groundnut haulms	48.0	2.3	0.24	1.7	12.1	6.2	20.9	6.7
	Maize stover	48.1	0.6	0.05	1.3	8.3	6.8	80.2	2.6
Cheyohi									
Farmer 2	Cowpea haulms	45.0	1.7	0.14	1.4	13.0	6.0	26.4	5.6
	Maize stover	45.4	0.3	0.03	0.6	10.0	7.3	151.4	1.4
	Maize husk	47.7	0.4	0.05	0.7	5.9	5.4	119.3	1.9
Farmer 3	Cowpea haulms	46.9	1.6	0.27	2.6	13.8	5.3	29.3	5.2
	Maize stover	47.9	0.6	0.06	1.5	9.2	5.0	79.9	2.6
	Maize husk	47.2	0.3	0.05	0.6	5.1	4.3	157.3	1.4

Garin Labo									
Farmer 2	Cowpea haulms	42.5	1.4	0.07	1.0	14.6	3.3	30.4	5.1
	Millet stover	48.9	0.4	0.05	2.2	11.4	3.8	122.3	1.7
Farmer 3	Cowpea haulms	50.4	2.1	0.12	1.1	9.0	2.6	24.0	6.9
	Millet stover	50.1	0.3	0.03	2.6	10.9	3.1	167.0	1.3

* Lig = Lignin, OC = Organic carbon

3.3.1.6 Crop management

The amounts of N, P_2O_5, and K_2O applied to cereals and legumes at the selected sites are given in Table 3-5. These application rates represent two-thirds ($^2/_3$) of the national NPK recommendations specific to the selected farms. At Cheyohi, the application of mineral nutrients was done with NPK: 15-15-15 at 2 WAP followed by sulphate of ammonia at 5 WAP. At Sarauniya, single super phosphate (SSP) and muriate of potash were incorporated into ridges before planting. Equal doses of urea were applied at 2 and 5 WAP. At Garin Labo, SSP was broadcast and incorporated into the upper 20 cm of the soil during land preparation, followed by split application of N as urea at 2 and 5 WAP.

Weeds on the fields were controlled manually by hoeing at 4 and 7 WAP. To minick the standard crop management practice by the farmers in the selected villages, no herbicides or pesticides were applied to the crops.

Table 3-5 Application rates of mineral fertiliser at the study sites

Site (Soil)	Crop	Mineral nutrients applied (kg ha^{-1})		
		N	P_2O_5	K_2O
Cheyohi (Ferric Luvisol)	Maize	40.0	26.7	26.7
	Cowpea	0.0	26.7	26.7

Sarauniya	Maize	80.0	40.0	20.0
(Regosol)	Groundnut	0.0	36.0	16.7
Garin Labo	Milllet	30.7	12.0	0.0
(Eutric Gleysol)	Cowpea	0.0	12.0	0.0

3.3.1.7 Harvesting and plant sample preparation

At the end of the cropping season in 2008, crops were harvested from net plots of sizes 4 m x 5 m at Cheyohi, 4 m x 3 m at Sarauniya, and 3 m x 4 m at Garin Labo. Samples of the grain, stover and haulm were collected; oven dried at 65 ºC for 48 h and milled for chemical analysis.

3.3.1.8 Biochemical analysis of plant materials

Dry matter content of plant samples were determined by drying plant materials at 105 ºC for 16 h (AOAC, 1990). Plant materials were ashed in a muffle furnace at 550 ºC for 8 h to determine ash content. About 0.3g of plant materials were digested with 4.4 ml of selenium powder, lithium sulphate, hydrogen peroxide, and sulphuric acid mixture. The total N and P concentrations in the digest were determined using the automated analytical (Technicon Auto-Analyser II) procedure of Novozamsky *et al*. (1983). The total K in the digest was then determined by flame emission spectroscopy. The total C was determined by the modified wet combustion technique described by Nelson and Sommers (1982). Acid detergent fibre (ADF), lignin, cellulose and polyphenol were determined by the methods described by Anderson and Ingram (1993). Plant samples were categorized using the index proposed by Tian *et al*. (1995) as PRQI = [1/ (0.423 C:N + 0.439 lignin + 0.138 polyphenols)] x 100, with the coefficients of C:N, lignin and polyphenol representing their relative contributions to the index.

3.3.1.9 Soil physical and chemical analysis

Air-dried soil samples were passed through a 2 mm sieve and analysed for particle size distribution by the Bouyoucos hydrometer method (Bouyoucos, 1963). Bulk density was determined by the core method (Blake and Hartge, 1986). Soil pH was determined in water (1:1 soil-water ratio). Soil organic carbon was determined by the wet combustion method (Nelson and Sommer, 1975). 5 g of soil samples for NH_4^+-N and NO_3^--N determination were extracted with 50 ml of 2 *M* KCl and analysed with the Technicon Auto-Analyser II. Total N was analysed by the auto-analyser after digesting with a mixture of H_2SO_4, selenium, and salicylic acid. Available phosphorus was extracted by Bray 1 method and determined with the auto-analyser. Exchangeable acidity was determined in 1 *M* KCl extracts (5 g of soil in 30 ml of extract) by titrating with 0.01 *M* NaOH. The Al in the titrate was complexed with NaF and back titrated with 0.01 *M* HCl to determine Al levels. 2.5 g of soil samples for exchangeable bases were extracted with 50 ml of 1 *M* ammonium acetate. The amounts of Na^+ and K^+ in the extract were determined by flame photometry, while atomic absorption spectrophotometry was used to determine the concentrations of Ca^{2+} and Mg^{2+}.

3.3.1.10 Determination of microbial biomass C

The amount of C in the microbial biomass of soil was determined by the fumigation extraction technique of Anderson and Ingram (1993). Two subsamples of fresh soil (15 g = 10 g on dry weight basis) of which one was immediately extracted with 50 ml of 0.5 *M* K_2SO_4 after being shaken on a rotary shaker for 25 minutes, and the other was fumigated with ethanol-free chloroform in the dark for 24 h before extraction.

The organic carbon in the extract was determined using dichromate oxidation. Amounts of C released from microbial cells during chloroform fumigation were calculated from the difference between extractable C in fumigated and unfumigated samples.

3.3.1.11 Determination of vesicular-arbuscular mycorrhizal (VAM) spore count

Spore abundance of VAM was determined by the sucrose centrifugation method (Jenkins, 1964). About 100 g of fresh soil (85 g on dry weight basis) was suspended in 300 ml of water for 30 sec. The suspension was decanted over a series of sieves. The contents of 106 and 53 mm sieves were transferred into 20-60 w/v sucrose gradient solution in 100 ml centrifuge tubes. Centrifugation was done at 3000 rpm for 4 min. Spores in the supernatant were examined and counted at 40 x with a dissecting microscope.

3.3.1.12 Determination of β-glucosidase

The method used to estimate β-glucosidase was based on the determination of the released p- nitrophenol after the incubation of soil with p- nitrophenyl glucoside solution (Eivazi and Tabatabai, 1988). A mixture of 1 g soil, 0.25 ml of toluene, 4 ml of modified universal buffer (MUB), and 1 ml p- Nitrophenyl- β-D-glucoside (PNG) was incubated at 37 °C for 1 h. After the incubation, 1 ml of 0.5 *M* $CaCl_2$ and 4 ml of 0.1 *M* Tri(hydroxymethyl) aminomethane buffer (pH 12) were added, shaken, and filtered. The optical intensity of the resultant filtrate was measured with a spectrophotometer at 400 nm. A control was made in the same way without the addition of PNG.

3.3.1.13 Economic analysis

The economic viability of crop residue incorporation was assessed on the basis of net farm benefit (NFB) and value cost ratio (VCR). The partial budgeting technique for onfarm research (CYMMYT, 1988) was used to evaluate the NFB. Crop prices and the operational cost were the average prices prevailing in the study area during the trial. Gross benefit accruing from each treatment was calculated as the product of the grain yield from the treatment and the average unit price of the grains. The cost of land preparation, planting and fertiliser application did not differ among treatments and were ignored in the partial budget. Variable input costs were the actual prices of labour paid for spreading and incorporation of crop residues. The NFB was calculated as the difference between gross benefit and variable input cost. The VCR was calculated as follows: $VCR = \frac{(Y_{CR} - Y_C) P_G}{Q_{CR} \times P_{CR}}$ where Y_{CR} is the grain yield from plots with crop residue application, Y_C is the grain yield from control plots, P_G is the unit price of grains yield and P_{CR} is unit price for crop residue incorporation, , and Q_{CR}, the quantity of crop residues applied.

3.3.1.14 Social acceptability appraisal

A total of 10 farmers were interviewed in each of the three locations. Social indicators of agricultural sustainability assessed were indigenous knowledge, perceived fears and risks and physical stress on the use of crop residues as a soil amendment. The questionnaire used to collect data on the social acceptability of crop residue incorporation is presented in Appendix (1).

3.3.1.15 Statistical analysis

Measured variables and estimated parameters were subjected to analysis of variance for randomized complete block design with 3 replicates using GenStat discovery edition 12 (Payne *et al*., 2009). Treatment means were separated by least significant difference (LSD) at P = 0.05%. Correlation analysis was used to determine the degreee of association between the yield components and either the amount of biomass or nutrients added to the soil through crop residue incorporation.

3.3.2 Study 2b: Effect of crop residues intake on productivity of livestock

3.3.2.1 Acquisition of experimental animals

This study was conducted in the homesteads of the farmers selected for the study 2a during the dry season of 2007 (December 2007 to March 2008). Thirty male Sahelian sheep (initial live weight = 26.0 kg (± 2.5)) were bought from a livestock market in Maradi for the study at Garin Labo, while thirty male goats (initial live weight = 11.9 kg (± 1.4)) were bought from a similar market at Bejuwa (in Jigawa State) for the study at Sarauniya. The thirty male sheep (initial live weight = 13.1 kg (± 1.4)) used for the study at Cheyohi were bought from a livestock market at Savelugu. All the test animals were aged between 12 and 18 months.

3.3.2.2 Experimental design, feeding and management

At each farm, 15 animals were blocked according to their initial live weights and assigned to the 5 dietary treatments of legume haulms and cereal stover mix (0% H 0% S (T1), 25% H 75% S (T2), 50% H 50% S (T3), 75% H 25% S (T4), and 100% H 100% S

(T5)) corresponding to the proportion of crop residues not used for soil incorporation. Table (3-6) shows the biochemical composition of the crop residues used. The experimental design was a randomized complete block design with 3 replications.

Table 3-6: Chemical composition and digestibility of crop residues used

Location	Crop Residue*	Chemical constituents[1] (%)									OMD
		Ash	DM	CP	NDF	ADF	Lig	Cell	Hcel	NDFL	
Sarauniya											
Farmer 2	G haulms	11.3	89.3	13.6	52.2	41.4	12.4	28.0	10.8	23.8	555.4
	Mz stover	5.9	91.2	4.0	75.0	46.8	7.5	37.5	28.2	10.0	519.3
Farmer 3	G haulms	10.8	88.7	14.1	46.4	39.0	12.1	25.6	7.4	26.1	573.9
	Mz stover	6.5	91.2	3.6	74.9	44.9	8.3	35.5	30.0	11.1	505.5
Cheyohi											
Farmer 2	C haulms	6.2	90.0	10.4	51.8	37.6	13.0	26.1	14.2	25.1	553.9
	Mz stover	5.6	92.9	2.1	75.6	48.7	10.0	24.0	26.9	13.2	479.4
	Mz husk	2.6	90.6	2.1	83.5	40.0	5.9	32.8	43.5	7.1	524.2
Farmer 3	C haulms	7.4	90.2	9.9	55.0	40.5	13.8	29.9	14.5	25.1	539.5
	Mz stover	4.4	91.9	3.9	76.7	46.2	9.2	35.5	30.5	12.0	483.9
	Mz husk	1.7	90.2	2.8	83.1	37.2	5.1	31.7	45.9	6.1	558.7
Garin Labo											
Farmer 2	C haulms	5.1	89.9	8.8	60.2	47.2	14.6	33.0	13.0	24.3	516.4
	Mlt stover	5.1	91.4	2.3	76.7	50.0	11.4	38.4	26.7	14.9	460.1
Farmer 3	C haulms	6.8	89.5	13.3	47.2	29.4	9.0	22.8	17.8	19.1	591.6
	Mlt stover	5.0	91.9	1.8	80.7	50.9	10.9	40.9	29.8	13.5	443.6

*G = groundnuts, Mz = maize, C = cowpea, Mlt =millet, CP = crude protein, NDF = neutral detergent fibre [1]Lig =lignin, Cell = cellulose, Hcell = hemicellulose, OMD =organic matter digestibility.

Animals were housed individually in roofed pens of 1 m x 2 m floor spacing. The animals underwent standard quarantine procedures for 14 d before the start of the experiment. Crop residues were offered daily at a rate of 50 g DM per kg liveweight of livestock (Tanner *et al*., 2001). Haulms and stover were supplied in separate feeders.

Crop residues were offered to test animals at 8:00 h; control animals were herded on range lands from 8:00 h to 17:00 h. Water and mineral lick were supplied *ad libitum*. The duration of the feeding trial ranged from 34 to 58 d depending on the amount of crop residues produced.

3.3.2.3 Measurements of growth and faecal output

The quantity of crop residues offered was recorded daily during the study period. The refusals (orts) were collected from the feeders and the floor and weighed before the morning feeding at 8:00 h. After every 14 days, animals were weighed in the morning, before feed was supplied, fitted with faecal bags and the faecal matter collected over 24 h, emptied into plastic bags, air dried, and stored for chemical analysis.

Mean animal live weight change per day was determined from the biweekly live weights after the 2-week adaptation period. Average daily gains (ADG) were also determined for the study period. Faecal organic matter excretion (FOM) was calculated from the organic matter intake (IOM) and the average organic matter digestibility (OMD) of the stover and haulms as: $FOM = IOM \times (1 - OMD)$. The OMD was estimated with the transfer function $OMD\ (g\ kg^{-1}) = 607.6 - 0.00042 \times NDF^2 - (14797/NDFL)$ developed by Coleman *et al.* (2003). Where NDF ($g\ kg^{-1}$) is the neutral detergent fibre and NDFL is the lignin content of NDF expressed as g lignin kg^{-1}NDF.

3.3.2.4 Economic viability and social acceptability appraisal

Economic viability of feeding crop residues to livestock was assessed on the basis of NFI and VCR as in section 3.3.1.13. Livestock prices and the operational cost were the average prices prevailing in the study area during the study. A survey was conducted to obtain information on the social factors influencing farmers to feed crop residues to livestock, as described in section 3.3.1.14.

3.3.2.5 Statistical analysis

Data on dry matter intake, weight gain and nutrient concentration in faecal samples were subjected to analysis of variance for randomized complete block design with 3 replicates using GenStat discovery edition 12 (Payne *et al.*, 2009). Where significant differences occurred, LSD (at P = 0.05%) was used to separate means. Correlation analysis was used to determine the degreee of association between the livestock products and either the amount of biomass or nutrients ingested by livestock through the crop residue rations. Linear regression analysis was used to establish the relationship between farm revenue and true tradeoff.

3.3.2.6 Quantification of tradeoffs

Tradeoffs related to the quantities of crop produce sacrificed by a farmer for a unit benefit from livestock by allocating less than optimum amount of the crop residues into crop production. The apparent tradeoffs (ATO) referred to the quantities of grains sacrificed for a unit gain in live weight, and was calculated as: $ATO = P_G \left(Gy_{max} - Gy_i \right) / P_{LW} \times LWG_{100-i}$

where PG is price of a unit quantity of grain;

P_{LW} is price of a unit live weight of livestock; Gy_{max} is the mean grain yield attained by applying the optimum amount of crop residues; Gy_i is the grain yield attained by applying a given amount of the crop residues and LWG_{100-i} is weight gained by feeding the remaining amount of crop residues to livestock.

The true tradeoff (TTO) referred to the quantities of grains and crop residues sacrificed for a unit gain in live weight and manure voided and was calculated as:

$TTO = \left[P_G\left(Gy_{max} - Gy_i\right) + P_R\left(Ry_{max} - Ry_i\right)\right] / \left[P_{LW}\left(LWG_{100-i}\right) + P_M\left(M_{100-i}\right)\right]$. Where P_R is price of a unit quantity of crop residues; P_M is the price of a unit quantity of manure; Ry_{max} is the mean crop residue yield attained by applying the optimum amount of crop residues; Ry_i is the crop residue yield attained by applying a given amount of the crop residues and M_{100-i} is the manure voided by feeding crop residues to livestock.

3.4 Study 3: Assessment of agricultural sustainability of crop residue use

3.4.1 Selection of indicators

The agricultural sustainability of crop residue incorporation was assessed by evaluating its impact on soil quality and crop performance together with the economic viability and social acceptability of the technology. The sustainability of feeding crop residues to livestock on the other hand, was evaluated by monitoring livestock performance indicators such, weight gain, fertiliser value of the manure produced and fodder balance together with indicators for the economic viability and social acceptability of the feeding strategies. Table 3-7 indicates the minimum data set (MDS) for assessing the agricultural sustainability of the five scenarios of crop residue allocations tested.

3.4.2 Transformation and integration of indicators

Measured values of the selected indicators were transformed into unitless values with the aid of linear scoring functions (Appendix 5). Scored values ranged from 1 to 10 with 1 as the least and 10 as the highest indicator strength.

Table 3-7: MDS for assessing the sustainability of crop residue incorporation

Parameter	Indicator	Scoring function
Soil quality	Bulk density(kg dm^{-3})	Less is better
	Organic matter content (%)	More is better
	Nutrient stock (kg ha^{-1})	More is better
	Microbial biomass C and N (mg kg^{-1})	More is better
	Mycorrhizal spore count	More is better
	β-glucosidase activity (µg PN g^{-1} h^{-1})	More is better
Crop performance	Crop produce yield (kg ha^{-1})	More is better
	Crop residue yield (kg ha^{-1})	More is better
Livestock performance	Live weight gain (kg $head^{-1}$)	More is better
	Manure quality (g N kg^{-1})	More is better
Economic viability	Net farm benefit ($ $farm^{-1}$)	More is better
	Value cost ratio	More is better
Social acceptability	Indigenous knowledge on technology	More is better
	Perceived fear and risk of technology	Less is better
	Physical stress	Less is better

The transformed values of the indicators of soil quality were used to estimate the aggregate score for soil quality. Transformed values of indicators were integrated into ecological or economic or social sub index of sustainability by summing the scores for each indicator and dividing by the total number of indicators as shown below:

$$\left(\sum^{n} S_i \right)$$

$$SSI = \left(\frac{\sum S_i}{n} \right)$$

Where SSI is the sustainability subindex, S represents the scored indicator value, and n is the number of indicators in the MDS for a given dimension of agricultural sustainability.

Considering that agricultural sustainability is a three dimensional concept, the triangular approach used by Kang *et al*. (2005) to assess the sustainability of wheat-based cropping system was adopted in this study. Consequently, the overall sustainability index (SI) was calculated as the area of triangle ABC with ecological sustainability, economical sustainability and social sustainability at its vertices (Fig. 3-2). The index was expressed on a scale of 1 to 10, with 1 as least sustainable and 10 as most sustainable.

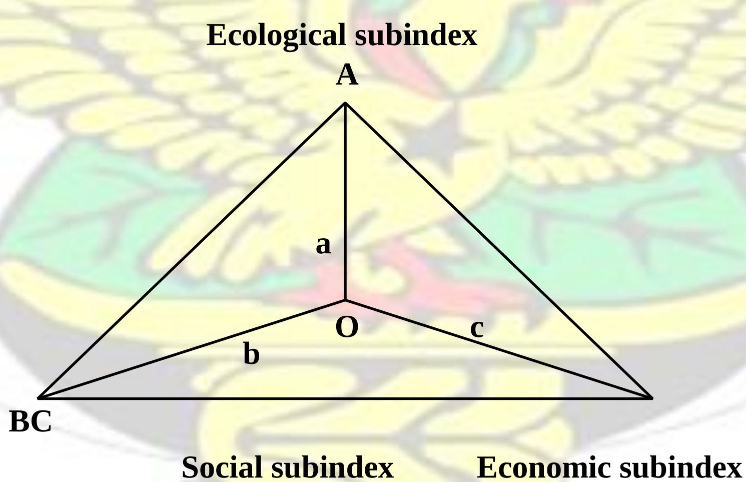


Figure 3-2: Sustainability triangle indicating sub-indices of sustainability (adapted from Kang *et al*., 2005).

$$SI = \frac{(\Delta ABC)}{10} = \frac{(\Delta AOB + \Delta BOC + \Delta COA)}{10}$$

$$= \frac{\left(\frac{1}{2} ab \sin(120) + \frac{1}{2} bc \sin(120) + \frac{1}{2} ca \sin(120) \right)}{10}$$

$$= \frac{\frac{\sqrt{3}}{4} (ab + bc + ca)}{10}$$

Where SI is the sustainability index, a is the SSI for the ecological dimension, b is the SSI for the social dimension and c is the SSI for the economic dimension.

3.5 Study 4: Effect of oil cakes and storage methods on the quality of manure

3.5.1 Acquisition of manure and oil cakes

This study was conducted at the Animal Research Institute (ARI), Nyankpala, Ghana, National Animal Production Research Institute (NAPRI), Zaria, Nigeria and Institut National de Recherche Agronomique du Niger (INRAN), Maradi, Niger. Fresh manure from small ruminants was collected from the Animal Production Department of the Ministry of Food and Agriculture at Savelugu and ARI for the study at Nyankpala. Fresh cattle manure from NAPRI was used for the study at Zaria. Similar cattle manure collected from the livestock unit of INRAN was used for the study at Maradi. The oil cakes composted with manure were sheanut cake at ARI, groundnut cake at NAPRI, and cottonseed cake at INRAN. Sheanut cake was obtained free of charge from sheanut processing company (Sheabu, Ghana Ltd) at Savelugu; groundnut cake and cottonseed cake were bought from local markets. Table 3-8 shows the chemical and biochemical properties of manures and oil cakes used at various locations.

Table 3-8. Chemical characteristics of manures and oil cakes

Site (Soil)	Material*	Chemical parameter (%)						C:N	PRQI
		TN	TP	TK	TOC	Lignin	Phenol		
Nyankpala	Manure			18.2	2.0 8.3	7.8	0.5	0.4	36.3 7.2
(Ferric Luvisol)	S cake	1.6	0.1	0.2	48.0	4.6	32.3	30.6	5.2
Sarauniya	Manure	1.5	0.3	0.4	37.5	11.2	6.0	24.7	6.2
(Regosol)	G cake	7.5	0.6	0.2	47.4	3.1	8.8	6.4	19.0
Maradi	Manure	1.3	0.4	0.2	20.1	10.1	6.6	15.6	8.4
(Eutric Gleysol)	CS cake	3.2	0.5	0.4	48.7	7.4	9.3	15.1	9.1

*S = Sheanut, G= groundnut, CS = cotton seed

3.5.2 Manure storage treatments and experimental design

Eight treatments were tested as follows; T1 – manure heap uncovered, T2 – manure heap covered with plastic sheets, T3 – manure + oilcake heap uncovered, T4 – manure + oilcake heap covered with plastic sheets, T5 – manure stored in pits not lined with plastic sheets, T6 – manure stored in pits lined with plastic sheets, T7 – manure + oilcake stored in pits not lined with plastic sheets, and T8 – manure + oilcake stored in pits lined with plastic sheets.

The experimental design was a completely randomise design with three replicates. Manures and oil cakes were thoroughly homogenized and composted in 2:1 ratio on dry weight basis (40 kg manure: 20 kg oil cake) or as manure only (60 kg). Composts were watered (to 40 % moisture content) only at the beginning of the composting process to mimick the composting practice in the dry savannas. About 200 g of sample was collected from each heap or pit on days 14, 28, 58, 88, 108, and 148 and stored for chemical and biochemical analysis. At the end of the storage period, compost in pits or heaps was harvested and weighed.

3.5.3 Laboratory analysis

Manure samples were analysed for DM, ash contents and total N, total P, total K, total C lignin and phenols concentration as described in section 3.3.1.9. The phytotoxicity of composting mixtures was evaluated by the seed germination index (GI). Ten seeds of each plant were placed on cotton wool moistened with water extracted from composts. The extract was obtained by adding 50 ml of water to 5 g of compost in a flask and agitating at 150 rpm for 1 h, and filtering the extract. After incubation at 25ºC for 72 h, the seed germination percentage and root length of seedlings were determined. Seed germination and root length of plants moistened with deionized water were also measured and used as the control.

The germination index was calculated with the formula of Zucconi *et al*. (1981) as GI = (% Seed $germination_{trt}$ x root $length_{trt}$)/(% Seed $germination_{con}$ x root $length_{con}$) x 100.

Nutrient losses during composting was estimated on mass balance basis as % Nutrient loss = ((DM_i x %N_i) – (DM_f x %N_f))/(DM_i x %N_i) x 100. Where DM_i was the initial mass of the compost, DM_f: final mass of compost on dry matter basis, N_i: initial nutrient concentration of compost and N_f: final nutrient concentration of compost.

3.5.4 Cost and returns of manure management options

The profitability of the manure management options were evaluated with the partial budgeting technique for estimating NFB as described in section 3.3.1.13. Oil cake prices and the operational cost were the average prices prevailing in the study area during the study.

3.5.5 Statistical analysis

Data on DM yield of compost, N P K concentration, total C, lignin and phenols were subjected to analysis of variance for completely randomized design with 3 replicates using GenStat discovery edition 12 (Payne *et al*., 2009); where significant differences occurred, LSD (at P = 0.05%) was used to separate means. Multiple linear regression analysis was used to establish the relationship between GI and the biochemical properties of manure.

3.6 Study 5: Quantification of added benefits from combined application of manure and mineral fertiliser

3.6.1 Study sites

This study was conducted at ARI, Nyankpala, Ghana, Sarauniya, Nigeria and INRAN, Maradi, Niger. The soils based on the FAO and UNESCO (1994) legend were Ferric Luvisols at Nyankpala, Regosol at Sarauniya, and Eutric Gleysols at Maradi. The initial physical, chemical and microbiological characteristics of the soil are given in Table 3-9.

Table 3-9: Initial soil physical, chemical, and microbiological properties (0 – 15 cm)

Soil parameters	Location (Soil)		
	Nyankpala (Ferric Luvisol)	Sarauniya (Regosol)	Maradi (Eutric Gleysol)
pH (1:1 H_2O)	5.7 ± 0.6	5.7 ± 0.4	5.5 ± 0.2
Organic C (g kg^{-1})	5.4 ± 1.3	2.3 ± 0.3	1.6 ± 0.1
Total N (g kg^{-1})	0.6 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Avial P (mg kg^{-1})	17.5 ± 13.6	6.2 ± 1.5	18.3 ± 5.7
NO_3^--N (mg kg^{-1})	13.9 ± 0.1	11.6 ± 1.1	7.5 ± 1.0
NH_4^+-N (mg kg^{-1})	0.4 ± 0.4	0.0	0.0
Ca ($cmol_c$ kg^{-1})	3.8 ± 2.1	1.7 ± 0.4	1.1 ± 0.0
Mg ($cmol_c$ kg^{-1})	0.6 ± 0.1	0.3 ± 0.1	0.2 ± 0.0

K ($cmol_c\ kg^{-1}$)	0.4 ± 0.0	0.4 ± 0.1	0.4 ± 0.0
Na ($cmol_c\ kg^{-1}$)	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.0
Exch acidity	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
ECEC ($cmol_c\ kg^{-1}$)	5.6 ± 2.3	3.2 ± 0.5	2.5 ± 0.0
Sand ($g\ kg^{-1}$)	430.0 ± 0.0	783.3 ± 11.5	843.3 ± 11.5
Silt ($g\ kg^{-1}$)	420.0 ± 0.0	106.7 ± 11.5	66.7 ± 11.5
Clay ($g\ kg^{-1}$)	150.0 ± 0.0	110.0 ± 0.0	90.0 ± 0.0

Values are averages of three replicates with standard deviations

3.6.2 Experimental design

The trial was a factorial combination of 4 application rates of inorganic fertiliser (0 %, 25 %, 50 % and 100 % of the NPK rate recommended for the location) and 4 application rates of farmyard manure (0, 2.5, 5 and 10 t ha $^{-1}$ on dry matter basis) in a randomized complete block design with three replicates. Dimensions of plots were 4 m x 6 m at Cheyohi and Maradi, and 4 m x 4.5 m at Sarauniya. Adjacent plots within the blocks were separated by 1 m wide access; blocks were separated by 2 m wide access.

3.6.3 Farm yard manure and mineral fertiliser application

The small ruminant manure used for the study at Nyankpala was obtained from ARI. At Sarauniya, cattle manure from NAPRI was used. The study at Maradi acquired cattle manure from the livestock unit of INRAN. Manure was mixed thoroughly and composite samples formed from five sub-samples were used for chemical analysis. The quality characteristics of the manure used in the trials are shown in Table 3-10.

Table 3-10: Chemical characteristics of manures applied

Site (Soil)	Organic C (%)	Total N (%)	Total P (%)	Total K (%)	C/N Ratio	Lignin (%)	Phenol (%)	PRQI

Nyankpala (Ferric Luvisol)	46.5	2.3	0.6	1.1	20.4	24.1	2.4	5.1
Sarauniya (Regosol)	41.1	1.2	0.4	0.9	34.0	13.6	2.8	4.8
Maradi (Eutric Gleysol)	68.7	1.5	0.3	2.6	45.0	16.0	8.4	3.7

Farmyard manure was mixed thoroughly, weighed for each plot, spread evenly, and incorporated into the soil before planting. The fertiliser recommendations for maize were 60-40-40 kg ha^{-1} of N-P_2O_5-K_2O (Agyenim-Boateng *et al*., 2006) at Nyankpala and 12060-30 kg ha^{-1} of N-P_2O_5-K_2O at Sarauniya. At Maradi, the fertiliser recommendation for millet was 46-18-0 kg ha^{-1}of N-P_2O_5-K_2O (Maman *et al*., 2000). At Cheyohi, the application of mineral nutrients was done with NPK: 15-15-15 at 2 WAP followed by sulphate of ammonia at 5 WAP.

The methods of fertiliser applications adopted were compactible with the standard farmer practices at the various locations. At Sarauniya, SSP and muriate of potash were incorporated into ridges before planting. Split application of N as urea was done at 2 and 5 WAP. At Maradi, SSP was broadcast and incorporated into the upper 20 cm of the soil during land preparation, followed by split application of N as urea at 2 and 5 WAP.

3.6.4 Soil sampling

Soil samples were randomly collected before planting and after harvest as described in section 3.3.1.3. The samples were analysed for their chemical and physical properties as described in section 3.3.1.9.

3.6.5 Land preparation and planting

Animal drawn mould board ploughs and tine harrows were used to prepare plots for seeding during the major rainy season of 2008. At Cheyohi, maize seed (variety Obaatanpa) were planted at a spacing 75 cm x 40 cm. An extra-early maize genotype obtained from IITA, 2004 TZEE-W POP STR C4, was planted at a spacing of 75 cm x 25 cm at Sauarniya. At Maradi, pearl millet (variety Zatib) was planted at a spacing of 100 cm x 50 cm.

3.6.6 Crop management

Weeds on the fields were controlled manually by hoeing at 4 and 7 WAP. Diseases and pests of economic importance to the crops were not encountered during study; consequently, no herbicides and pesticides were applied to the crops. Grain yield was determined from the central two rows (4 m^2). Samples of yield components (stover, grain, and husk) were collected, oven-dried at 65 ºC for 48 h.

3.6.7 Laboratory analysis

Soil samples were analysed for chemical and physical properties as in section 3.3.1.9. Plant material and manures were analysed for DM, ash contents and total C, N, P and K concentrations as described in section 3.3.1.8. In addition, manure samples were analysed for lignin and phenol as described in section 3.3.1.8.

3.6.8 Quantification of added benefits

The added benefits from the combined application of manure and mineral fertiliser was calculated using the equation: AB = Y comb – (Y fert – Y con) – (Y fym – Y con) – Y con developed by Vanlauwe *et al*. (2002 b), where AB represents the added benefits, Y con, the mean grain yields from control treatments, Y fert,, the mean grain yields from the sole application of mineral fertiliser, Y fym, the mean grain yields from the sole application of manure, and Y comb, the mean grain yields from the combined application of mineral fertiliser and manure.

3.6.9 Returns on investiment in combined manure and mineral fertiliser use

The approach described in section 3.3.1.13 was used to estimate the VCR of the manure and mineral fertiliser treatments tested.

3.6.10 Statistical analysis

Data on grain yield was analysed with GenStat discovery edition 12 (Payne *et al*., 2009) using the two–way analysis of variance with randomised blocks procedure. Mean separations were performed using LSD. Treatment comparisons were deemed significant at $P < 0.05$. T-tests were used to determine the significance of the added benefits. Correlation analysis was used to determine the contribution of N:P ratio to the added benefits.

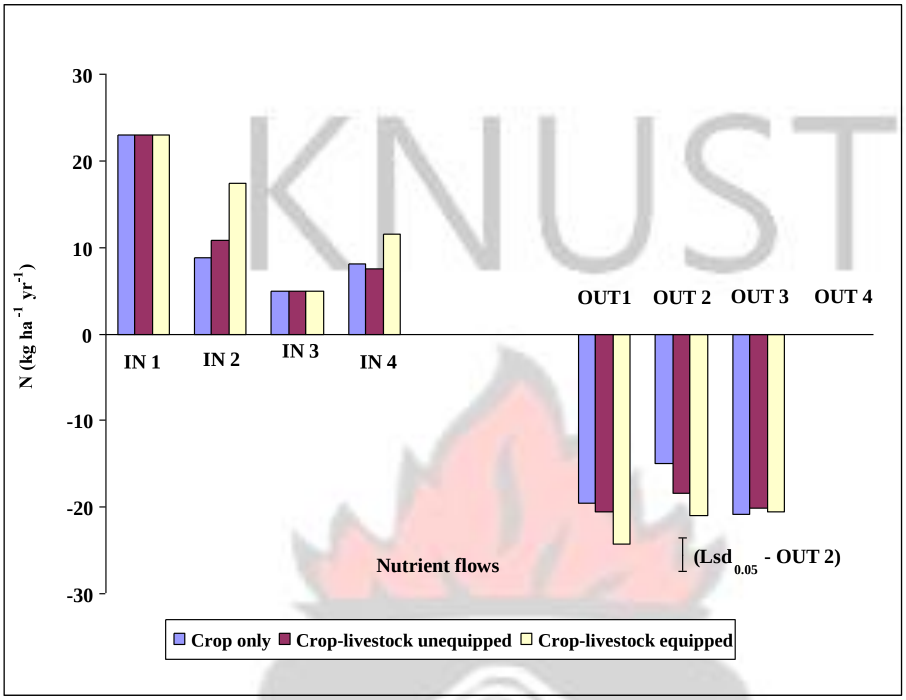
CHAPTER FOUR

4.0 RESULTS

4.1 Nutrient flows and balances of cereal-legume-livestock systems

4.1.1 Nitrogen inputs and outputs

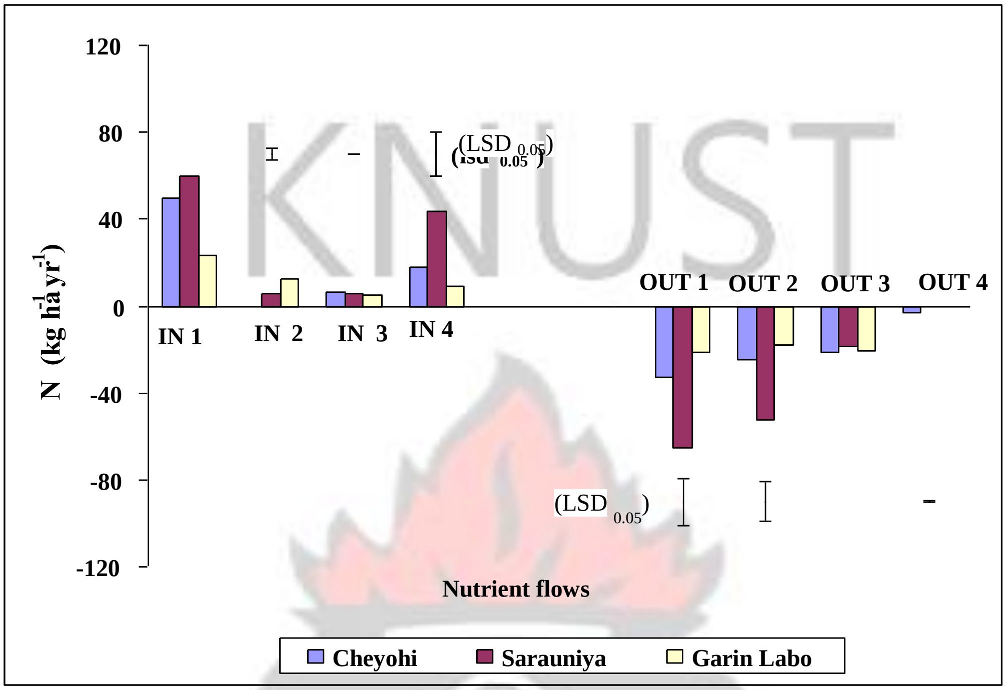
The resource base of the farming systems in Garin Labo (Eutric Gleysol) had no significant effect on their N inputs although equipped crop-livestock system supplied more N through manure than the other systems (Fig. 4-1). Equipped crop-livestock system also lost significantly higher amount of N (21 kg ha^{-1}) through crop residue than the crop only system (15 kg ha^{-1}). All systems, regardless of their resource endowment, suffered similar losses of N from crop produce and leaching.



Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-1: Nitrogen flows at the farm level.

Following the existing fertiliser recommendations for the study locations, farmers in Sarauniya (on the Regosol) applied more N through mineral fertilisers than those in Cheyohi (on the Ferric Luvisol) and Garin Labo (on the Eutric Gleysol) (Fig. 4-2). Nitrogen inputs through the manure application, atmospheric deposition and BNF also differed significantly across the study locations (Fig. 4-2). Groundnuts supplied significantly higher amount of N through BNF than cowpea in either Cheyohi or Garin Labo. Farmers in Sarauniya lost significantly higher amount of N through harvested crop produce and residues than farmers in Cheyohi and Garin Labo (Fig. 4-2).

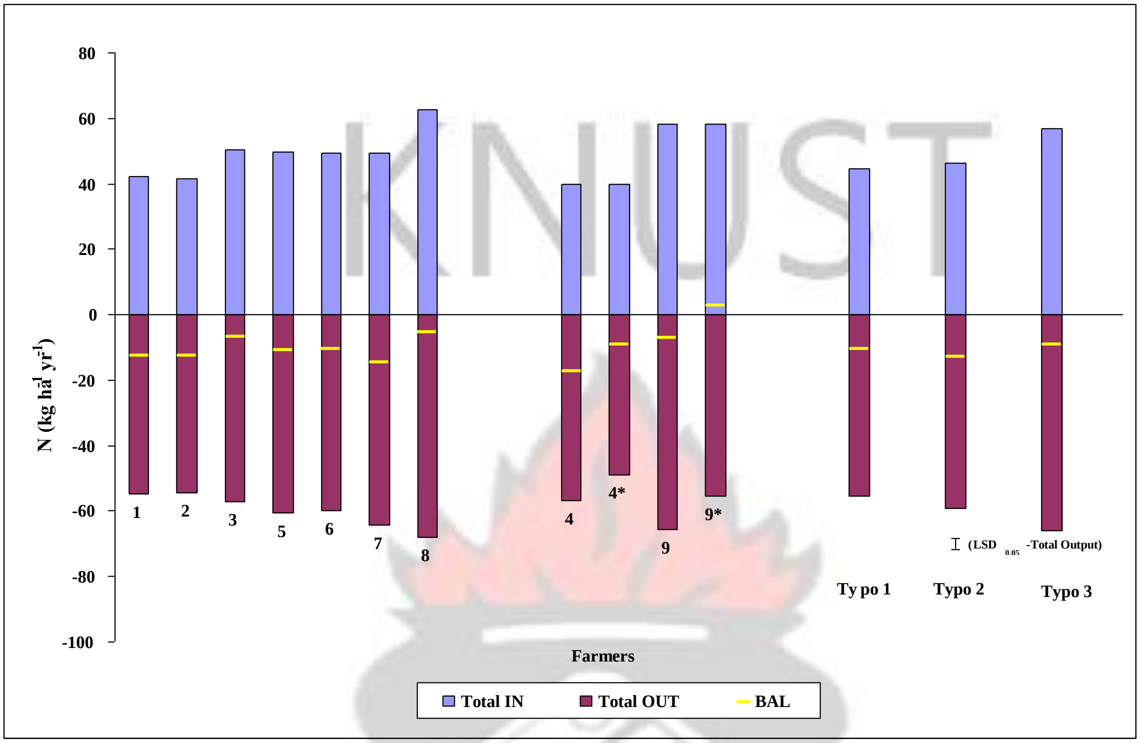


Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-2: Nitrogen flows at the village level.

4.1.2 Nitrogen balances

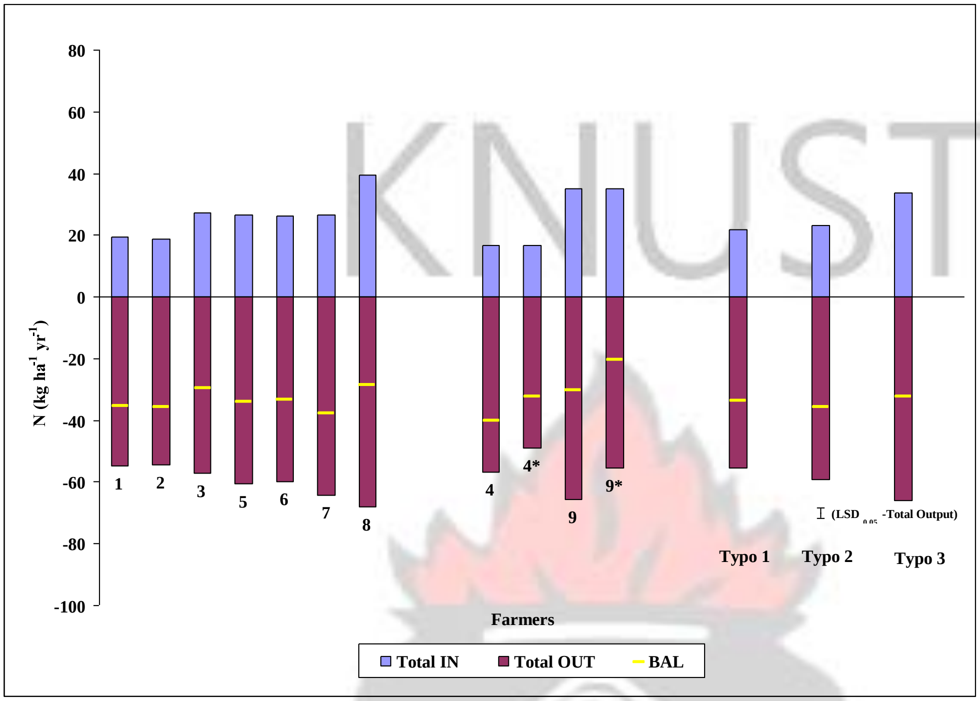
At Garin Labo (on the Eutric Gleysol) under the current farmer practice where all crop residues are removed from the field, N balances were negative (-6.9 to -18.6 kg ha^{-1}) on all farms (Fig. 4-3). In a Scenario where farmers 4 and 9 incorporated half of their residues, farmer 4 defrayed the negative balance by 8 kg ha^{-1} while farmer 9 attained a positive balance (2.7 kg ha^{-1}) as indicated in Fig. 4-3. In the absence of fertiliser application more negative (-20.3 to -40.2 kg ha^{-1}) N balances were obtained on all fields (Fig. 4-4).



* 50 % of the crop residues incorporated into the soil
Flows with no error bars were not significantly different ($p > 0.05$)

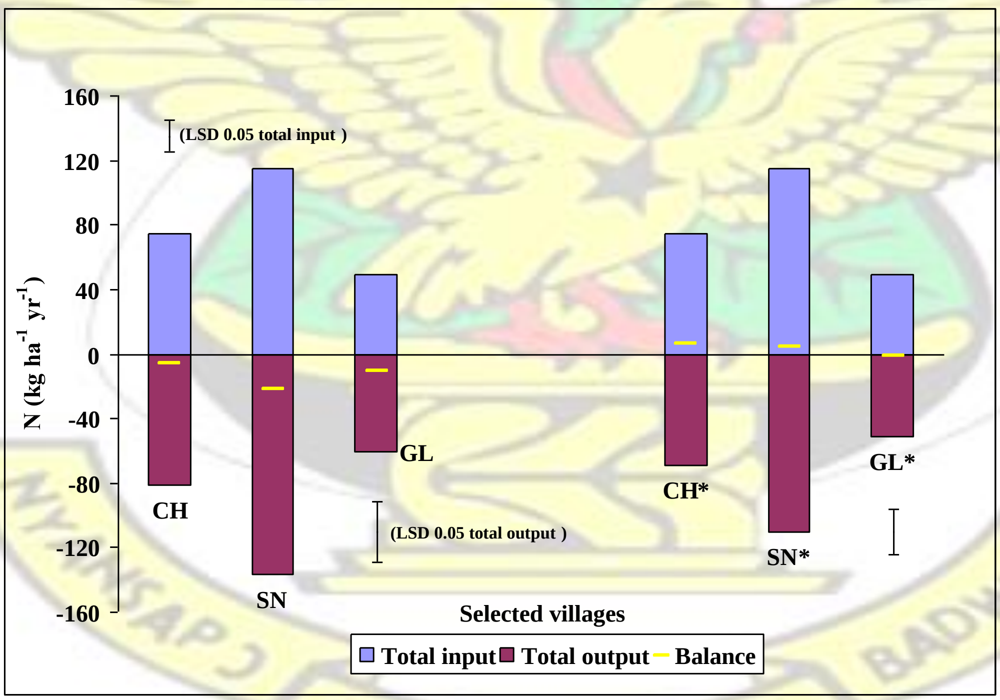
Figure 4-3: Nitrogen balances at farm level with the application of N fertiliser.

As indicated in Fig. 4-5, across the study locations N balance was more negative at Sarauniya (-22.0 kg ha^{-1}) than either Cheyohi (-6.5 kg ha^{-1}) or Garin Labo (-10.8 kg ha^{-1}). In sencarios where farmers applied no mineral fertiliser high negative balances (-33.83 to -81.85 kg ha^{-1}) were obtained (Fig. 4-6). Whether farmers applied mineral fertilisers or not, the N balances estimated for these villages improved tremendously with the incorporation of half of the crop residue produced (Figs. 4-5 to 4-6).



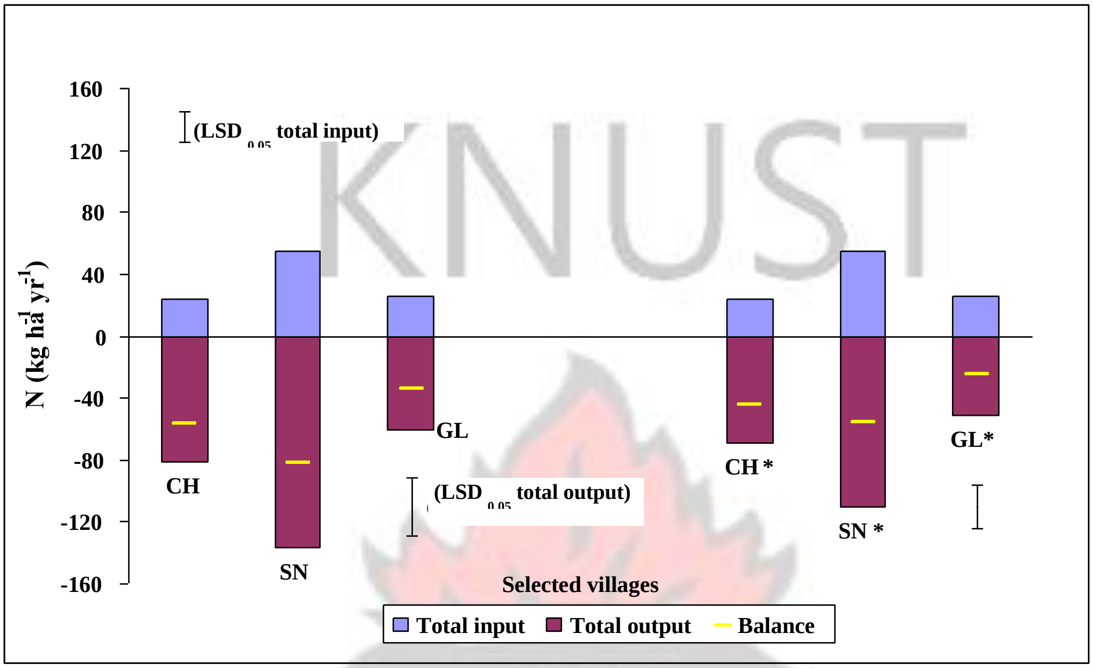
* 50 % of the crop residues incorporated into the soil

Figure 4-4: Nitrogen balances at farm level without the application of N fertiliser.



* 50 % of the crop residues incorporated into the soil, CH = Cheyohi, SN = Sarauniya, GL = Garin Labo
Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-5: Nitrogen balances at the village level with the application of N fertiliser.



* 50 % of the crop residues incorporated into the soil, CH = Cheyohi, SN = Sarauniya, GL = Garin Labo
Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-6: Nitrogen balances at the village level without the application of N fertiliser.

4.1.3 Nitrogen stocks and balances

The NS:NB ratios estimated in the various farms at Garin Labo (on the Eutric Gleysol) are presented in Fig. 4-7. Nitrogen stocks measured in these farms were low and ranged from 178 to 271 kg ha^{-1}. Following the application of mineral N fertiliser, the highest NS:NB ratio of 41 was observed in Farm 3 with the lowest value of 11 occurring in Farm 4. In the absence of mineral fertiliser application however, the NS:NB ratios decreased exponentially to 5 – 9.

Nitrogen stocks in the the Ferric Luvisol at Cheyohi (867 kg ha^{-1}) and the Regosol at Sarauniya (600 kg ha^{-1}) were higher than those in the Eutric Gleysol at Garin Labo (218 kg ha^{-1}) .The NS:NB ratios at the village level were 133 at Cheyohi, 27 at Sarauniya and

20 at Cheyohi with the application of mineral fertiliser as indicated by Fig. 4-7. Without the use of mineral fertiliser, ratios dropped to 15 at Cheyohi, and 7 at both Sarauniya and Garin Labo.

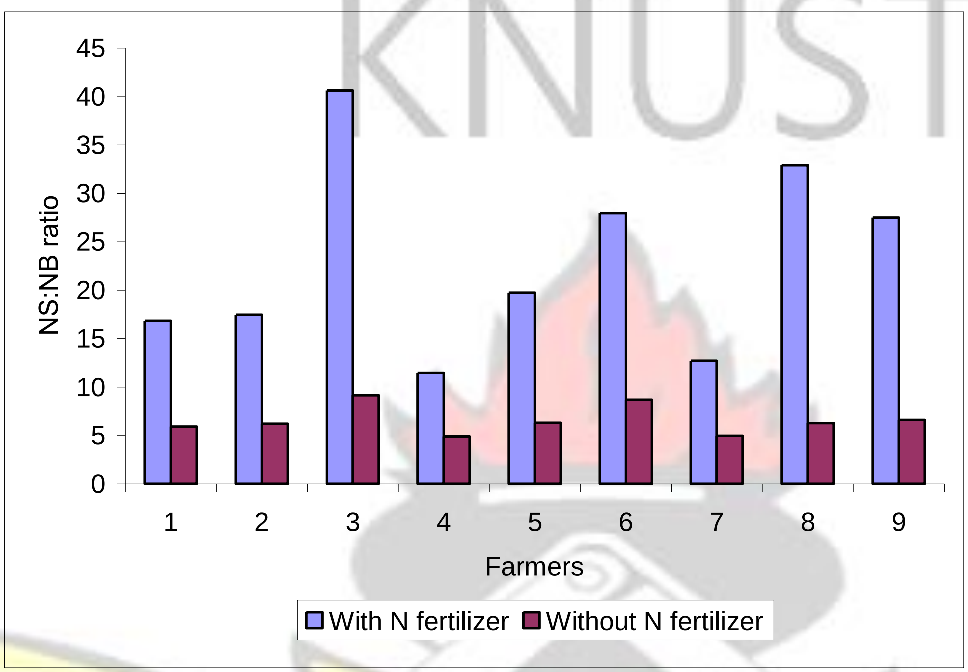
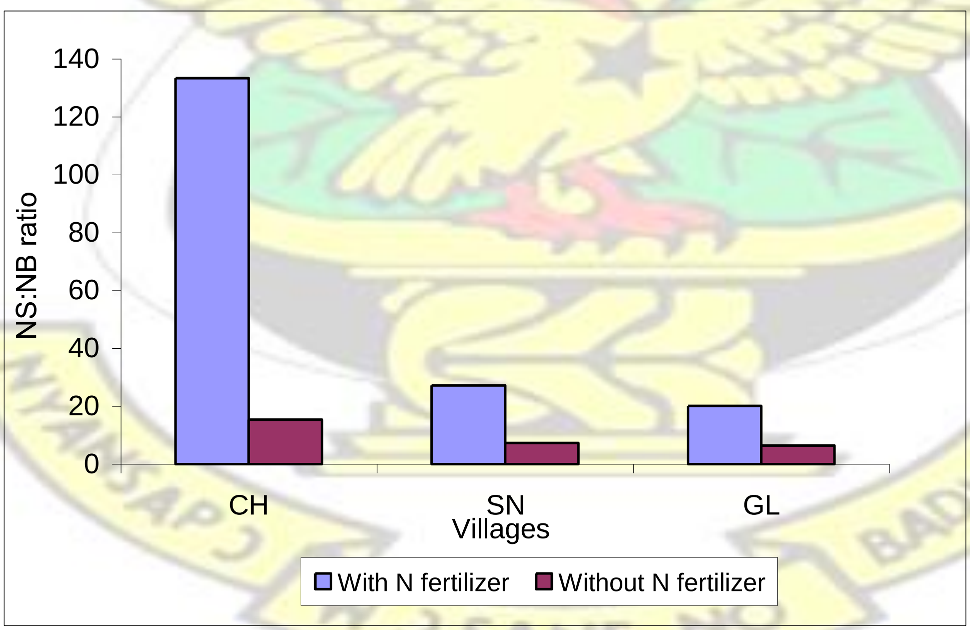


Figure 4-7: Nitrogen stock to N balance ratio at the farm level at Garin Labo.



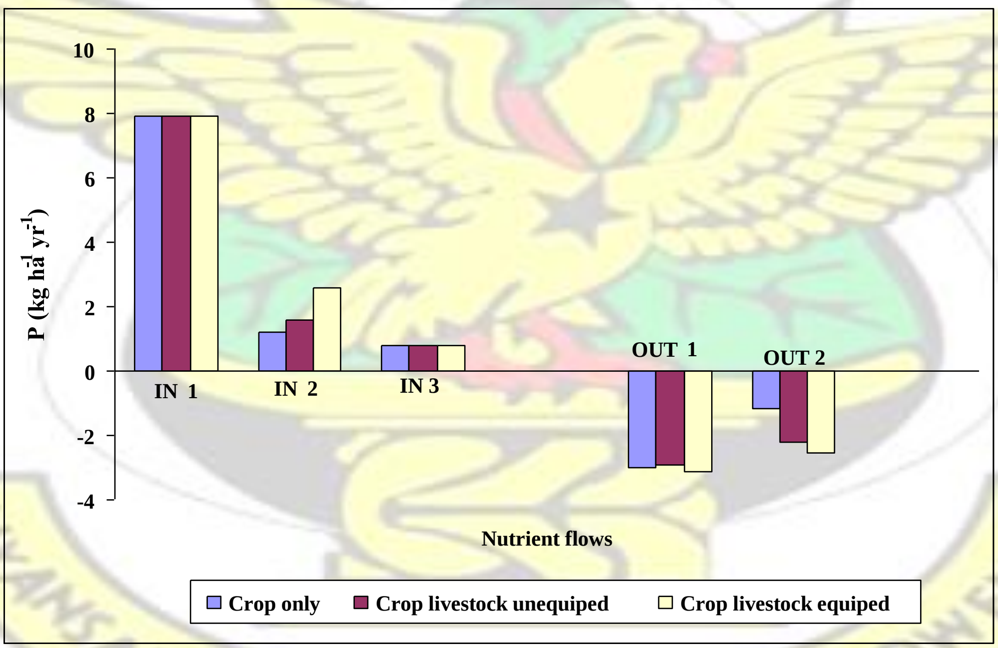
CH = Cheyohi, SN = Sarauniya, GL = Garin Labo

Figure 4-8: Nitrogen stock to N balance ratio at the village level.

4.1.4 Phosphorus inputs and outputs

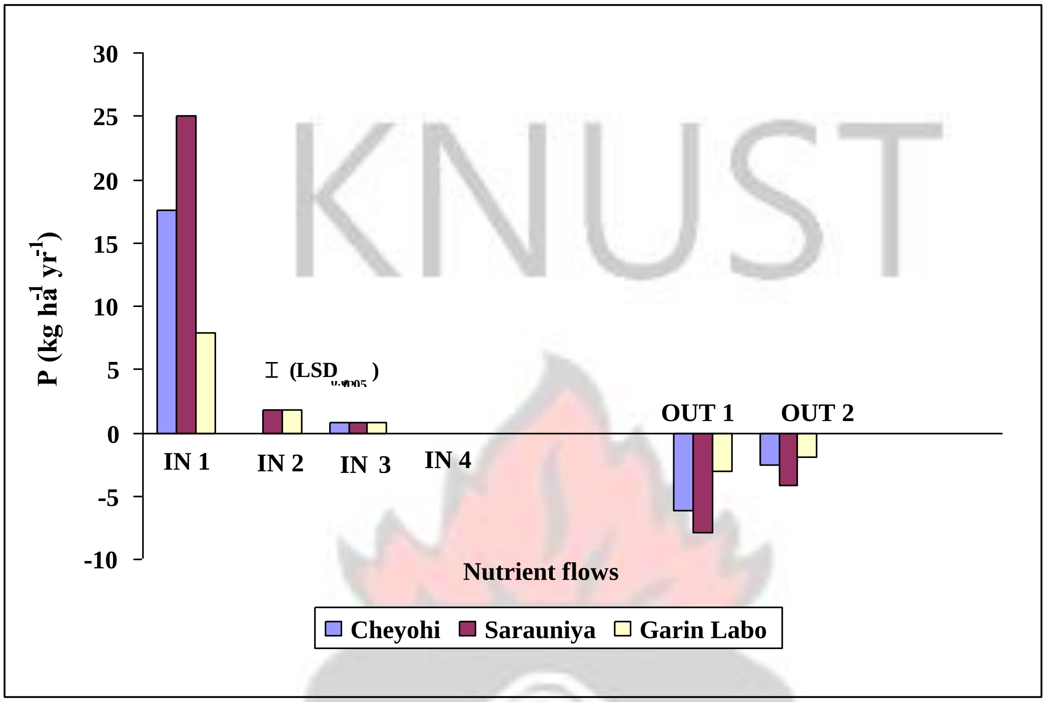
The socio-economic status of the farmers had no significant effect on the amount of P supplied by the farmers into the cereal-legume unit of the farm as all the selected farmers in Garin Labo received 100 kg ha^{-1} of SSP from the SLP team in Niger (Fig. 4-9). All farmers regardless of their socio-economic status suffered similar losses of P from crop produce and crop residue.

In accordance with the existing fertiliser recommendations for the study locations, farmers in Sarauniya (on the Regosol) applied more P through mineral fertilisers than those in Cheyohi (on the Ferric Luvisol) and Garin Labo (on the Eutric Gleysol) (Fig. 410). Phosphorus inputs through the manure application at Sarauniya and Garin Labo differed significantly from P input via manure at Cheyohi.



Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-9: Phosphorus flows in cereal-legume-livestock systems at farm level in Garin Labo.



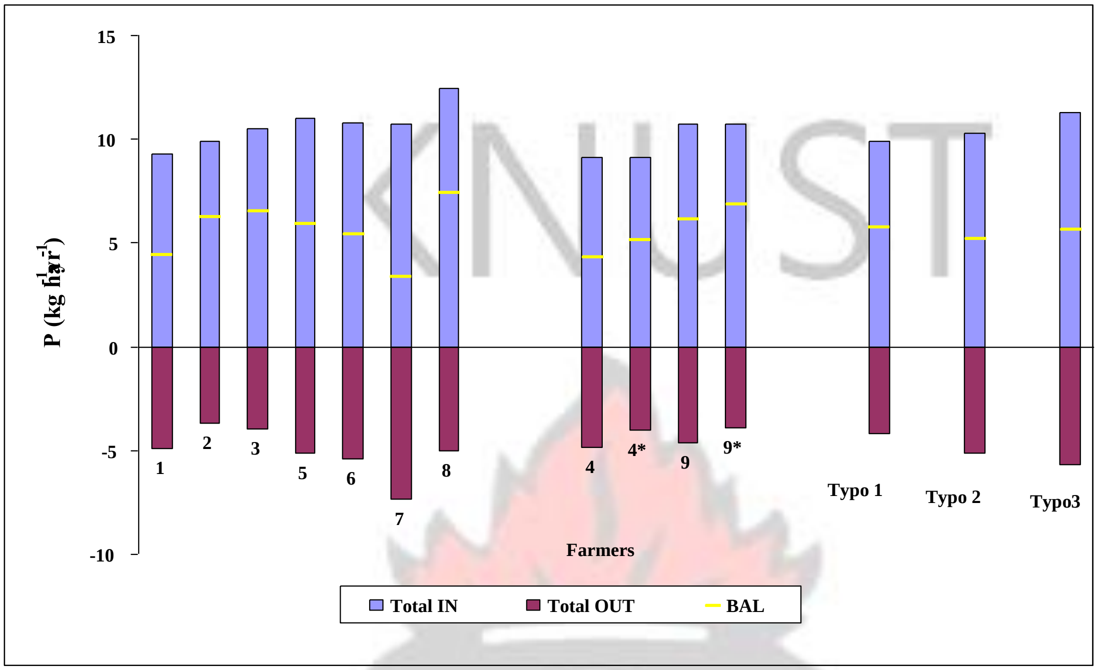
Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-10: Phosphorus flows in cereal-legume-livestock systems at village level.

4.1.5 Phosphorus balances

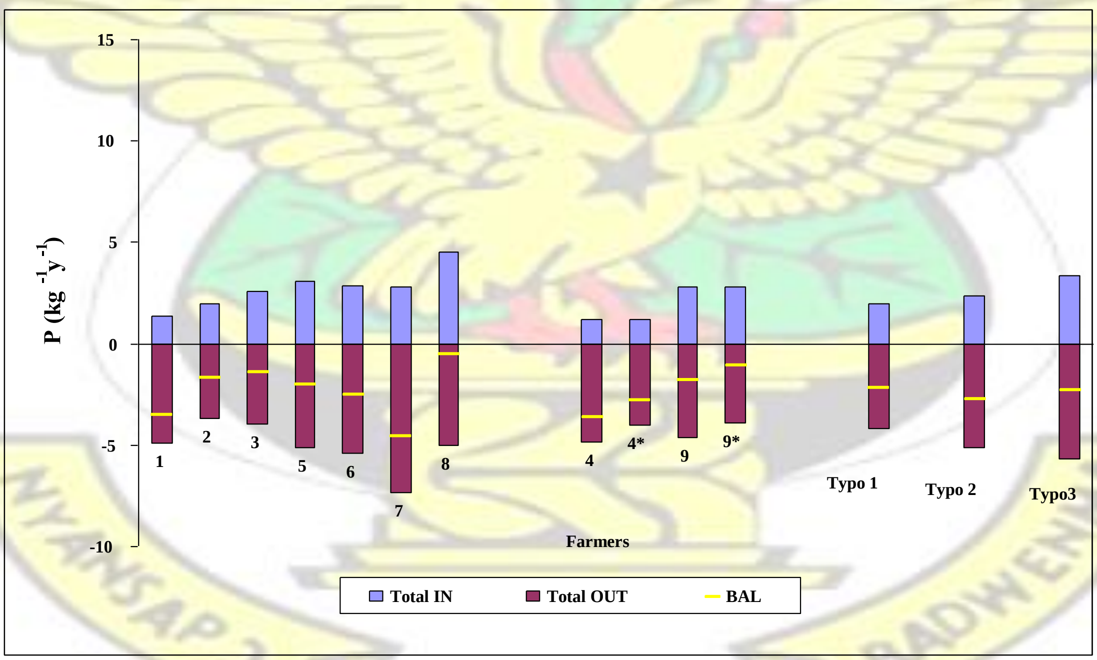
At Garin Labo even under the current farmer practice of total crop residue removal, P balances were positive (3.3 to 7.4 kg ha^{-1}, Fig. 4-11). However, by incorporating half of the residues of farmers 4 and 9 only a marginal improvement in the P balances of farmer 4 and farmer 9 were observed. In the absence of SSP use, negative (-0.5 to -4.6 kg ha^{-1}) P balances were obtained on all fields (Fig. 4-12).

As indicated in Fig. 4-13, across the study locations P balance was more positive in the Regosol at Sarauniya (15.7 kg ha^{-1}) than either the Ferric Luvisol at Cheyohi (9.7 kg ha^{-1}) or the Eutric Gleysol at Garin Labo (5.4 kg ha^{-1}). In sencarios where farmers do not apply mineral fertiliser, negative balances (-2.4 to -7.9 kg ha^{-1}) were obtained (Fig. 4-14).



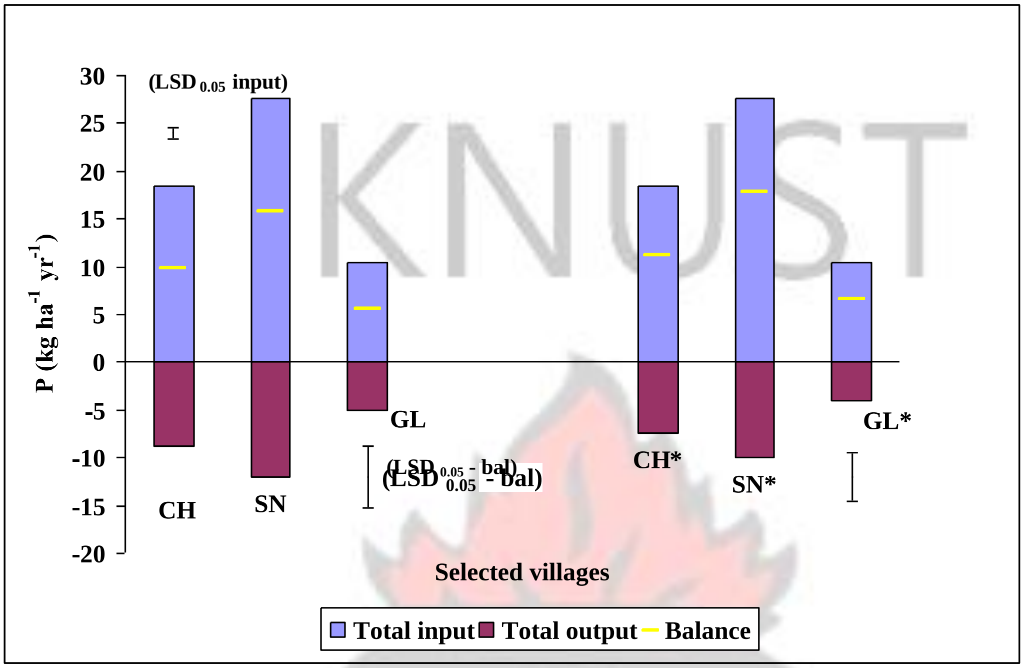
Flows with no error bars were not significantly different ($p > 0.05$)

Figure 4-11: Phosphorus balances at farm level in Garin Labo with the application of P fertiliser.



Flows with no error bars were not significantly different ($p > 0.05$)

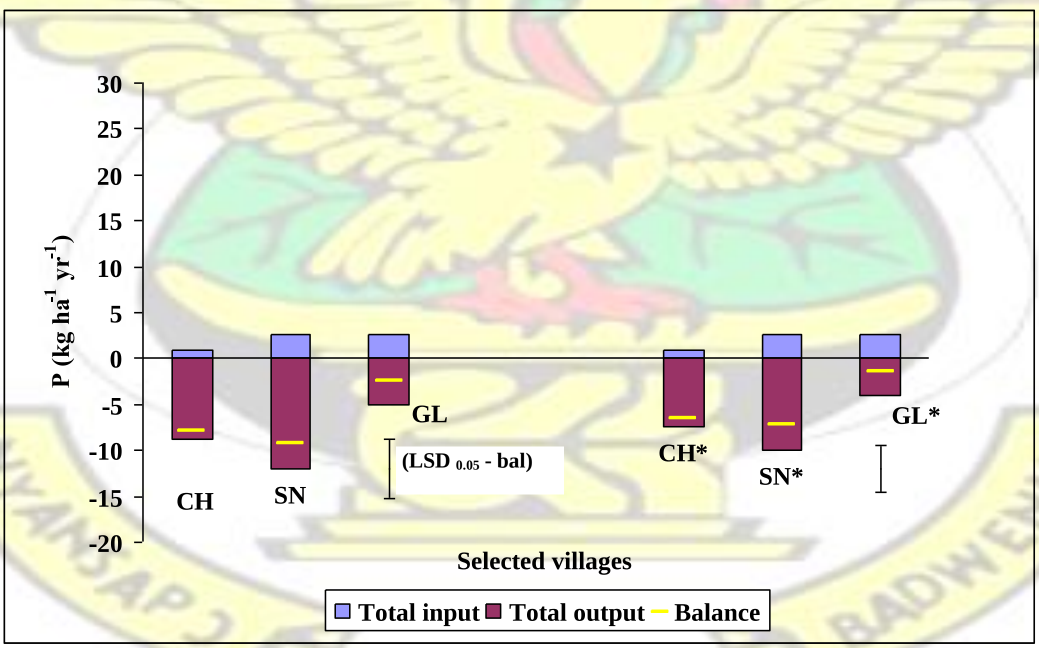
Figure 4-12: Phosphorus balances at farm level in Garin Labo without the application of P fertiliser.



* 50 % of the crop residues incorporated into the soil, CH = Cheyohi, SN = Sarauniya, GL = Garin Labo

Flows with no error bars were not significantly different (p > 0.05)

Figure 4-13: Phosphorus balances at the village level with the application of P fertiliser.



* 50 % of the crop residues incorporated into the soil, CH = Cheyohi, SN = Sarauniya, GL = Garin Labo

Flows with no error bars were not significantly different (p > 0.05)

Figure 4-14: Phosphorus balances at the village level without the application of P fertiliser.

4.1.6 Entry points for improving cereal-legume-livestock productivity

Farmers in Garin Labo used about 20 % of the total crop residues generated to satisfy their fuel wood and raw material needs for the construction of granaries, fences and roofing mats leading to an export of 3 - 4.2 kg ha^{-1} of N annually from the farming system (Fig. 4-15). Secondly farmers generally do not retain crop residues on the field for soil fertility restoration. As a result, there is a severe nutrient mining of 35 - 45 kg ha^{-1} of N and 66 - 76 kg ha^{-1} of K annually (Fig. 4-15). Thirdly, farmers heaped manure at a place near the kraal without any protection against the rainfall or sunshine and caused 60% of N in the manure to be lost during storage. Lastly, about of 20.2 - 20.8 kg ha^{-1} corresponding to 57 % of the total N input into the cropping system was lost through leaching.

Hence, the four hotspots for research intervention to improve the nutrient cycling efficiency of the farming system shown on Fig. 4-15 are:

i. Reduction of the use of crop residues for fuel wood and construction purposes by identifying other locally available sources.
ii. Quantification of the short and long-term benefits of crop residue retention and packaging the technology appropriately to boost its adoption.
iii. Development of cost–effective options for improving the quality of manure.
iv. Development of cost-effective technologies to control leaching.

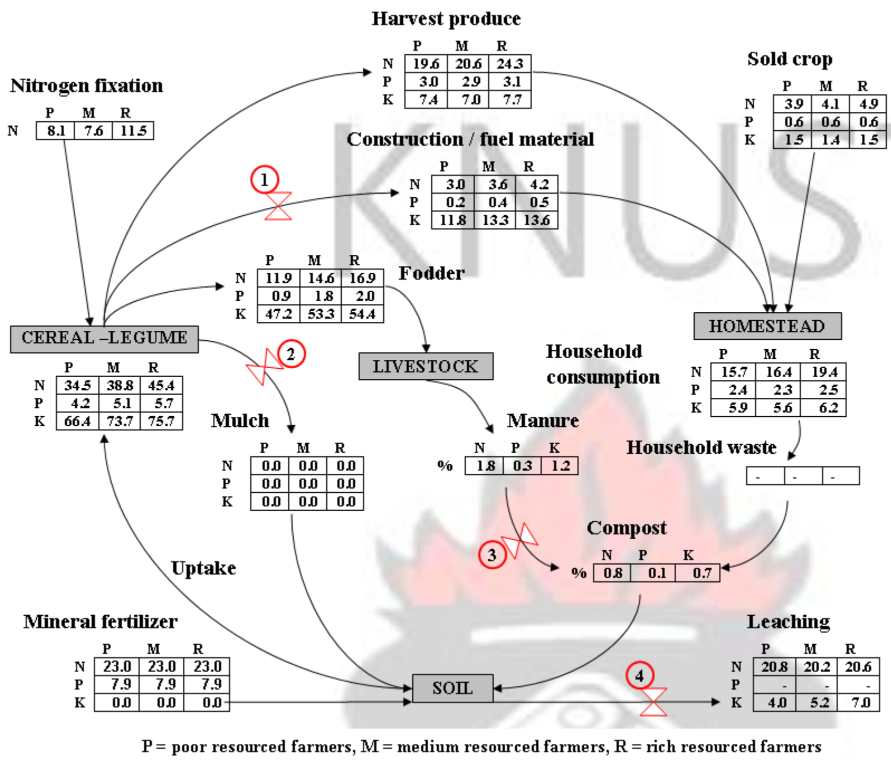


Figure 4-15: Hot spots for research interventions in cereal-legume-livestock farms at Garin Labo.

4.2 Impact of crop residue allocation on crop and livestock productivities

4.2.1 Effect of crop residue use on grain yield and liveweight

At Cheyohi (on the Ferric Luvisol) the incorporation of maize stover, maize husk and cowpea haulm gave rise to significantly higher grain yields of maize but had no effect on grain yield of cowpea (Fig. 4-16) in Farm 1. The amount of crop residues generated by the Farmer 1 supported livestock feeding for 48 days. During this period sheep fed on the rangeland lost 8.3 g d^{-1} while those fed crop residues significantly ($P < 0.05$) increased their live weight by 15 – 40 g d^{-1} (Fig. 4-16). In Farm 2, the application of maize stover and cowpea haulm had no significant ($P > 0.05$) effect on the grain yields of maize. No cowpea grain yield was recorded on this farm as the farmer harvested the crop earlier than expected (Fig. 4-16).

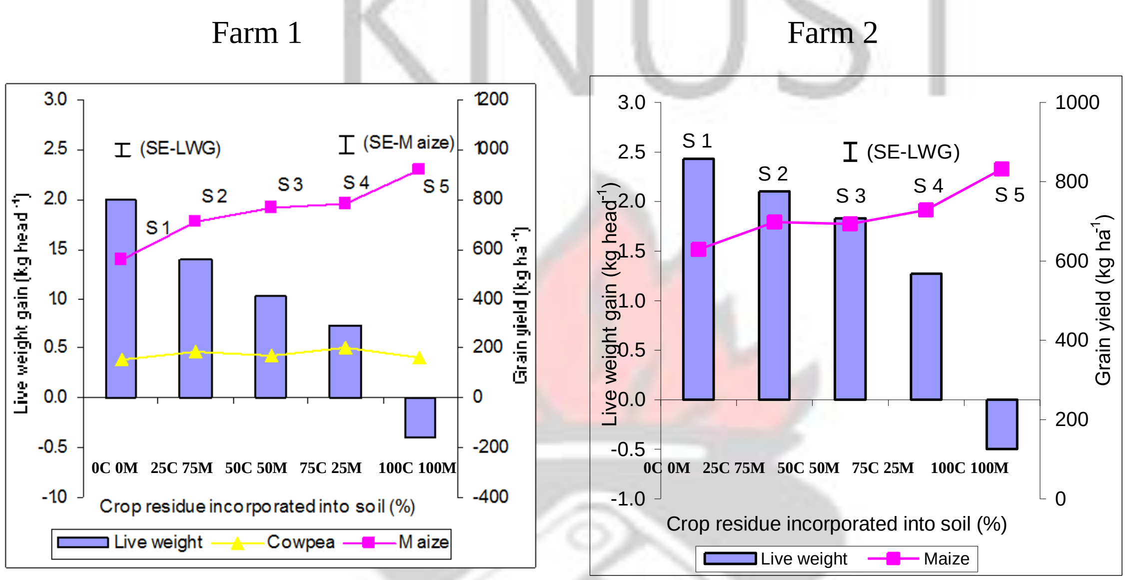


Figure 4-16: Grain yield and live weights measured in the farms at Cheyohi.

The amount of crop residues generated by the farmer 2 supported livestock feeding for 58 days. Sheep fed with crop residues increased their live weight significantly ($P < 0.05$) by 21 – 41 g d^{-1} compared to animals grazed on the rangelands.

At Sarauniya (on the Regosol), the incorporation of maize stover and groundnut haulms had no significant ($P > 0.05$) effect on the grain yields of both maize and groundnut (Fig. 4-17). At Farm 1 in Sarauniya the amount of crop residues obtained, supported livestock feeding for 56 days. Goats used in the study increased their live weights regardless of the source of feed. Weights gained by animals fed with 100, 75 and 50 % of the haulms were significantly ($P < 0.05$) higher than animals fed on the rangeland (Fig. 4-17). Also at Farm 2, the incorporation of maize stover and groundnut haulms had no significant ($P > 0.05$) effect on the grain yields of both maize and groundnut (Fig. 4-17). The amount of crop residues obtained supported livestock feeding for 56 days. Animals grazed on the rangeland attained a marginal growth rate of 3.3 g d^{-1} while those fed on maize stover and groundnut haulm grew significantly by 15 – 58 g d^{-1}.

Farm 1 Farm 2

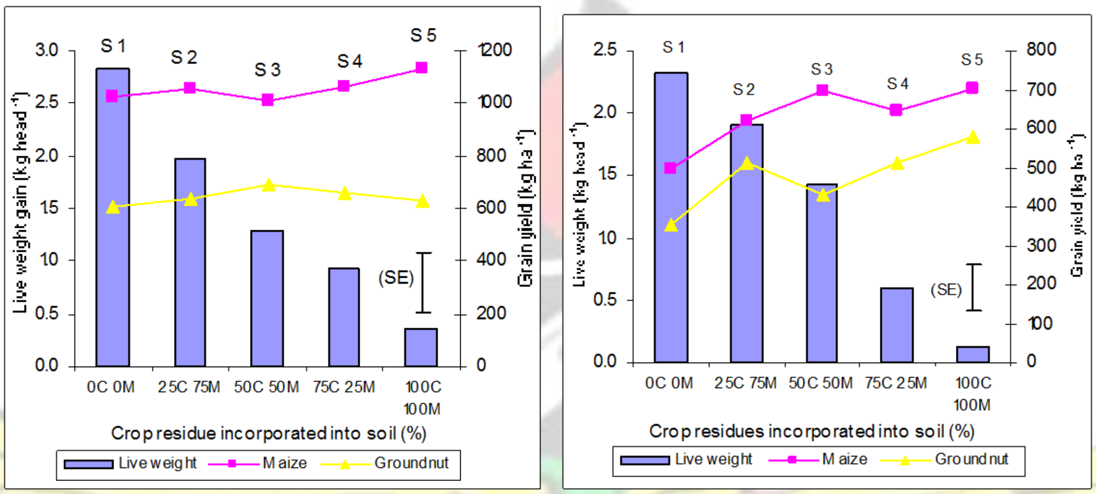


Figure 4-17: Grain yield and live weights measured in the farms at Sarauniya.

At Garin Labo (on the Eutric Gleysol), the incorporation of millet stover and cowpea haulms had no significant (P > 0.05) effect on the grain yields of both millet and cowpea (Fig. 4-18). No cowpea grain yield was recorded on the Farm 2 as the farmer harvested the crop earlier than expected (Fig 4-18). The amount of crop residues obtained from the study farms fed sheep for a period of 30 to 32 days. As indicated in Fig. 4-18, weights gained by animals fed on the rangelands were comparable to weights gained by animals fed on the crop residues. Compared to animals raised at Cheyohi and Sarauniya, animals used in the study at Garin Labo attained higher weight gains. Sheep fed on range land attained a weight gain of 38 – 39 g d^{-1} while those fed on CR rations grew at a rate of 42- 70 g d^{-1}.

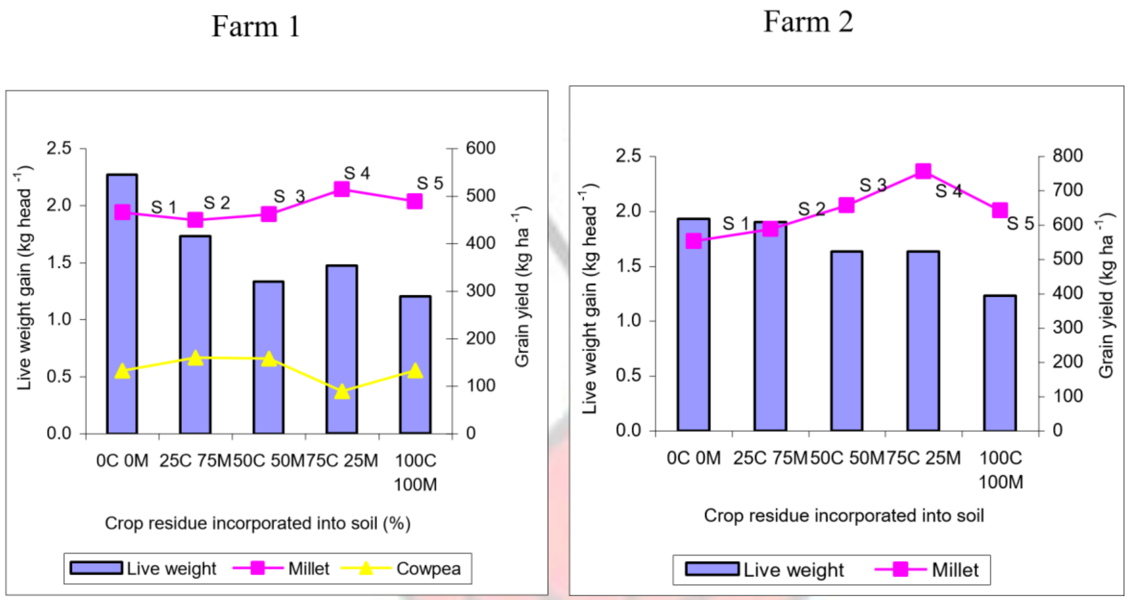


Figure 4-18: Grain yield and live weights measured in the farms at Garin Labo.

4.2.2 Quantification of tradeoffs in using crop residue as soil amendment or fodder Table 4-1 indicates the quantities of maize and cowpea grains sacrificed and live weights gained by allocating more crop residues into either crop or livestock production in Farm 1 at Cheyohi. Allocation of crop residues had no significant ($P > 0.05$) effect on the apparent tradeoffs and the true tradeoffs calculated for Farm 1 (Tables 4-1 and 4-2) and Farm 2 (Table 4-3 and 4-4). On the basis of the apparent tradeoffs assessment, the best case Scenario was the incorporation of 25 % haulm, 75 % stover into the soil and the feeding of 75 % haulm, 25 % stover to livestock (Scenario 2). However, the true tradeoffs appraisal identified the incorporation of 75 % haulm, 25 % stover into the soil and feeding of 25 % haulm, 75 % stover to livestock (Scenario 4) as the best case Scenario (Table 4-1). In both analyses, the use of all crop residues as soil amendment and none as fodder (Scenario 5), which mimicked the standard farmer practices of leaving all crop residues on the field, was the worst case Scenario.

Depending on the amount of crop residues incorporated or fed, the farmer sacrificed 66 to 99 pesewas of crop grains and residues for a cedi benefit from live weight and manure. In Scenario 5, where the animals grazed on the rangeland, the farmer sacrificed 72 pesewas of crop grains and residues, but lost 62 pesewas of livestock produce (Table 4-1). Also at Sarauniya, the allocation of crop residues had no significant ($P > 0.05$) effect on the apparent tradeoffs and the true tradeoffs calculated for Farms 1 (Tables 4-5 and 4-6) and 2 (Tables 4-7 and 4-8). In Farm 2, both the apparent tradeoff and true tradeoff analyses found the use of 25 % haulm - 75 % stover as soil amendment and 75 % haulm - 25 % stover as fodder (Scenario 2) to be the best case Scenario. The incorporation of all crop residues into the soil and feeding of none to livestock (Scenario 5) was found to be the worst case Scenario.

Depending on the amount of crop residues incorporated or fed, the farmer sacrificed 0.35 to 0.78 Naira of grains and crop residues for a Naira benefit from liveweight and manure (Table 4-8). Where animals grazed on the rangeland, the farmer sacrificed neither grains nor crop residues and got 40 Naira worth of livestock produce (Table 4-8).

Also at Garin Labo, the allocation of crop residues had no significant ($P > 0.05$) effect on the apparent tradeoffs and the true tradeoffs calculated for the two farms (Tables 4-9 to 412). The standard farmer practices of feeding all crop residues to livestock and leaving none on the field for soil application (Scenario 1) was found to be the best case Scenario by both apparent tradeoffs and true tradeoffs assessments in Farm 1.

Table 4-1: Apparent tradeoff for the crop residues use – scenarios evaluated in Farm 1 at Cheyohi on a Luvisol.

Scenario	Grain yields sacrificed (kg 200 m^{-2})			Grain yields sacrificed (¢ 200 m^{-2})			Live weight gained		Apparent Tradeoffs	
	Maize	Cowpea	Totals	Maize	Cowpea	Totals	(kg head^{-1})	(¢ head^{-1})	(kg kg^{-1})	(¢/¢)
1	7.27	0.92	8.19	2.18	0.50	2.68	2.00	3.62	4.09	0.74
2	4.25	0.25	4.51	1.28	0.14	1.41	1.40	2.53	3.22	0.56
3	3.09	0.59	3.67	0.93	0.32	1.24	1.03	1.87	3.55	0.66
4	2.73	0.00	2.73	0.82	0.00	0.82	0.73	1.33	3.73	0.62
5	0.00	0.85	0.85	0.00	0.46	0.46	-0.40	-0.72	-2.13	-0.64
Contrast probabilities										
F pr	0.089	0.858	0.355	0.089	0.857	0.355	<.001	<.001	0.439	0.443
1 vrs 2+3+4+5	0.024	0.541	0.077	0.024	0.541	0.077	<.001	<.001	0.49	0.489
2+3+4 vrs 5	0.094	0.496	0.443	0.093	0.496	0.443	<.001	<.001	0.092	0.093
3 vrs 2+4	0.833	0.604	0.895	0.834	0.602	0.895	0.665	0.652	0.96	0.965
2 vrs 4	0.502	0.803	0.588	0.501	0.799	0.588	<.001	<.001	0.939	0.982

Cedi currency used in this table refers to the new Ghana cedis (GH ¢), exchange rate in October, 2008 was 1$ = 1.01 GH ¢

Table 4-2: True tradeoff for the crop residues use – scenarios evaluated in Farm 1 at Cheyohi on a Luvisol.

Scenario	Crop products sacrificed (kg 200 m^{-2})		(¢ 200 m^{-2})				Livestock products benefited (kg head^{-1})	(¢ head^{-1})			True Tradeoffs (¢/¢)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	17.13	1.63	0.81	0.34	2.68	3.83	15.30	0.59	3.62	4.21	0.91
2	11.66	0.67	0.55	0.14	1.41	2.10	6.93	0.26	2.53	2.79	0.75
3	6.26	0.87	0.29	0.18	1.24	1.72	7.46	0.32	1.87	2.19	0.78
4	6.17	0.00	0.29	0.00	0.82	1.11	9.45	0.36	1.33	1.68	0.66
5	0.00	1.22	0.00	0.26	0.46	0.72	2.47	0.10	-0.72	-0.62	-1.16
Contrast probabilities											
F pr	0.159	0.807	0.163	0.804	0.355	0.381	<.001	<.001	<.001	<.001	0.596
1 vrs 2+3+4+5	0.052	0.412	0.054	0.414	0.077	0.085	<.001	<.001	<.001	<.001	0.575
2+3+4 vrs 5	0.149	0.548	0.149	0.539	0.443	0.487	<.001	<.001	<.001	<.001	0.148
3 vrs 2+4	0.632	0.669	0.624	0.667	0.895	0.935	0.151	0.595	0.652	0.79	0.981

2 vrs 4	0.399	0.638	0.403	0.633	0.588	0.541	0.001	0.027	<.001	<.001	0.93

Cedi currency used in this table refers to the new Ghana cedis (GH ¢), exchange rate in October, 2008 was 1$ = 1.01 GH ¢

Table 4-3: Apparent tradeoff for the crop residues use – scenarios evaluated in Farm 2 at Cheyohi on a Luvisol.

Scenario	Grain yields sacrificed (kg 200 m^{-2})			Grain yields sacrificed (¢ 200 m^{-2})			Live weight gained		Apparent Tradeoffs	
	Maize	Cowpea	Totals	Maize	Cowpea	Totals	(kg head^{-1})	(¢ head^{-1})	(kg kg^{-1})	(¢/¢)
1	4.06	-	4.06	1.22	-	1.22	2.43	4.41	1.67	0.28
2	2.68	-	2.68	0.80	-	0.80	2.10	3.80	1.28	0.21
3	2.78	-	2.78	0.83	-	0.83	1.83	3.32	1.52	0.25
4	2.08	-	2.08	0.62	-	0.62	1.27	2.29	1.64	0.27
5	0.00	-	0.00	0.00	-	0.00	-0.50	-0.91	0.00	0.00
Contrast probabilities										
F pr	0.596	-	0.596	0.596	-	0.596	<.001	<.001	0.974	0.975
1 vrs 2+3+4+5	0.295	-	0.295	0.295	-	0.295	<.001	<.001	0.866	0.866
2+3+4 vrs 5	0.245	-	0.245	0.246	-	0.246	<.001	<.001	0.556	0.558
3 vrs 2+4	0.855	-	0.855	0.855	-	0.855	0.508	0.507	0.849	0.854

2 vrs 4	0.813	-	0.813	0.813	-	0.813	0.01	0.011	0.929	0.925

No yield parameters of cowpea were recorded as the farmer harvested the crop ealier than the scheduled harvesting date
Cedi currency used in this table refers to the new Ghana cedis (GH ¢), exchange rate in October, 2008 was 1$ = 1.01 GH ¢

Table 4-4: Tradeoff for the crop residues use – scenarios evaluated in Farm 2 at Cheyohi on a Luvisol.

Scenario	Crop products sacrificed						Livestock products benefited				True Tradeoffs
	(kg 200 m^{-2})		(¢ 200 m^{-2})				(kg $head^{-1}$)	(¢ head-1)			(¢/¢)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	9.97	-	0.44	-	1.22	1.66	19.46	0.82	4.41	5.23	0.32
2	6.59	-	0.29	-	0.80	1.09	8.29	0.33	3.80	4.13	0.26
3	8.33	-	0.36	-	0.83	1.20	9.77	0.41	3.32	3.73	0.32
4	6.45	-	0.28	-	0.62	0.91	11.00	0.44	2.29	2.73	0.33
5	0.00	-	0.00	-	0.00	0.00	3.22	0.18	-0.91	-0.72	0.00
Contrast probabilities											
F pr	0.454	-	0.453	-	0.596	0.56	<.001	<.001	<.001	<.001	0.988
1 vrs 2+3+4+5	0.302	-	0.302	-	0.295	0.296	<.001	<.001	<.001	<.001	0.92

2+3+4 vrs 5	0.139	-	0.138	-	0.246	0.213	<.001	<.001	<.001	<.001	0.627
3 vrs 2+4	0.705	-	0.713	-	0.855	0.817	0.848	0.182	0.507	0.479	0.883
2 vrs 4	0.979	-	0.978	-	0.813	0.851	0.005	0.001	0.011	0.017	0.945

No yield parameters of cowpea were recorded as the farmer harvested the crop ealier than the scheduled harvesting date.
Cedi currency used in this table refers to the new Ghana cedis (GH ¢), exchange rate in October, 2008 was 1$ = 1.01 GH ¢

Table 4-5: Apparent tradeoff for the crop residues use – scenarios evaluated in arm 1 at Sarauniya on a Regosol

Scenario	Grain yields sacrificed (kg 200 m^{-2})			(₦ 200 m^{-2})			Live weight gained		Apparent Tradeoffs	
	Maize	Groundnut	Totals	Maize	Groundnut	Totals	(kg head^{-1})	(₦ head^{-1})	(kg kg^{-1})	(₦/₦)
1	1.32	1.00	2.32	71.83	64.00	135.83	2.83	631.16	0.82	0.22
2	1.00	0.59	1.59	54.50	38.02	92.52	1.97	438.10	0.81	0.21
3	1.54	0.00	1.54	83.82	0.00	83.82	1.30	289.59	1.18	0.29
4	0.90	0.35	1.25	49.05	22.40	71.45	0.93	207.91	1.34	0.34
5	0.00	0.69	0.69	0.00	44.16	44.16	0.37	81.68	1.88	0.54
Contrast probabilities										
F pr	0.992	0.999	0.999	0.992	0.999	0.999	0.092	0.092	0.997	0.988
1 vrs 2+3+4+5	0.87	0.833	0.826	0.87	0.833	0.825	0.026	0.026	0.91	0.808
2+3+4 vrs 5	0.693	0.896	0.876	0.693	0.897	0.896	0.147	0.147	0.791	0.931
3 vrs 2+4	0.848	0.878	0.982	0.848	0.878	0.995	0.832	0.832	0.97	0.69
2 vrs 4	0.977	0.945	0.955	0.977	0.945	0.953	0.226	0.226	0.841	0.821

Exchange rate in October, 2008 was 1$ = 125.1 ₦

F

Table 4-6: True tradeoff for the crop residues use – scenarios tested in Farm 1 at Sarauniya on a Regosol.

Scenario	Crop products sacrificed (kg 200 m^{-2})		(₦ 200 m^{-2})				Livestock products benefited (kg head^{-1})	(₦ head^{-1})			True Tradeoffs (₦/₦)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	2.30	1.53	8.16	34.70	135.83	178.69	16.29	69.94	631.16	701.10	0.25
2	1.45	0.83	5.17	18.86	92.52	116.54	8.25	32.47	438.10	470.57	0.25
3	1.78	0.00	6.33	0.00	83.82	90.15	8.34	40.95	289.59	330.54	0.27
4	1.86	0.80	6.61	18.10	71.45	96.17	6.59	27.86	207.91	235.77	0.41
5	0.00	1.24	0.00	27.99	44.16	72.15	3.19	13.81	81.68	95.49	0.76
Contrast probabilities											
F pr	0.997	0.998	0.997	0.998	0.999	0.999	<.001	<.001	0.092	0.063	0.455
1 vrs 2+3+4+5	0.847	0.837	0.847	0.837	0.825	0.823	<.001	<.001	0.026	0.017	0.62
2+3+4 vrs 5	0.757	0.866	0.757	0.866	0.896	0.941	<.001	<.001	0.147	0.119	0.543
3 vrs 2+4	0.983	0.851	0.983	0.851	0.995	0.969	0.061	<.001	0.832	0.885	0.103

2 vrs 4	0.952	0.995	0.952	0.995	0.953	0.966	0.009	0.055	0.226	0.218	0.982

Exchange rate in October, 2008 was 1$ = 125.1 ₦

Table 4-7: Apparent tradeoff for the crop residues use – scenarios evaluated in arm 2 at Sarauniya on a Regosol

Scenario	Grain yields sacrificed (kg 200 m^{-2})			(₦ 200 m^{-2})			Live weight gained		Apparent Tradeoffs	
	Maize	Groundnut	Totals	Maize	Groundnut	Totals	(kg $head^{-1}$)	(₦ $head^{-1}$)	(kg kg^{-1})	(₦ / ₦)
1	2.51	2.69	5.20	136.90	172.03	308.94	2.33	519.78	2.23	0.59
2	0.99	0.79	1.78	54.06	50.43	104.50	1.90	423.25	0.94	0.25
3	0.10	1.79	1.89	5.23	114.69	119.92	1.43	319.29	1.32	0.38
4	0.72	0.76	1.48	39.24	48.64	87.88	0.60	133.66	2.47	0.66
5	0.00	0.00	0.00	0.00	0.00	0.00	0.13	29.70	0.00	0.00
Contrast probabilities										
F pr	0.604	0.499	0.377	0.602	0.501	0.372	0.014	0.014	0.769	0.579
1 vrs 2+3+4+5	0.161	0.167	0.078	0.161	0.168	0.078	0.012	0.012	0.676	0.600

F .

2+3+4 vrs 5 0.674 0.402 0.416 0.673 0.404 0.403 0.022 0.022 0.941 0.314

3 vrs 2+4 0.618 0.468 0.907 0.617 0.469 0.854 0.689 0.689 0.712 0.269 2 vrs 4 0.877 0.985 0.906 0.876 0.986 0.911 0.034 0.034

0.26 0.685

Exchange rate in October, 2008 was 1$ = 125.1 ₦

Table 4-8: True tradeoff for the crop residues use – scenarios evaluated in Farm 2 at Sarauniya on a Regosol.

Scenario	Crop products sacrificed (kg 200 m^{-2})		(₦ 200 m^{-2})				Livestock products benefited (kg head^{-1})	(₦ head-1)			True Tradeoffs (₦ / ₦)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	4.86	3.42	18.99	98.47	308.94	426.39	11.08	47.59	519.78	567.37	0.75
2	1.32	1.48	5.16	42.73	104.50	152.38	5.46	21.46	423.25	444.71	0.34
3	0.12	2.36	0.47	67.95	119.92	188.34	5.68	27.87	319.29	347.17	0.54
4	1.23	1.06	4.82	30.52	87.88	123.22	5.81	24.57	133.66	158.23	0.78
5	0.00	0.00	0.00	0.00	0.00	0.00	2.32	10.00	29.70	39.71	0.00

Contrast probabilities

F pr	0.614	0.516	0.614	0.516	0.372	0.376	<.001	<.001	0.014	0.01	0.548
1 vrs 2+3+4+5	0.15	0.193	0.151	0.193	0.078	0.085	<.001	<.001	0.012	0.008	0.910
2+3+4 vrs 5	0.795	0.336	0.795	0.336	0.403	0.373	<.001	<.001	0.022	0.018	0.743
3 vrs 2+4	0.67	0.538	0.67	0.538	0.854	0.78	0.9	0.004	0.689	0.657	0.587
2 vrs 4	0.98	0.834	0.98	0.834	0.911	0.888	0.371	0.056	0.034	0.037	0.131

Exchange rate in October, 2008 was 1$ = 125.1 ₦

Table 4-9: Apparent tradeoff for the crop residues use –scenarios evaluated in arm 1 at Garin Labo on a Gleysol

Scenario	Grain yields sacrificed (kg 200 m-2)			Grain yields sacrificed (CFA 200 m-2)			Live weight gained		Apparent Tradeoffs	
	Millet	Cowpea	Totals	Millet	Cowpea	Totals	(kg head^{-1})	(CFA head^{-1})	(kg kg^{-1})	(CFA / CFA)
1	0.29	0.26	0.56	59.33	92.17	151.50	2.27	2241.92	0.25	0.07
2	0.77	0.00	0.77	154.67	0.00	154.67	1.73	1714.41	0.45	0.09
3	0.63	0.02	0.65	126.00	7.00	133.00	1.33	1318.78	0.49	0.10
4	0.00	0.85	0.85	0.00	297.50	297.50	1.47	1450.65	0.58	0.21
5	0.29	0.32	0.61	58.67	112.00	170.67	1.20	1186.90	0.51	0.14
Contrast probabilities										
F pr	0.567	0.917	0.95	0.568	0.917	0.98	0.564	0.564	0.757	0.594
1 vrs 2+3+4+5	0.639	0.969	0.727	0.64	0.969	0.806	0.155	0.155	0.995	0.891
2+3+4 vrs 5	0.422	0.972	0.603	0.424	0.972	0.742	0.586	0.586	0.233	0.167
3 vrs 2+4	0.993	0.66	0.713	0.992	0.66	0.673	0.659	0.659	0.891	0.868
2 vrs 4	0.178	0.43	0.763	0.179	0.43	0.899	0.702	0.702	0.673	0.47

Table

Exchange rate in October, 2008 was 1$ = 437.8 CFA franc

The incorporation of 75 % haulm, 25 % stover in soil and feeding 25 % haulm, 75 % stover to livestock (scenario 4) was the worst case scenario. Depending on the amount of crop residues incorporated or fed to livestock, the farmer sacrificed 0.8 to 0.26 CFA Franc of grains and crop residues for 1 CFA Franc benefited from live weight and manure (Table 4-10).

4-10: True tradeoff for the crop residues use –scenarios evaluated in Farm 1 at Garin Labo on a Gleysol.

Scenario	Crop products sacrificed (kg 200 m^{-2})		Crop products sacrificed (CFA 200 m^{-2})				Livestock products benefited (kg hd^{-1})	Livestock products benefited (CFA hd^{-1})			True Tradeoffs (CFA /CFA)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	1.80	0.37	13.24	31.02	44.26	195.76	11.78	127.40	2241.92	2369.32	0.08
2	2.63	0.00	9.79	0.00	9.79	164.46	5.66	75.12	1714.41	1789.53	0.09
3	2.07	0.27	5.15	22.56	27.71	160.71	5.96	75.01	1318.78	1393.79	0.12
4	0.00	1.23	0.00	104.34	104.34	401.84	6.25	66.15	1450.65	1516.80	0.26
5	0.71	0.47	1.77	39.48	41.25	211.92	3.71	45.67	1186.90	1232.57	0.17
Contrast probabilities											

Table F

F pr	0.668	0.948	0.163	0.948	0.98	0.984	<.001	<.001	0.564	0.511	0.799
1 vrs 2+3+4+5	0.578	0.923	0.448	0.923	0.806	0.863	<.001	<.001	0.155	0.132	0.978
2+3+4 vrs 5	0.525	0.98	0.294	0.98	0.742	0.785	<.001	<.001	0.586	0.557	0.253
3 vrs 2+4	0.96	0.806	0.444	0.806	0.673	0.692	0.988	0.409	0.659	0.666	0.813
2 vrs 4	0.234	0.461	0.038	0.461	0.899	0.797	0.146	0.16	0.702	0.694	0.829
SE	1.851	1.126	5.84	95.2	267.1	354.8	0.256	4.1	469.8	471.9	0.444

Exchange rate in October, 2008 was 1$ = 437.8 CFA franc

4-11: Apparent tradeoff for the crop residues use –scenarios evaluated in arm 2 at Garin Labo on a Gleysol.

Scenario	Grain yields sacrificed (kg 200 m^{-2})			Grain yields sacrificed (CFA 200 m^{-2})			Live weight gained		Apparent Tradeoffs	
	Millet	Cowpea	Totals	Millet	Cowpea	Totals	(kg hd^{-1})	(CFA hd^{-1})	(kg kg^{-1})	(CFA / CFA)
1	2.44	-	2.44	488.38	-	488.38	1.93	1912.22	1.26	0.26
2	2.03	-	2.03	405.78	-	405.78	1.90	1879.25	1.07	0.22
3	1.18	-	1.18	236.89	-	236.89	1.63	1615.50	0.73	0.15
4	0.00	-	0.00	0.00	-	0.00	1.63	1615.50	0.00	0.00
5	1.38	-	1.38	275.47	-	275.47	1.23	1219.87	1.12	0.23

Table

Contrast probabilities

F pr	0.084	-	0.084	0.084	-	0.084	0.54	0.54	0.368	0.369
1 vrs 2+3+4+5	0.062	-	0.062	0.062	-	0.062	0.361	0.361	0.454	0.446
2+3+4 vrs 5	0.632	-	0.632	0.633	-	0.633	0.206	0.206	0.133	0.134
3 vrs 2+4	0.801	-	0.801	0.802	-	0.802	0.732	0.732	0.886	0.885
2 vrs 4	0.028	-	0.028	0.028	-	0.028	0.557	0.557	0.253	0.257

No yield parameters of cowpea were recorded as the farmer harvested the crop ealier than the scheduled harvesting date.

Exchange rate in October, 2008 was 1$ = 437.8 CFA franc

Table 4-12: True tradeoff for the crop residues use –scenarios evaluated in Farm 2 at Garin Labo on a Gleysol.

Scenario	Crop products sacrificed (kg 200 m^{-2})		Crop products sacrificed (CFA 200 m^{-2})				Livestock products benefited (kg hd^{-1})	Livestock products benefited (CFA hd^{-1})			True Tradeoffs (CFA /CFA)
	Stover	haulms	Stover	haulms	Grain	Totals	Manure	Manure	LWG	Total	
1	7.00	-	75.47	-	488.38	563.85	9.89	92.94	1912.22	2005.16	0.28
2	6.83	-	73.68	-	405.78	479.46	4.89	58.46	1879.25	1937.72	0.25
3	4.13	-	44.57	-	236.89	281.45	5.49	64.80	1615.50	1680.30	0.17
4	0.00	-	0.00	-	0.00	0.00	5.55	60.84	1615.50	1676.34	0.00
5	4.33	-	46.72	-	275.47	322.20	3.63	43.24	1219.87	1263.11	0.26
Contrast probabilities											
F pr	0.103	-	0.103	-	0.084	0.084	<.001	<.001	0.54	0.499	0.358
1 vrs 2+3+4+5	0.134	-	0.134	-	0.062	0.068	<.001	<.001	0.361	0.315	0.467
2+3+4 vrs 5	0.739	-	0.739	-	0.633	0.646	<.001	<.001	0.206	0.192	0.135
3 vrs 2+4	0.74	-	0.74	-	0.802	0.791	0.341	0.162	0.732	0.743	0.893
2 vrs 4	0.022	-	0.022	-	0.028	0.026	0.062	0.556	0.557	0.561	0.227

No yield parameters of cowpea were recorded as the farmer harvested the crop ealier than the scheduled harvesting date Exchange rate in October, 2008 was 1$ = 437.8 CFA franc

4.2.3 Tradeoff and farm revenue relations

A strong linear negative relationship (r^2 = 0.80 - 0.87, P < 0.001) was found between the true tradeoff and the farm revenue in all the selected farms (Fig. 4-19). At Farm1 in Cheyohi and Farm 2 in Sarauniya, tradeoff accounted for 87 % of variations in the farm revenues accruing from the scenarios tested. About 80 % of fluctuations in the farm revenue of Farm 1 in Garin Labo could be attributed to the tradeoff (Fig. 4-19).

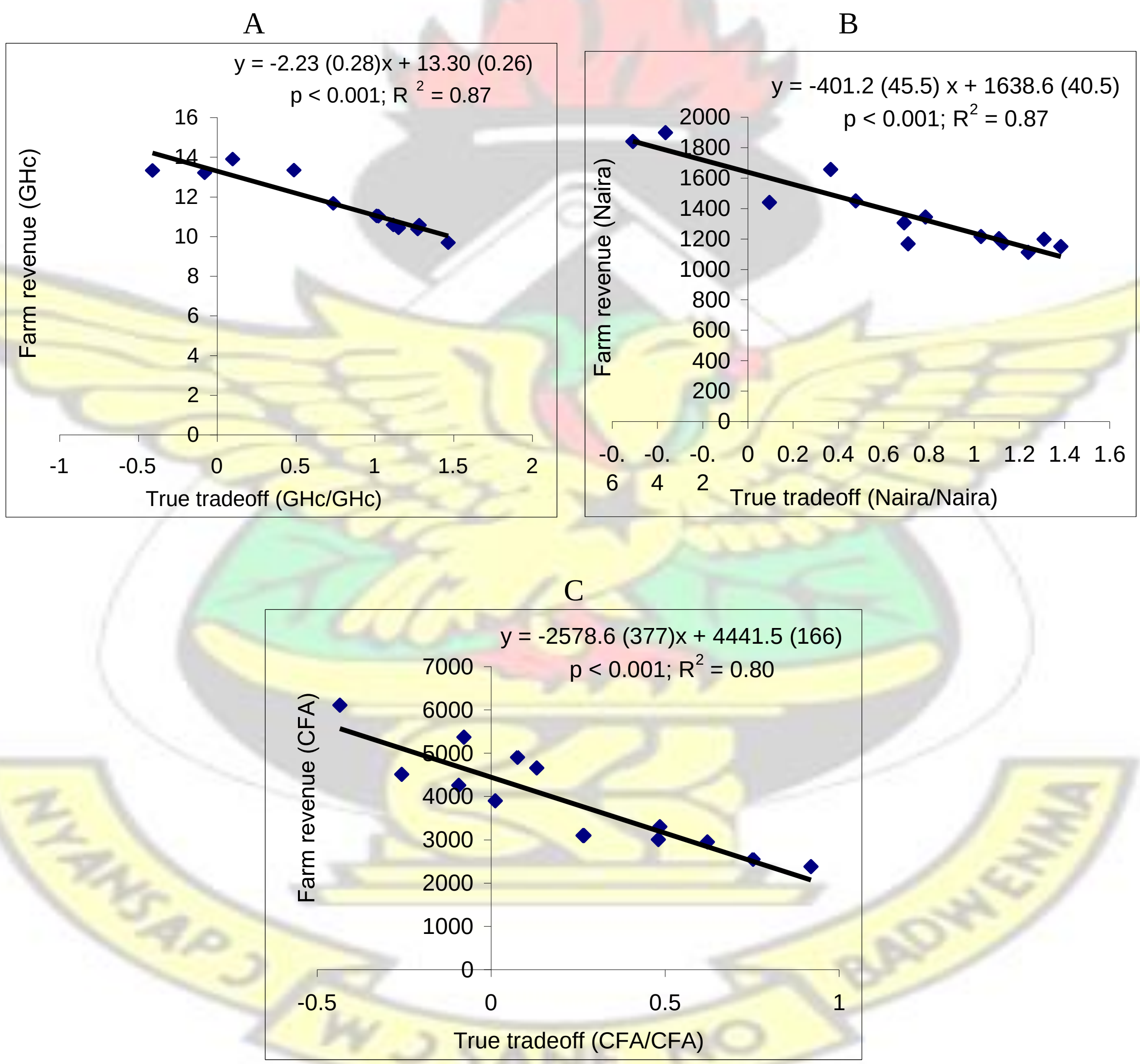


Figure 4-19: Revenue - tradeoff relationships (A = Farm 1 at Cheyohi, B = Farm 2 at Sarauniya, C = Farm 1 at Garin Labo).

4.2.4 Relationship between tradeoff components and crop residue inputs

The proportion of maize stover and husk incorporated into the soil had no effect on grain yield and crop residue yield (Table 4-13). The amount of haulm incorporated and the quantities of N, P and K supplied through crop residue application significantly correlated with grain yield, total grain yield and total crop residue yield of maize (Table 4-13). While about 93% of the variations in maize yield could be attributed to the linear effect of the amount of haulm incorporated, only 2 % of the variation in cowpea yield was due to the incorporation of the haulm.

Both the amount of haulm offered to livestock and the quantity ingested correlated significantly with the live weight but not the faecal output. Feeding of stover, though had no effect on live weight, correlated significantly with faecal output (Table 4-14).

The quantities of crude proteins and NDF ingested also correlated significantly with both live weight and faecal output (Table 4-14). However crude protein intake exerted a stronger effect (r^2 = 0.97) on live weight than faecal output (r^2 = 0.79). On the contrary, the linear effect of NDF ingested was stronger on faecal output (r^2 = 0.98) than live weight (r^2 = 0.77).

Table

4-13: Correlation co-efficient (r) for crop products in Farm 1 at Cheyohi.

Parameter	Amount of crop residue and nutrient applied (kg 200 m^{-2})					
	Stover	Haulm	Husk	Total N	Total P	Total K
Maize grain (kg 200 m^{-2})	0.781 (ns)	0.963 (**)	0.781 (ns)	0.997 (***)	0.966 (**)	0.975 (**)
Cowpea grain (kg 200 m^{-2})	-0.048 (ns)	0.156 (ns)	-0.048 (ns)	0.096 (ns)	0.051 (ns)	0.060 (ns)
Total grain yield (kg 200 m^{-2})	0.752 (ns)	0.959 (**)	0.752 (ns)	0.983 (**)	0.946 (*)	0.956 (*)
Total residue yield (kg 200 m^{-2})	0.685 (ns)	0.977 (**)	0.685 (ns)	0.973 (**)	0.915 (*)	0.929 (*)

ns = non significant, * = significant at $p \leq 0.05$,** =significant at $p \leq 0.01$, ***= significant at $p \leq 0.001$.

Table 4-14: Correlation co-efficient (r) for livestock products in Farm 1 at Cheyohi.

Parameter	Offer rate (g d^{-1})			Intake rate (g d^{-1})				
	Stover	Haulm	Husk	Stover	Haulm	Husk	CP	NDF
Weight gain (kg h^{-1})	0.732 (ns)	0.970 (**)	0.732 (ns)	0.694 (ns)	0.964 (**)	0.737 (ns)	0.985 (**)	0.877 (ns)
Manure (kg h^{-1})	0.956 (*)	0.785 (ns)	0.956 (*)	0.921 (*)	0.793 (ns)	0.970 (**)	0.896 (*)	0.990 (***)

ns = non significant, * = significant at $p \leq 0.05$,** =significant at $p \leq 0.01$, ***= significant at $p \leq 0.001$.

4.3 Agricultural sustainability of crop residue options

4.3.1 Effect of crop residue application on soil quality

Tables 4-15 to 4-17 show the physical (BD), chemical (OM and TN) and microbiological (MBC, MSC and β-glu) indicators used to assess the quality of the soils of the selected farms at the end of the 2008 cropping season.

In relation to the OM content of the Ferric Luvisol (0.87 % for Farm 1 and 0.85 % for Farm 2) at start of the study, removal of CR decreased the OM content of soils at Cheyohi by 2 to 5 % (Tables 3-3 and 4-15). On the contrary, no decline in OM concentrations was observed at either Sarauniya or Garin Labo following removal of CR (Tables 3-3, 4-16 and 4-17).

The incorporation of stover (480 to 3500 kg ha^{-1}) and haulm (200 to 2100 kg ha^{-1}) had no significant ($p > 0.05$) effect on OM content of the top soil (0 - 15 cm) in all the three soils as indicated by Tables 4-15 to 4-17. In general, however, OM increased marginally by 2 to 28 % following the incorporation of CR.

The total N concentrations of the top soils (0 - 15 cm) were also not significantly ($p > 0.05$) affected by the incorporation of CR. Apart from the Ferric Luvisol of the Farm 2 at Cheyohi and the Eutric Gleysol at Garin labo, trends in total N of the soils did not show any clear pattern. The total N content of the soil of Farm 2 at Cheyohi increased steadily with increasing application rate of haulm up to 50 % and thereafter declined (Table 4-15).

Table

At the Farm 2 of Garin Labo on the other hand, the total N content of the Eutric Gleysol increased with increasing application rate up to 100 percent.

4-15: Impact of crop residues on soil properties of a Ferric Luvisol at Cheyohi.

CR applied (%)	Soil quality indicators*						SQS
	OM	TN	BD	MBC	AMSC	β-glu	
Farm 1							
0H 0S	0.85	630	1.25	1100	89.7	89.0	3.2
25H 75S	0.88	662	1.32	1200	101.3	109.7	4.5
50H 50S	0.94	705	1.29	1300	147.3	91.7	5.0
75H 25S	0.96	623	1.26	1267	167.3	85.5	5.1
100H 100S	0.98	638.0	1.23	1500	177.0	112.3	8.4
Pr	0.86	0.94	0.45	0.43	0.19	0.002	nd
LSD (0.05)	0.32	245.60	0.11	434	91.2	11.7	nd
CV %	18.6	20	4.6	17.8	35.5	6.4	nd
Farm 2							
0H 0S	0.81	598	1.26	1067	108.3	79.9	2.5
25H 75S	0.93	613	1.32	1100	149.0	101.5	4.1
50H 50S	0.92	750	1.30	1133	111.3	87.1	3.1
75H 25S	1.01	747	1.30	1533	138.7	90.4	7.4
100H 100S	1.00	670	1.26	1300	154.7	103.0	9.1
Pr	0.28	0.21	0.50	0.35	0.95	0.015	nd
LSD (0.05)	0.20	170.8	0.08	555	167.6	12.9	nd

CV %	11.6	13.4	3.3	24.0	67.2	7.4	nd

* OM: organic matter (%), TN: total nitrogen (kg ha^{-1}), BD: bulk density (g cm^{-3}), MBC: microbial biomass carbon (mg kg^{-1}), AMSC: Arbuscular mycorrhiza spore count (spore 100g^{-1}), β-glu: β-glucosidase activity (mg PN kg^{-1} h^{-1}), SQS: soil quality score. nd: not determined, Pr: probability of significance.

Table

4-16: Impact of crop residues on soil properties of a Regosol at Sarauniya.

CR applied (%)	Soil quality indicators*						SQS
	OM	TN	BD	MBC	AMSC	β-glu	
Farm 1							
0H 0S	0.64	432	1.31	300	43.7	88.7	1.6
25H 75S	0.68	442	1.26	400	123.3	93.2	6.1
50H 50S	0.69	433	1.26	500	103.3	91.4	6.4
75H 25S	0.71	436	1.30	533	98.0	92.1	6.1
100H 100S	0.72	461	1.27	700	109.3	103.7	9.1
Pr	0.51	0.94	0.11	0.026	0.52	0.04	nd
LSD (0.05)	0.10	94.6	0.05	220	106.5	9.3	nd
CV %	7.7	11.4	2.1	24	43.4	5.2	nd
Farm 2							
0H 0S	0.63	396	1.37	313	99.0	112.5	2.1
25H 75S	0.64	399	1.28	513	131.3	128.9	6.7
50H 50S	0.78	423	1.33	413	92.3	110.5	4.9
75H 25S	0.70	402	1.31	523	69.0	116.1	4.7
100H 100S	0.75	444	1.31	466	171.0	152.4	8.6
Pr	0.31	0.89	0.16	0.028	0.34	0.017	nd
LSD (0.05)	0.18	127.5	0.08	127	112.6	23.6	nd
CV %	13.3	16.4	3.2	15.2	32.5	10.1	nd

* OM: organic matter (%), TN: total nitrogen (kg ha^{-1}), BD: bulk density (g cm^{-3}), MBC: microbial biomass carbon (mg kg^{-1}), AMSC: Arbuscular mycorrhiza spore count (spore $100g^{-1}$), β-glu: β-glucosidase activity (mg PN kg^{-1} h^{-1}), SQS: soil quality score. nd: not determined, Pr: probability of significance.

4-17: Impact of crop residues on soil properties of a Eutric Gleysol at Garin Labo.

CR applied (%)	Soil quality indicators*						SQS
	OM	TN	BD	MBC	AMSC	β-glu	
Farm 1							
0H 0S	0.47	136	1.43	650	185	21.7	1.7
25H 75S	0.50	164	1.43	684	232	27.7	4.6
50H 50S	0.50	155	1.42	684	234	25.5	4.7
75H 25S	0.55	173	1.41	729	506	25.3	8.4
100H 100S	0.53	164	1.42	797	433	29.4	8.8
Pr	0.21	0.61	0.64	0.76	0.04	0.44	nd
LSD (0.05)	0.07	55.2	0.03	290	227.40	9.16	nd
CV %	7.3	18.5	1.2	21.9	30.3	18.8	nd
Farm 2							
0H 0S	0.45	127	1.50	332	95	31.1	1.9
25H 75S	0.54	131	1.42	409	156	36.5	6.4
50H 50S	0.55	138	1.42	433	117	36.3	6.4
75H 25S	0.56	172.0	1.41	512	97	31.8	7.0
100H 100S	0.57	179	1.46	508	125	38.6	8.1
Pr	0.28	0.10	0.61	0.81	0.37	0.87	nd
LSD (0.05)	0.12	47.3	0.15	393	73	19.4	nd
CV %	12.3	16.8	5.4	47.5	32.8	29.5	nd

Table

* OM: organic matter (%), TN: total nitrogen (kg ha^{-1}), BD: bulk density (g cm^{-3}), MBC: microbial biomass carbon (mg kg^{-1}), AMSC: Arbuscular mycorrhiza spore count (spore $100g^{-1}$), β-glu: β-glucosidase activity (mg PN kg^{-1} h^{-1}), SQS: soil quality score. nd: not determined, Pr: probability of significance.

Tables 4-15 to 4-17 show that the retention of CR did not significantly ($p > 0.05$) affect the bulk density of the surface soil (0- 5 cm) at all the study sites. With the exception of the Ferric Luvisol at Cheyohi, however, the incorporation of CR lowered the bulk densities of the soils by 1 to 7 % compared with the unamended soils.

The indigenous microbial community size of the soils at Cheyohi was larger (1066 -1100 mg kg^{-1}) than those of the soils at Sauraniya (300 -313 mg kg^{-1}) and Garin Labo (332 – 650 mg kg^{-1}) as measured in control soils at the end of the 2008 cropping season (Tables 4-15 to 4-17). In general, the trend depicted by the microbial biomass C of the soils reflected the amount of CR returned to the soil. Incorporation of CR into the soils of the farms at Sarauniya significantly ($p < 0.05$) increased the microbial biomass C contents by 33 to 133 %, when compared with the soils of plots where residues were removed (Table 4-16). However, at Cheyohi and Garin Labo the incorporation of CR had no significant ($p > 0.05$) effect on microbial biomass C content of the soils.

The occurrence of AM fungi propagules varied widely within and across sites with the coefficient of variation ranging from 30 to 67 % (Tables 4-15 to 4-17). Spores of AM fungi were not affected by the incorporation of CR at five out of the six sites studies. The number of AM fungi spores detected in the Eutric Gleysol of the Farm 2 at Garin Labo was (185 – 506 counts 100 g^{-1}) higher than the number of spores (44 – 177 counts 100 g^{1}) encountered on all other farms. Furthermore, retention of CR significantly ($p < 0.05$) increased the abundance of AM spores following the incorporation of 75 % or more of the cowpea haulms on this farm.

The incorporation of CR influenced the activity of β-glucosidase significantly ($p<0.05$) at

Cheyohi and Sarauniya. At Cheyohi, the retention of 75 % or more of the maize stover stimulated significantly higher activity of β-glucosidase than the retention of 50 % or less of the stover. Table 4-16 indicated that a significant effect on activity of β-glucosidase was observed at Sarauniya, only when 100 % of maize stover was incorporated. Although β-glucosidase activities of the soils at Garin Labo increased with increasing retention of millet stover these differences were not statistically significant. Increasing the amount of CR incorporated improved the soil quality at all locations with the 100 % incorporation recording the highest indexes of 8.1 to 9.1 as indicated by Tables 4-15 to 4-17.

4.3.2 Social acceptability of crop residues management options

Tables 4-18 to 4-20 show the key indicators and questions used to elucidate the acceptability of the various CR management options to farmers. The indigenous knowledge on the alternative uses of CR was assessed on the basis of what the farmer knew and practised (Table 4-18). All the respondents in Cheyohi were aware of the option in which all CR were left on the field after harvest. However, only 20 % of the respondents in Sarauniya and none of the respondents at Garin Labo were conscious of the practice. In general, incorporation of CR residues into the soil was alien to farmers at all locations as they were neither aware of it nor practiced it. Whereas none of the farmers in Cheyohi was familiar with the option of harvesting all CR as fodder, all of the respondents at Sarauniya and Garin Labo acknowledged the existence of the practice. In practice, most of the respondents (80 %) in Cheyohi left all CR on the field after harvest. On the contrary the majority of the farmers in Sarauniya (80 %) and Garin Labo (90 %) harvested all CR for use as fodder. Although a sizeable number of the respondents

(Cheyohi = 50 %, Sarauniya = 40 % and Garin Labo = 30 %) were aware of the option of using part of the CR as fodder and the other part as soil amendment, fewer number of the respondents (Cheyohi = 20 %, Sarauniya = 20 % and Garin Labo = 10 %) have adopted the practice.

Table 4-18: Indigenious knowledge on crop residue uses (N =10).

	No. respondents (%)		
Indicator/issue	Cheyohi	Sarauniya	Garin Labo
Knowledge (awareness)			
All crop residues left on the field	100	20	0
All crop residues incorporated into soil	0	0	0
All crop residues harvested and fed to livestock	0	100	100
Crop residues shared between crop and livestock uses	50	40	30
Knowledge (Practice)			
All crop residues left on the field	80	0	0
All crop residues incorporated into soil	0	0	0
All crop residues harvested and fed to livestock	0	80	90
Crop residues shared between crop and livestock uses	20	20	10

The perceived constraints associated with the CR management options were assessed on the basis of what the farmers felt or thought were potential barriers to the adoption of the option. Table 4-19 indicated that as much as 80 % of the respondents in Cheyohi admitted that there were no constraints to the use of CR as soil amendments so long as the material was not worked into the soil. Majority of the respondents in Sarauniya (90 %) and Garin

Labo (80 %) however cited reduction in fodder supply as a key constraint to the use of CR as soil amendment.

Whereas, most of the respondents in Sarauniya (70 %) and Garin Labo (90 %) found no constraint on the use of CR as fodder, about 60 % of the respondents in Cheyohi identified the high labour requirement associated with the cut and carry as probable barrier to use of CR for livestock purposes. In general, there was no perceived health risk associated with the use of CR as either soil amendment or fodder.

Table 4-19: Perception on constraints to crop residue use (N =10).

	No. respondents (%)		
Indicator/issue	Cheyohi	Sarauniya	Garin Labo
Perceived constraints to soil application			
Reduction in supply of fodder to livestock	30	90	80
Reduction in supply materials for domestic uses	20	20	60
High labour requirement	0	10	0
Known health risk	10	0	0
Not aware of any constraint	80	0	0
Perceived constraints to livestock uses			
Leaves the soil surface bare	20	0	0
High labour requirement	60	10	10
Reduction in supply materials for domestic uses	20	20	20
Known health risk	0	0	0
Not aware of any constraint	20	70	90

Physical stress associated with the CR management options was assessed on the basis of the drudgery and time demanded by the activities entailed in the option (Table 4-20). Incorporation of all crop residues on the field was listed as the most tiring option by 60 % of the respondents at Cheyohi. About 50 % of the respondents in Sarauniya and 70 % of the respondents at Garin Labo felt that option involving the use half of CR as soil amendement and the other half as fodder was most tiring. Majority of the respondents irrespective of their location pointed out that the removal of all CR as fodder (cut and carry feeding system) was the most time demanding option.

Table 4-20: Physical stress associated with crop residue uses (N =10).

	No. respondents (%)		
Indicator/issue	Cheyohi	Sarauniya	Garin Labo
Physical stress (drudgery)			
Incorporating all CR to the soil is most tiring	60	40	30
Incorporating half of CR and feeding the rest is most tiring	30	50	70
Feeding all CR to livestock is most tiring	10	10	0
Physical stress (time consumption)			
Incorporating all CR to the soil is most time demanding	20	10	10
Incorporating half of CR and feeding the rest is most time demanding	30	20	40
Feeding all CR to livestock is most time demanding	50	70	50

The social acceptability of the CR management options was assessed with the sustainability sub index on social factors (SSI_{Social}). In all, the practice of leaving all CR on field while being the most acceptable to farmers at Cheyohi (SSI_{Social} = 6.8) was the least acceptable to farmers at Sauraniya (SSI_{Social} = 4.9) and Garin Labo (SSI_{Social} = 4.5, Appendix 4). Appendix 4, further showed that the removal of all CR as fodder on the other hand was the most acceptable to farmers at Sauraniya (SSI_{Social} = 7.1) and Garin Labo (SSI_{Social} = 7.5). At all locations, the social acceptability of the use of CR as soil amended and fodder concurrently was low (SSI_{Social} of 4.6 - 3.3).

4.3.3 Economic appraisal of CR uses

Tables 4-21 to 4-23 show the indicators used to appraise the economic viability of the CR management options. With the exception of the farms at Garin Labo, gross benefit from crop production increased steadily with increasing amount of CR incorporated. The CR management option in which all CR were incorporated recorded the highest variable cost of inputs on all farms yet, this option earned the highest net benefit in Farm 1 at Cheyohi (¢ 282 ha^{-1}), Farm 1 (₦ 97,196 ha^{-1}) and Farm 2 (₦ 70,939 ha^{-1}) at Sarauniya as indicated in Tables 4-21 and 4-23. Conversely, total removal of CR attained the highest net benefit on the Farm 2 at Cheyohi (¢188.7 ha^{-1}) and Farm 1 at Garin Labo (CFA 146,103 ha^{-1}). Both gross benefit and net benefit from livestock production increased with increasing amount of CR fed to livestock at all locations. Tables 4-21 to 4-23 illustrate that net benefit accrued from feeding of CR to livestock was highest at Garin Labo (CFA 1269 – 2142 $head^{-1}$ ≈ \$ 2.9 – 4.9 $head^{-1}$) followed by Sarauniya (₦ 114 -591 $head^{-1}$ ≈ \$ 0.9 – 4.7 $head^{-1}$) and Cheyohi, (¢1.1 – 3.9 $head^{-1}$ ≈ \$ 1.1 – 3.9 $head^{-1}$) in a descending order. Transportation of CR from the field to the homestead constituted the single most important variable input cost at Cheyohi and Sarauniya. In addition to the cost of transporting CR, animals fed on the rangeland (control) were charged a fee of 25

Table 4-21: Economic assessment of crop residue uses at Cheyohi.

Scenario	CR applied (%)	CR fed (%)	Net Benefit CPU (¢ ha^{-1})	Net Benefit LPU (¢ $head^{-1}$)	VCR CPU	SSI Economics
Farm 1						
1	0H 0S	100H 100S	251.6	3.1	0.0	5.4
2	25H 75S	75H 25S	237.3	2.3	2.3	7.0
3	50H 50S	50H 50S	245.8	1.6	2.2	5.6
4	75H 25S	25H 75S	266.9	1.1	2.5	7.0
5	100H 100S	0H 0S	282.4	-0.7	1.7	4.0
Farm 2						
1	0H 0S	100H 100S	188.7	3.9	0.0	7.0
2	25H 75S	75H 25S	131.9	3.5	0.4	4.2
3	50H 50S	50H 50S	130.4	3.1	0.4	3.0
4	75H 25S	25H 75S	140.9	2.0	0.6	4.7
5	100H 100S	0H 0S	169.6	-0.9	0.6	7.0

CFA $head^{-1}$ wk^{-1} for participating in the controlled grazing programme practiced at Garin Labo.

The returns on investments in CR incorporation were measured by the VCR. The VCR estimates in Tables 4-21 and 4-22 imply that Farmer 1 at Cheyohi (1.7 – 2.5) and Farmer 2 at Sarauniya (2.8 - 4.5) obtained positive net returns. Farmer 2 at Garin Labo on the other hand achieved positive net returns only when 50% or more of the haulms were incorporated (Table 4-23). The returns on investments in all other farms were negative. The economic

Table
viability of the CR management options was assessed by the sustainability sub index on economic factors (SSI $_{Economics}$).

4-22: Economic assessment of crop residue uses at Sarauniya.

Scenario	CR applied (%)	CR fed (%)	Net Benefit CPU (₦ ha^{-1})	Net Benefit LPU (₦ head^{-1})	VCR CPU	SSI $_{Economics}$
Farm 1						
1	0H 0S	100H 100S	94556	591	0.00	4.0
2	25H 75S	75H 25S	93666	418	0.68	7.0
3	50H 50S	50H 50S	94391	270	0.65	6.3
4	75H 25S	25H 75S	95422	188	0.67	7.0
5	100H 100S	0H 0S	97196	82	0.57	1.2
Farm 2						
1	0H 0S	100H 100S	49694	480	0.00	4.0
2	25H 75S	75H 25S	62731	403	4.49	8.4
3	50H 50S	50H 50S	61446	299	3.38	5.9
4	75H 25S	25H 75S	64116	114	3.33	6.7
5	100H 100S	0H 0S	70939	30	2.76	4.0

The concomitant use of CR as soil amendment and fodder (Scenarios 2 to 4) was the most economically viable option in Farm 1 at Cheyohi (SSI $_{Economics}$ of 5.6 to 7.0) and in the farms at Sarauniya (SSI $_{Economics}$ of 5.9 to 8.4). Conversely, in Farm 1 at Garin Labo the removal of all CR as fodder was the most economically viable option (SSI $_{Economics}$ = 9.9),

Table
as indicated in the Table 4-23. The economic assessment of the Farm 2 at both Cheyohi and Garin Labo were not the true reflection of the economic situation of the farms as cowpea was harvested by both farmers before the scheduled date for harvesting. 4-23: Economic assessment of crop residue uses at Garin Labo.

Scenario	CR applied (%)	CR fed (%)	Net Benefit CPU (CFA ha^{-1})	Net Benefit LPU (CFA head^{-1})	VCR CPU	SSI $_{Economics}$
Farm 1						
1	0H 0S	100H 100S	146103	2142	0.00	9.9
2	25H 75S	75H 25S	136333	1664	-0.04	8.1
3	50H 50S	50H 50S	138143	1269	0.20	7.0
4	75H 25S	25H 75S	124428	1401	-1.46	2.0
5	100H 100S	0H 0S	134500	1087	-0.10	3.2
Farm 2						
1	0H 0S	100H 100S	110635	1812	0.00	4.0
2	25H 75S	75H 25S	108018	1829	0.93	4.0
3	50H 50S	50H 50S	122093	1565	2.66	7.0
4	75H 25S	25H 75S	141812	1565	4.89	7.0
5	100H 100S	0H 0S	118377	1120	1.13	3.4

4.3.4 Sustainability Indices for CR allocation options

The ecological benignity (SSI $_{Ecology}$) of the CR management options was assessed on the basis of the impact of the option on soil quality, performance of crops and livestock.

Table

Although total retention of CR (Scenario 5) exerted the highest impact on soil quality in all farms, the superior contribution of Scenario 4 to crop and livestock performances made Scenario 4 more environmentally friendly ($SSI_{Ecology}$ = 6.2) than the other scenarios in Farm 1 at Cheyohi (Fig. 4-20) and in the farms at Garin Labo ($SSI_{Ecology}$ = 6.8 - 8) as shown in Figs. 4-24 and 4-25. Scenario 5 was however the most environmentally friendly option in Farm 2 at Cheyohi (Fig. 4-21) and Farm 1 at Sarauniya (Fig. 4-23). Further more, Fig. 4-23 illustrated that Scenario 2 ($SSI_{Ecology}$ = 7.2) was environmentally more benign that other management options in Farm 2 of Sarauniya.

The assessment of the agricultural sustainability of the CR options found Scenario 4 to be the most sustainable option in Farm 1 at Cheyohi (Fig. 4-20) and Farm 2 at Garin Labo (Fig. 4-25).

The *status quo* management of CR by farmers emerged the most sustainable options in Farm 2 at Cheyohi (Scenario 5), Farm 1 at Sarauniya (Scenario 1) and Farm 1 at Garin Labo (Scenario 1). In Farm 2 at Sarauniya on the other hand Scenario 2 attained the highest agricultural sustainability index (5.8). Limitations with regards to social acceptability were exhibited by total removal of CR for livestock use (Scenario 1) at Cheyohi, and by the concurrent use of CR as soil amendment and fodder (Scenarios 2 to 4) at Sarauniya and Garin Labo (Figs. 4-20 to 4-25). On the economic viability front, Scenario 5 had severe limitations at all locations in addition to Scenario 1 at Sarauniya and Scenario 4 at Garin Labo. Apart from the trends observed in Farm 2 at Cheyohi, the trends in the sustainability indexes were generally consistent with the trends in the tradeoff estimates (Figs. 4-20 to 4-25).

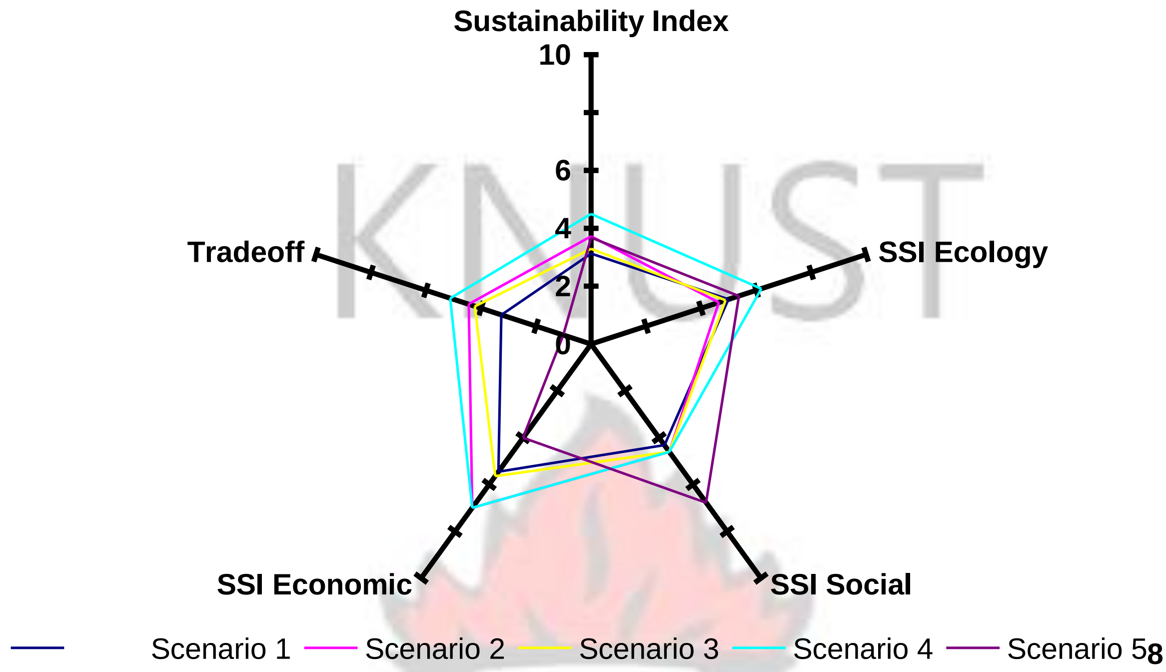


Figure 4-20: Sustainability of crop residue allocation options in Farm1 at Cheyohi.

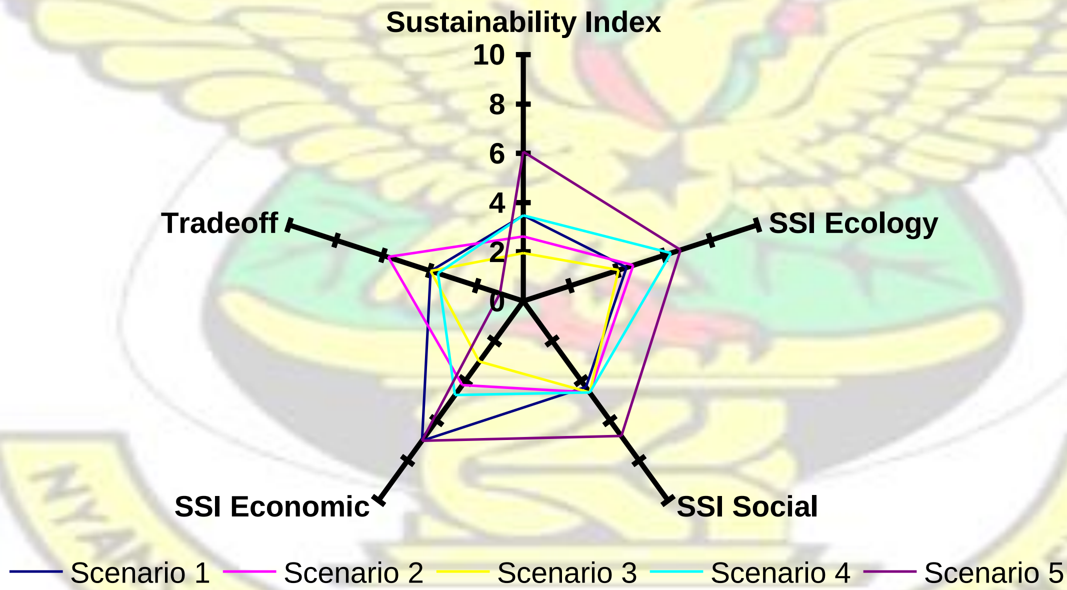


Figure 4-21: Sustainability of crop residue allocation options in Farm 2 at Cheyohi.

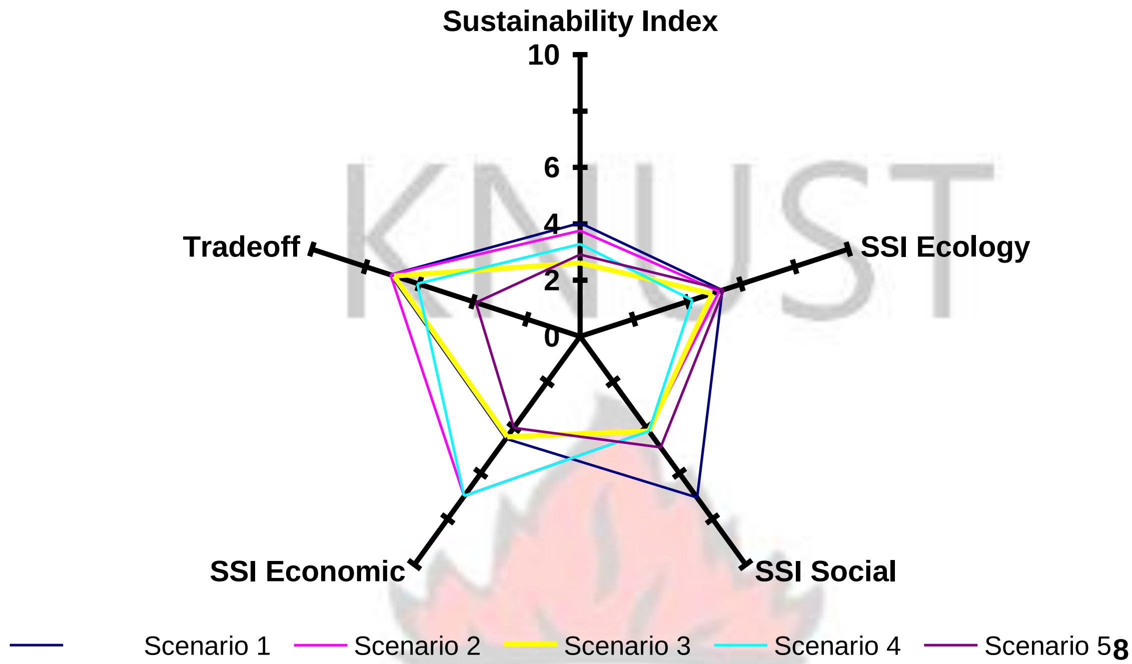


Figure 4-22: Sustainability of crop residue allocation options in Farm 1 at Sarauniya.

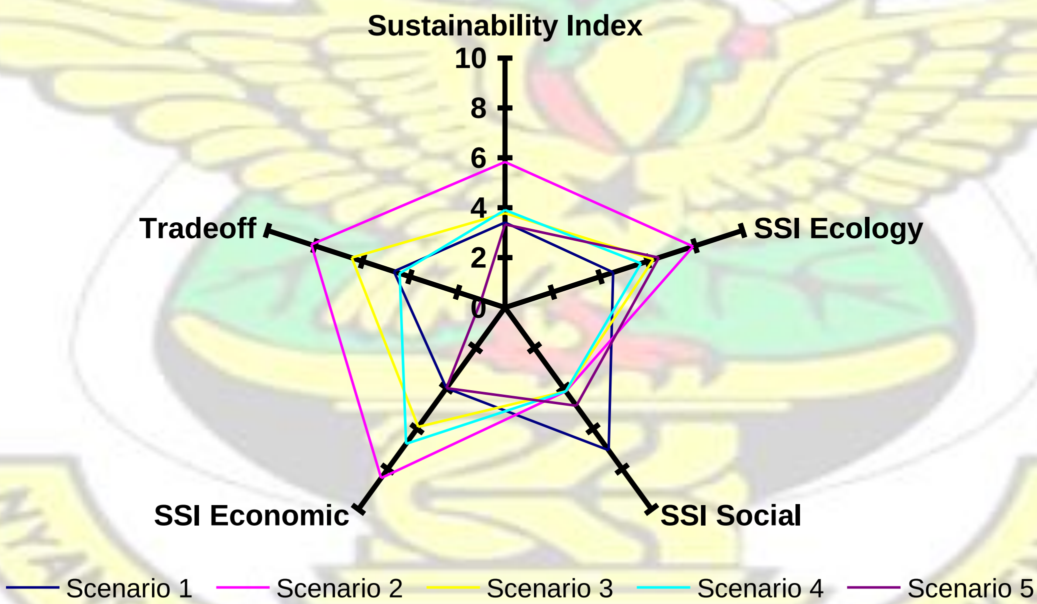


Figure 4-23: Sustainability of crop residue allocation options in Farm 2 at Sarauniya.

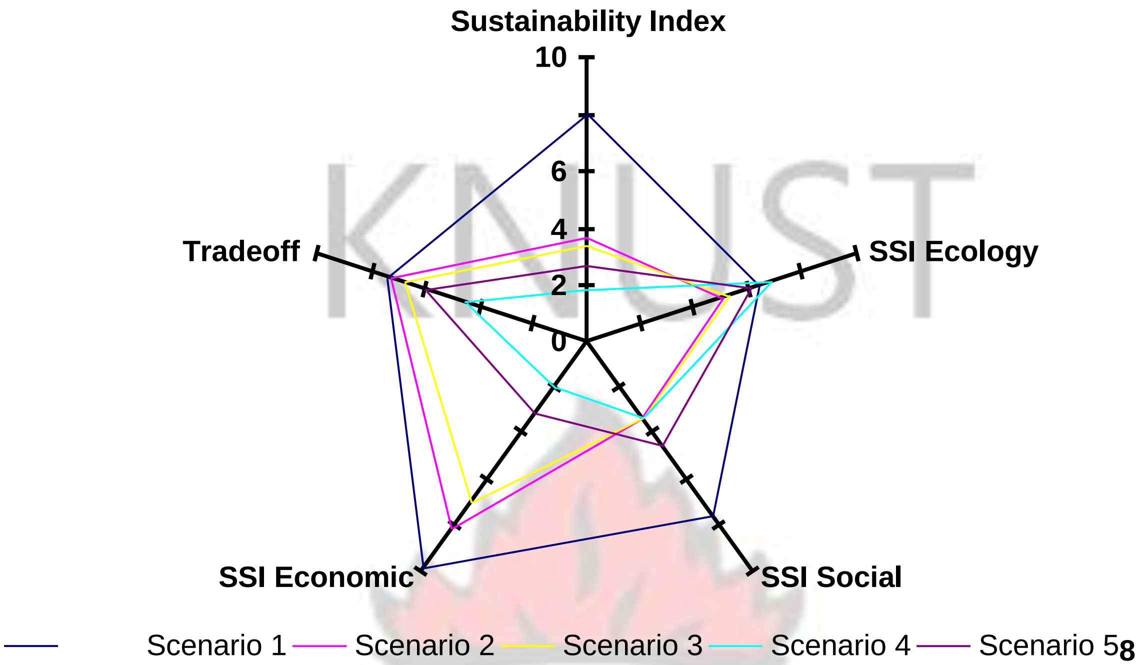


Figure 4-24: Sustainability of crop residue allocation options in Farm 1 at Garin Labo.

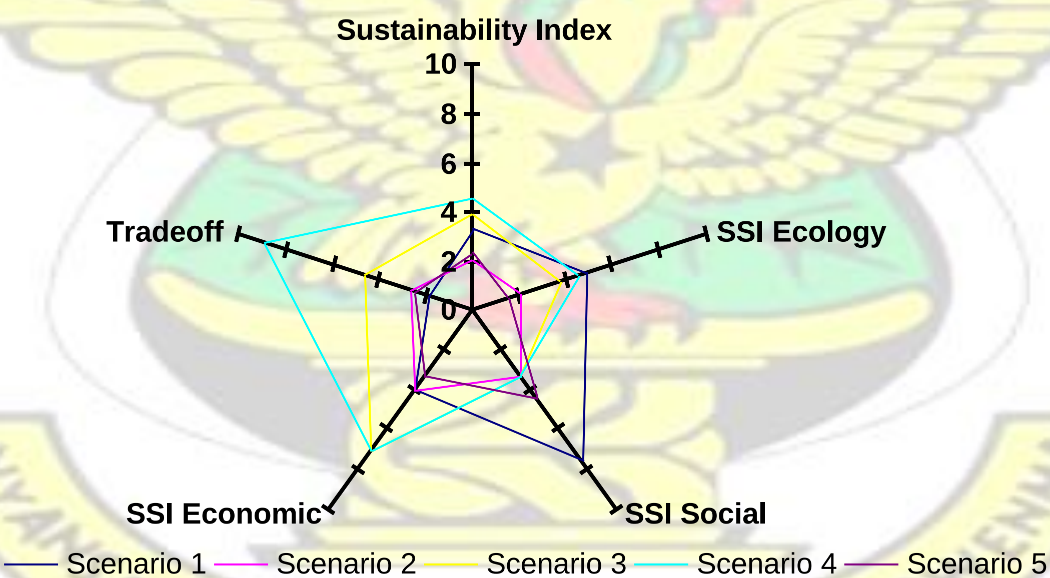


Figure 4-25: Sustainability of crop residue allocation options in Farm 2 at Garin Labo.

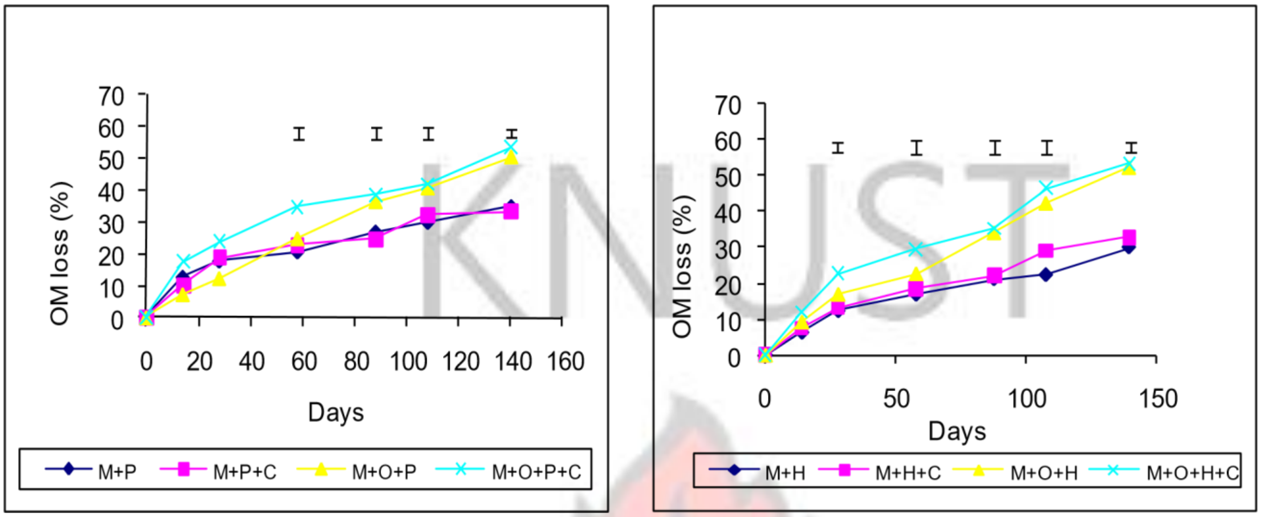
4.4 Evaluation of manure improvement options

4.4.1 Losses of organic matter during co-composting

At NAPRI in Zaria, composting manures in either pits or as heaps did not affect OM loss throughout the 140 days period. The use of polyethene sheet to line pits or cover heaps also did not affect the OM loss (Fig. 4-26). Fortifying manure with groundnut cakes significantly increased the rate of OM loss in both storage facilities (Fig. 4-26). At ARI in Tamale, heap stored manure decomposed more rapidly than pit stored manure from 28 DAC on wards (Fig. 4-27). Fortifying manure with sheanut cake significantly increased the decomposition rate in the manure heaps with or without polyethene covering. Among the manure stored in pits however, fortification with sheanut cake enhanced decomposition only in pit without polyethene lining (Fig. 4-27).

At INRAN in Maradi, the use of pit or heap as composting facility had no significant on the rate of OM degradation (Fig. 4-28). Neither co-composting with cotton seed cake nor use of plastic sheet covers significantly increased OM loss of manures stored in heaps (Fig. 4-28). Manure fortified with cotton seed cake and composted in pits without plastic sheet lining lost significantly higher amount of OM than those composted in pit with plastic sheet lining. The rate of OM loss was higher in manure fortified with groundnut cake (53 %) than manure fortified with cotton seed cake (29 - 19 %) and manures with sheanut cake (29-15 %) (Figs. 4-26 to 4-28).

A B

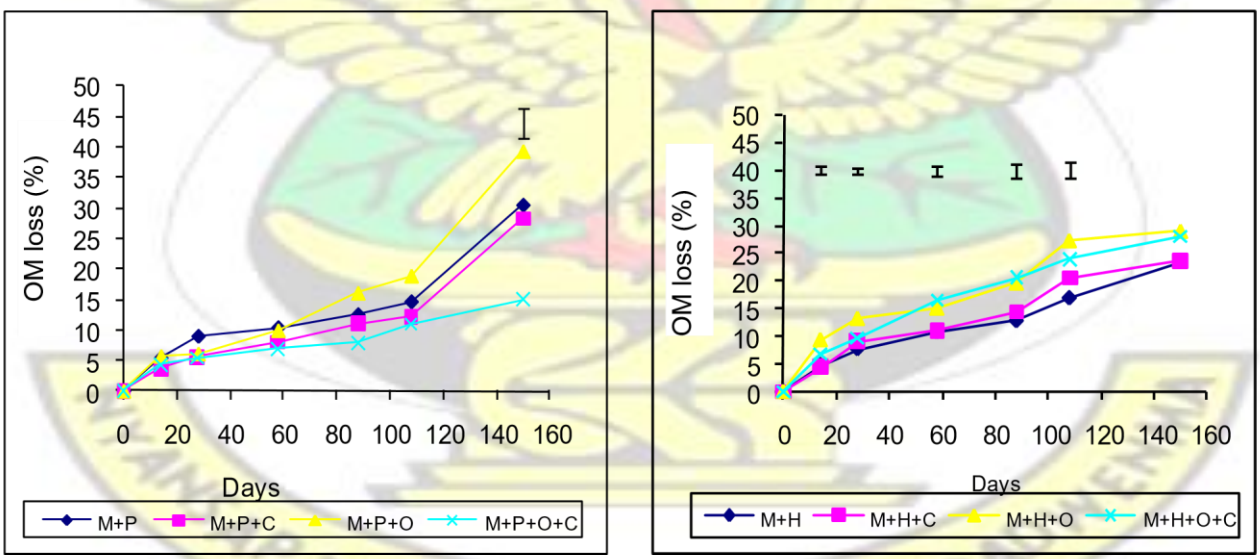


M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap and covered

M+O+P= ma nure with oilcake in pit, M+P+C = manure in pit linned with sheet M+O+H= manure with oilcake in heap, M+H+C = manure in heap and covered Absence of error bars indicate non significant mean differences

Figure 4-26: Changes in OM content of compost at NAPRI (A = pit, B = heap).

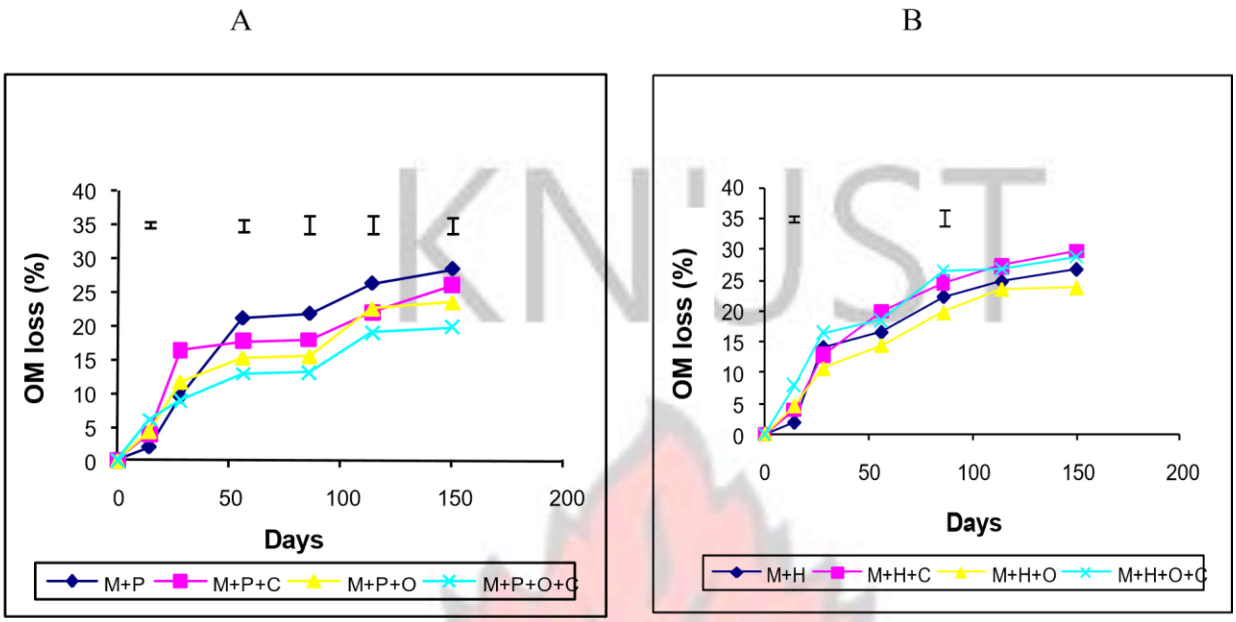
A B



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheetM+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet
M+H = manure in heap, M+O+H+C = manure witM+O+H= manure with oilcake in heap, M+H+C = manure in heap and covered h oilcake in heap and covered

Absence of error bars indicate non significant mean differences

Figure 4-27: Changes in OM content of compost at ARI (A = pit, B = heap).



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap and covered
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet M+O+H= manure with o ilcake in heap, M+H+C = manure in heap and covered

Absence of error bars indicate non significant mean differences

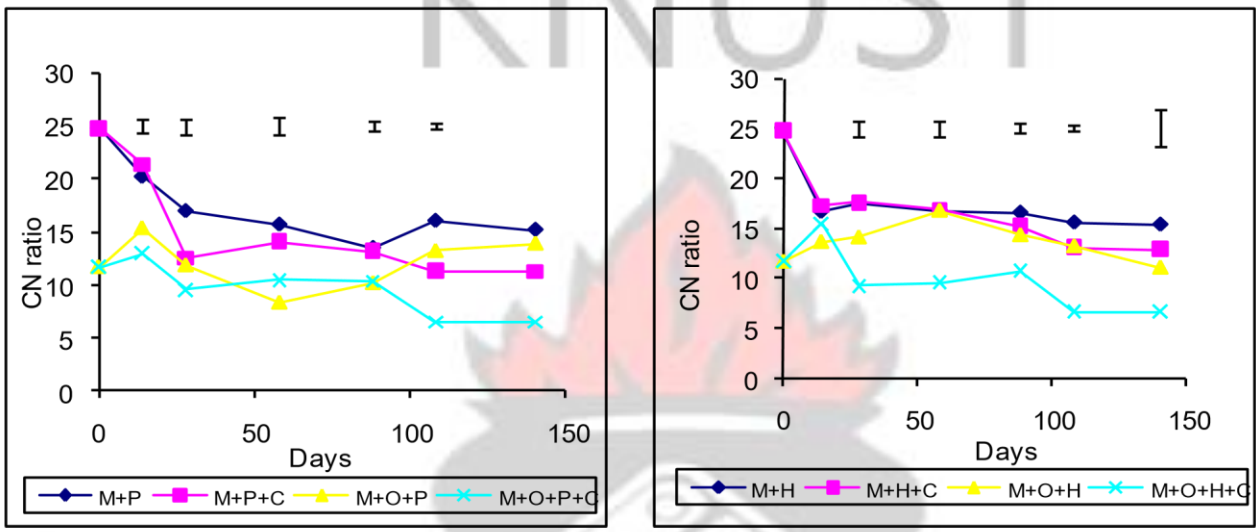
Figure 4-28: Changes in OM content of compost at INRAN (A = pit, B = heap).

4.4.2 Changes in C:N ratio

The C:N ratios of all the compost evaluated decreased during composting as indicated in Figs. 4-29 to 4-31. At NAPRI both compost heaped or stored in pits were cured after composting for 108 days (Fig. 4-29). Regardless of the storage facility used cocomposting with groundnut cake, produced compost with significantly ($P < 0.05$) lower C:N ratio than compost prepared from manure only (Fig. 4-29). The use of plastic sheet significantly reduced the C:N ratios of the compost (Fig. 4-29). The initial C:N ratio of compost containing groundnut cake decreased by (43 to 45 %) when covered with plastic sheet. Without the use of plastic sheet however, the percentage change over the initial C:N ratio ranged from -19 to 5 %. The C:N ratios of the compost evaluated at ARI also stabilised after composting for 108 days (Fig. 4-30). Although the use of plastic sheets reduced the C:N ratios of manure composted in heaps, it had no effect on manure composted in pits.

Irrespective of the storage facility used, compost containing sheanut cake had higher C:N ratios than compost prepared from manure only.

A B

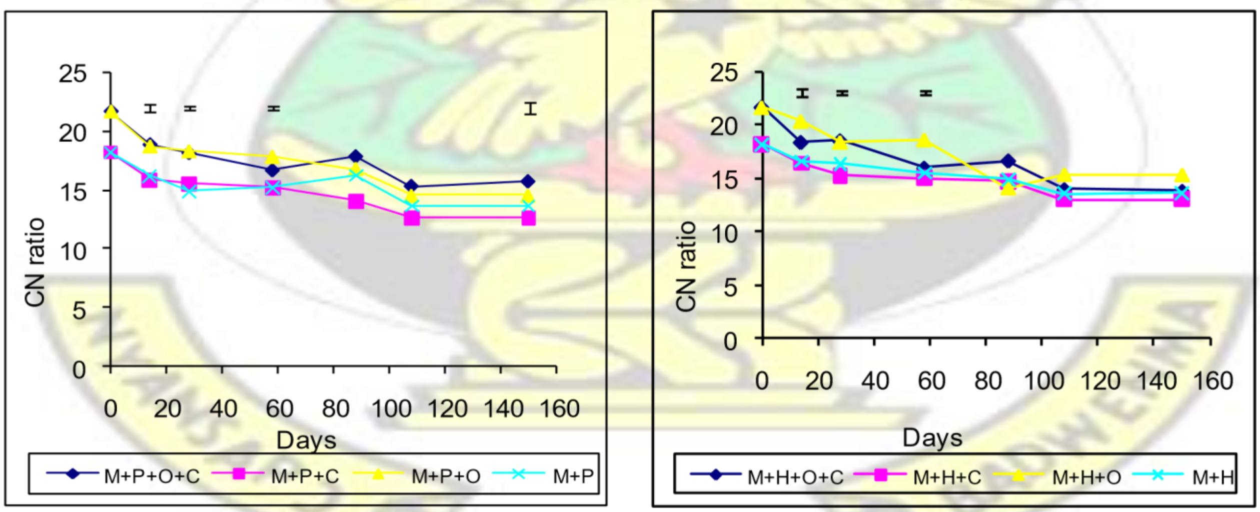


M +P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap and covered

M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheetAbsence of er ror bars indicate non significant mean differences M+O+H= manure with oilcake in heap, M+H+C = manure in heap and covered

Figure 4-29: Changes in C:N ratio of compost at NAPRI (A = pit, B = heap).

A B

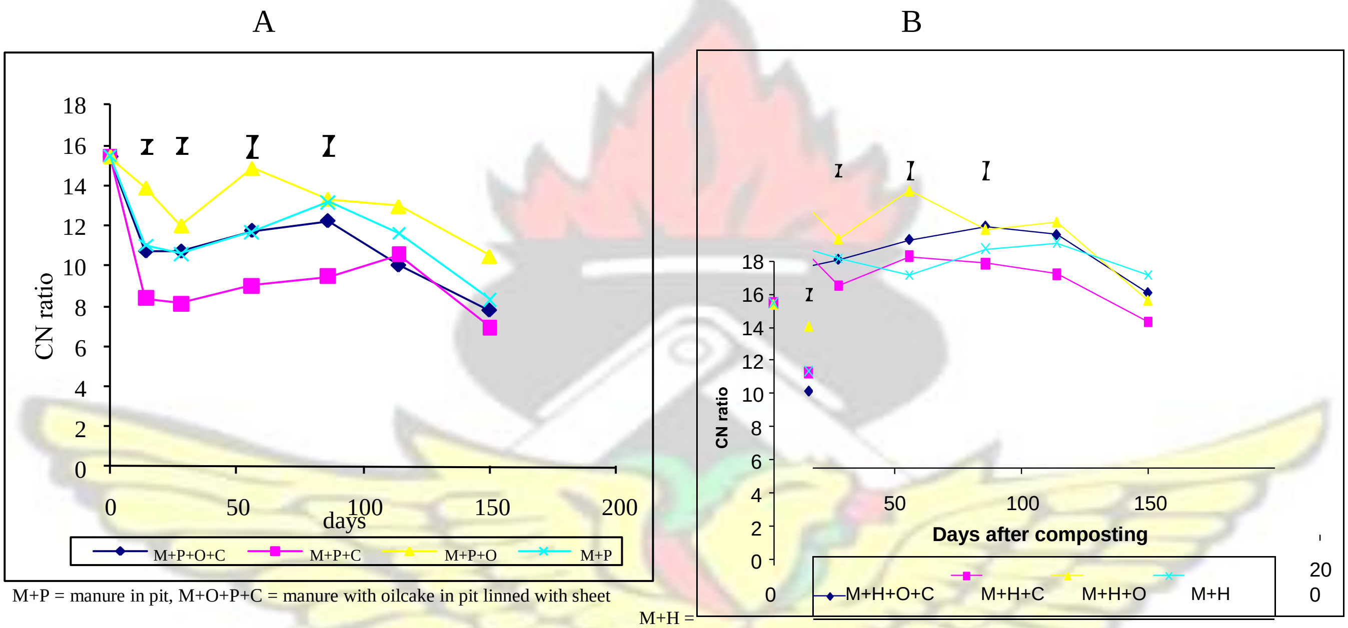


M+P = manure in pit, M+O+P+C = manure with oilcake inM+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet pit linned with sheet M+H = manure in heaM+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheetp, M+O+H+C = manure with oilcake in heap covered with sheet

Absence of error bars indicate non significant mean differences

Figure 4-30: Changes in C:N ratio of compost at ARI (A = pit, B = heap).

The C:N ratios of the compost evaluated at INRAN declined continuously throughout the composting period (Fig 4-31). Fortification of manure with cotton seed cake and the use of plastic sheets had no significant effect on the C:N ratios of the compost Fig. 4-31. A higher decrease in the initial C:N ratio of the compost was attained by using plastic sheets (55 – 56 %) than by fortifying it with cotton seed cake (31 - 47 %).



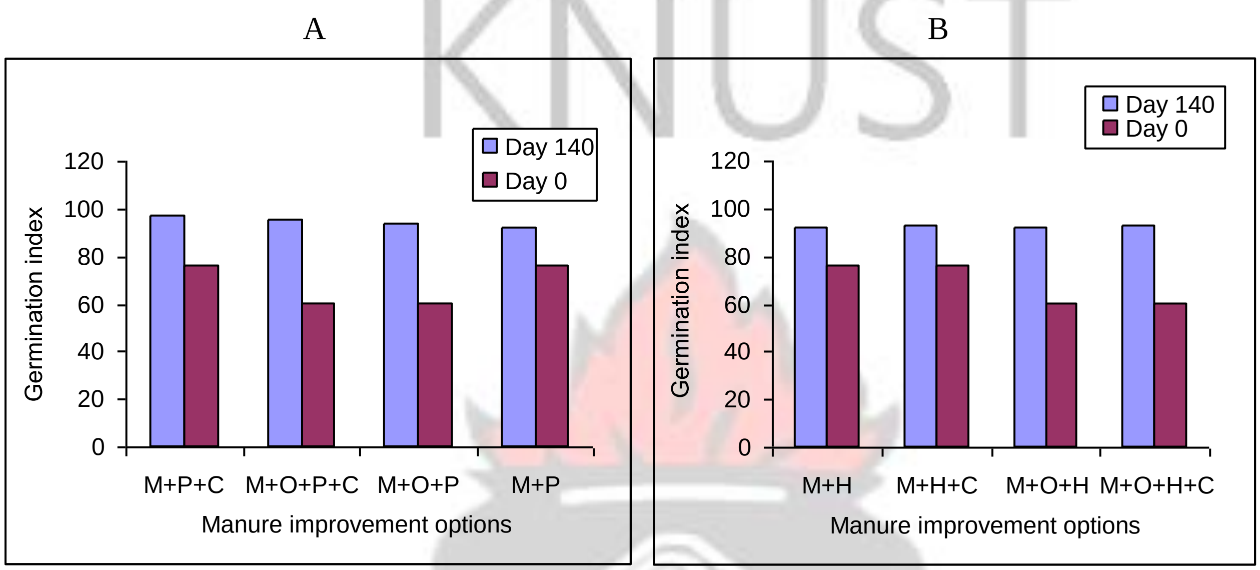
M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap and covered M+O+H= manure with oilcake in heap, M+H+C = manure in heap and covered M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

Absence of error bars indicate non significant mean differences

Figure 4-31: Changes in C:N ratio of compost at INRAN (A = pit, B = heap).

4.4.3 Germination index (GI)

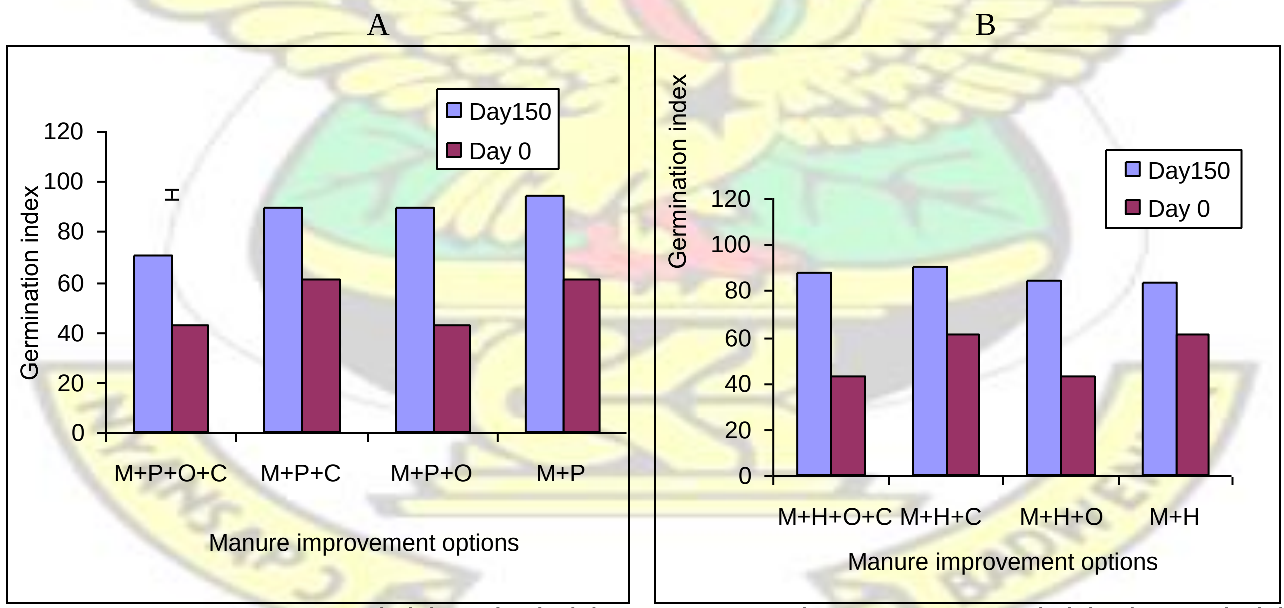
The GI of the compost materials before composting at NAPRI was 76 % for manure only and 60 % for manure mixed with groundnut cake. Regardless of the material and the facility used for composting the germination indices of the finished compost were greater than 90 percent (Fig. 4-32). Prior to composting, the germination index of manure mixed with sheanut cake was lower (42 %) than manure-only (61 %) (Fig.4-33). But for manure fortified with sheanut cake and composted in pits lined with plastic sheets lining, the GI of all the manure improvement options appraised at ARI exceeded 80 % after composting them for 150 days.



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet covered with sheet M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-32: Germination index of compost at NAPRI (A = pit, B = heap).

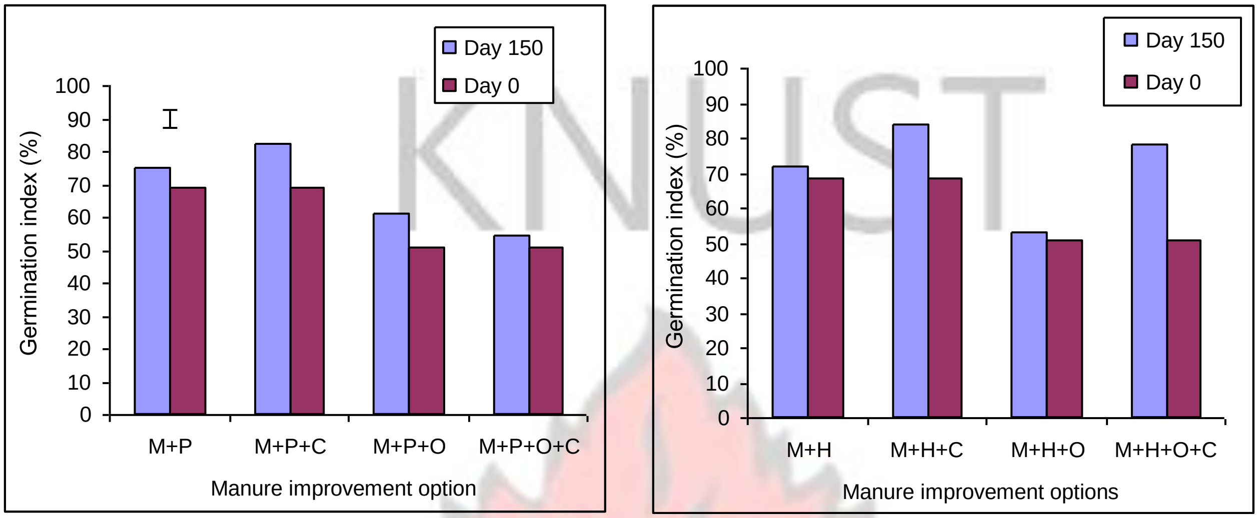


M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-33: Germination index of compost at ARI (A = pit, B = heap).

A B



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap and covered M+O+H= manure with oilcake in heap, M+H+C = manure in heap and covered

Figure 4-34: Germination index of compost at INRAN (A = pit, B = heap).

Among the materials used for composting at INRAN, the GI of fresh manure was higher (68 %) than fresh manure with cotton seed cake (51 %) (Fig. 4-34). The GI after composting the manure and manure-cotton seed cake mixtures for 140 days ranged from 53 to 84 %. Irrespective of the composting facility used, the addition of cotton seed cake reduced the GI by 6 to 28 percent.

4.4.4 Relationship between germination index and quality of cured compost

The GI of the finished compost prepared from manure or manure and groundnut cake was not linearly related to C:N, lignin and polyphenol concentrations of the finished compost (Table 4-15). The GI of the finished compost prepared from manure or manure and sheanut cake was depressed by increasing levels of C:N ratio and polyphenol (Table 416). The lignin content of the cured manure had no effect on GI. A multiple regression function describing the relationship between GI, C:N ratio and polyphenol concentration of cured compost is indicated by Equation 4-1. There was no relationship between GI and the lignin concentrations, and C:N ratios of compost prepared from manure or manure and cotton seed cake. However, the polyphenols concentration significantly decreased the GI of the compost (Table 4-17 and Equation 4-2).

Table 4-24: Multiple regression of GI with compost quality parameters at NAPRI.

Parameter	Coefficients	Std. error	Significance
Constant	93.5	3.7	< 0.001
Polyphenol (%)	-0.9	0.5	0.145
C:N ratio	-0.3	0.1	0.089
Lignin (%)	0.5	0.2	0.114

$R^2 = 0.71, P > 0.05$

Table 4-25: Multiple regression of GI with compost quality parameters at ARI.

Parameter	Coefficients	Std. error	Significance
Constant	138.7	13.0	< 0.001
Polyphenol (%)	-1.8	0.4	0.014
C:N ratio	-4.6	1.3	0.025
Lignin (%)	1.2	0.8	0.173

$$GI = 138.7 (\pm 13.0) - 1.8 (\pm 0.4) \text{ polyphenol} - 4.6 (\pm 1.3) \text{ C:N} \quad \text{Equation 4-1}$$

$(R^2 = 0.93, P < 0.01)$

Table 4-26: Multiple regression of GI with compost quality parameters at INRAN.

Parameter	Coefficients	Std. error	Significance
Constant	110.5	13.0	0.001
Polyphenol (%)	-7.9	2.1	0.019
C:N ratio	1.8	2.7	0.546
Lignin (%)	-1.7	1.8	0.406

$$GI = 110.5 (\pm 13.0) - 7.9 (\pm 2.1) \text{ polyphenol} \quad \text{Equation 4-2}$$

$(R^2 = 0.89, P < 0.05)$

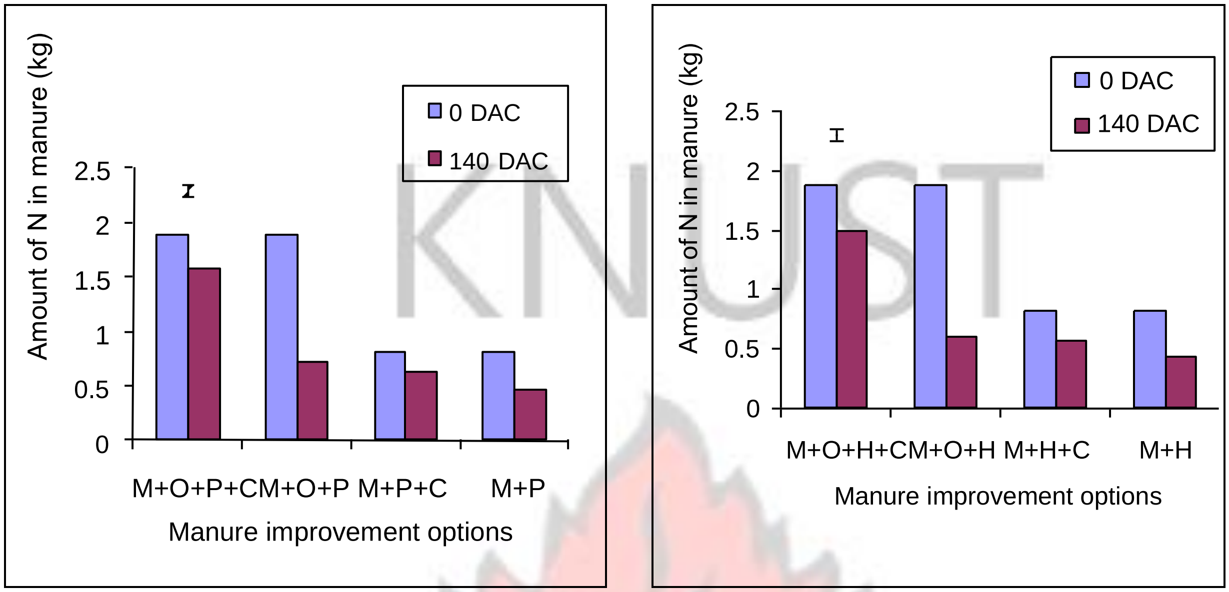
4.4.5 Nutrient losses during storage

4.4.5.1 Nitrogen losses

The total N losses recorded during composting ranged from 16 to 67 % at NAPRI, 5 to 47 % at ARI and 15 to 27 % at INRAN (Figs. 4-35 to 4-37). The addition of groundnut cake increased the initial N content of the manure-only by 130 % at NAPRI. Neither the fortification of manure with oil cake nor the storage facility used significantly ($p < 0.05$) affected the amount of N lost during the composting period at NAPRI (Fig. 4-35). Covering heaps or lining pits with plastic sheet reduced N losses significantly. In the absence of polyethene sheet covering, compost containing groundnut cake lost 61 – 67 % of their initial N content. The use of plastic sheets reduced these loses to 16 – 30 %.

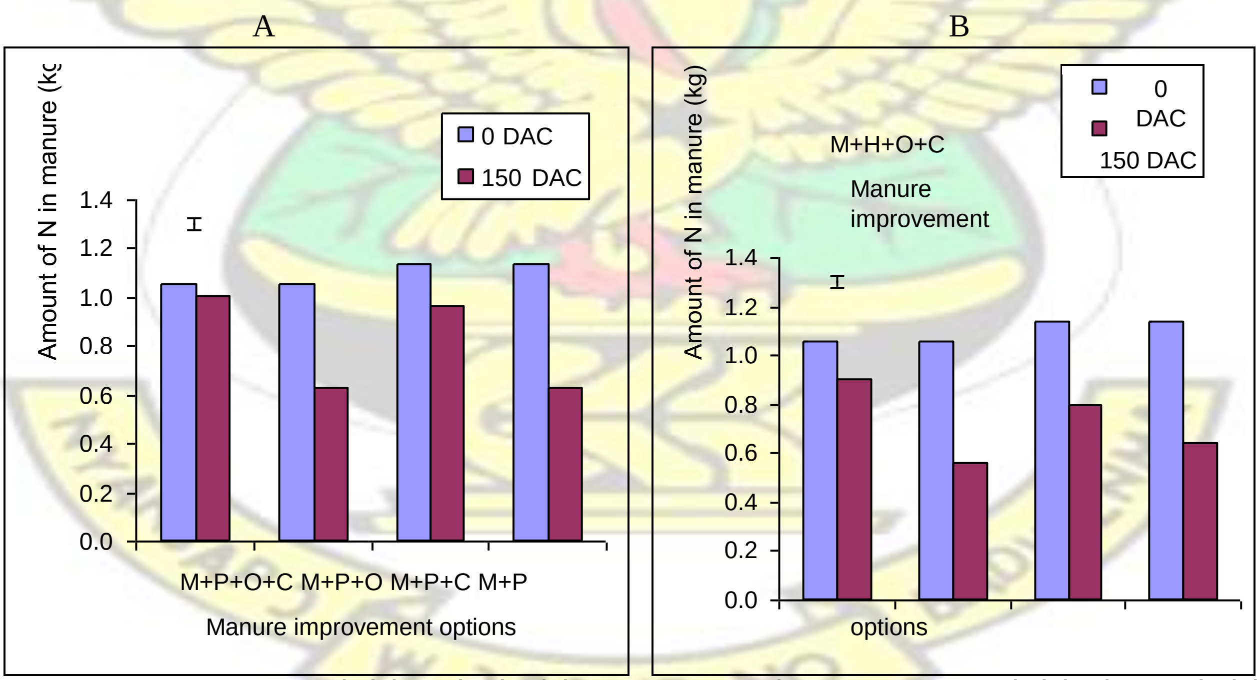
At ARI, the addition of sheanut cake reduced the initial N content of the manure by 7 %. The compost prepared in heaps at ARI lost higher amount of N during composting than those composted in pits, although these differences were not significant. The amount of N lost from materials composted in pits or heaps with plastic sheet covers were significantly ($p < 0.05$) lower (5 – 14 %) than those composted in pits or heaps without plastic sheet covers (29 – 47 %) (Fig. 4-36). The fortification of manure with sheanut cake had no effect on N losses. The addition of cotton seed cake increased the initial N content of the manure by 45 % at INRAN. Nitrogen losses were neither affected by the use of plastic sheets and cotton seed cake, nor storage in heaps or pits at INRAN, (Fig. 4-37).

A B



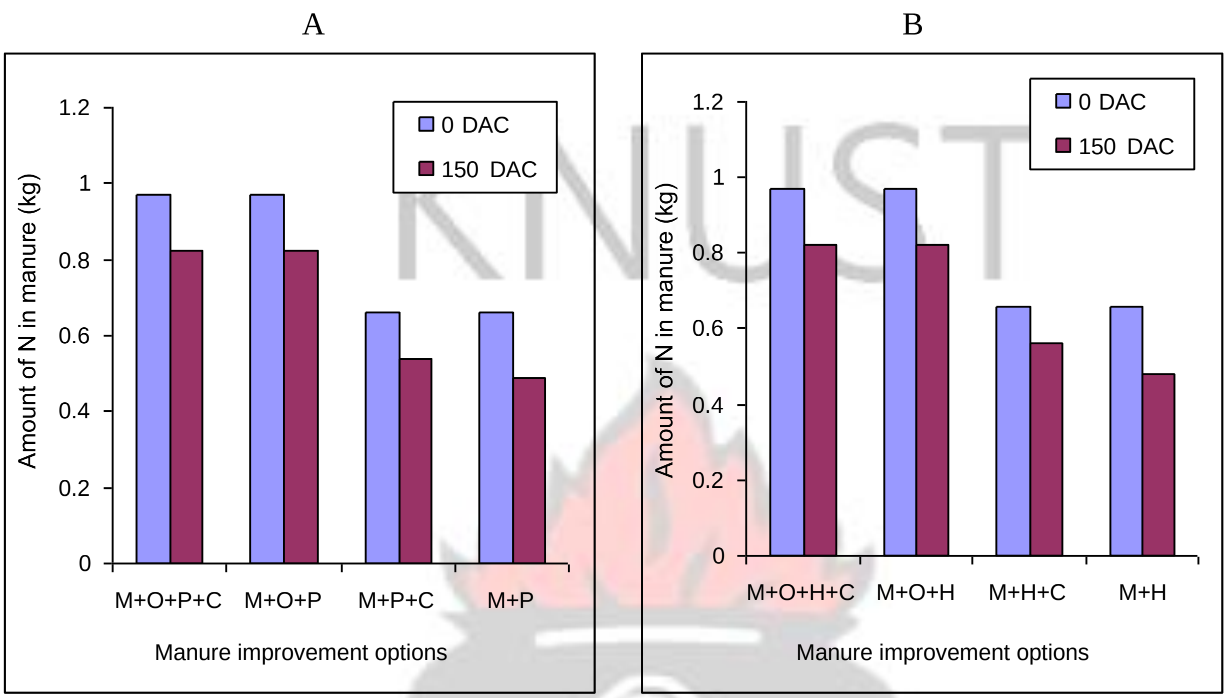
M+P = M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheetmanure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheetM+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-35: Nitrogen content of compost at NAPRI (A = pit, B = heap).



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet
M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-36: N content of compost at ARI (A = pit, B = heap).



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

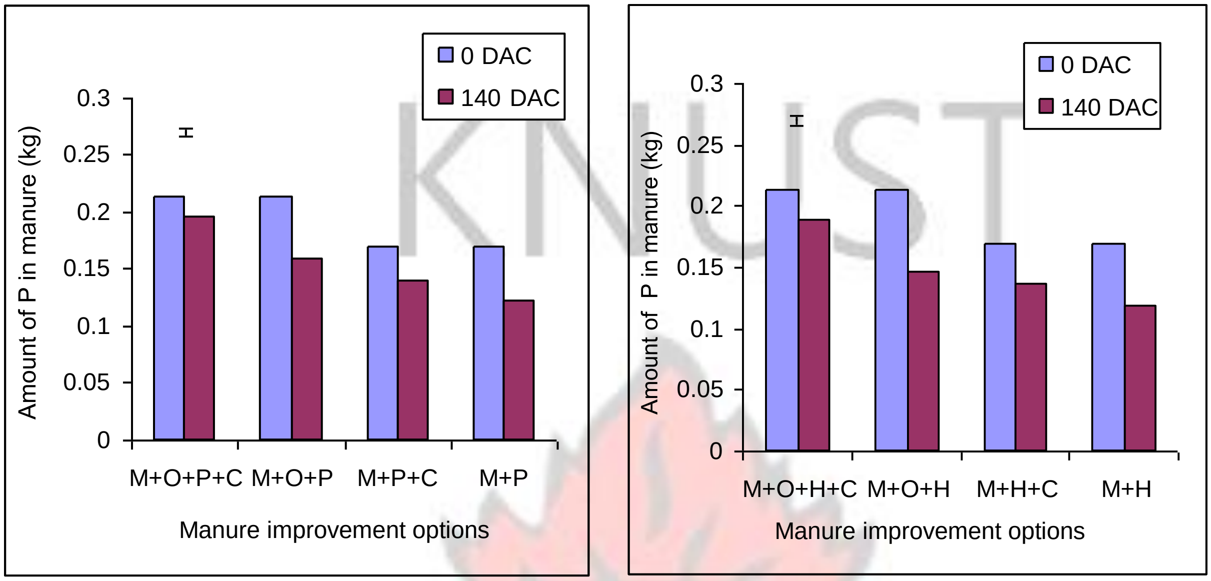
M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet
M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-37: Nitrogen content of compost at INRAN (A = pit, B = heap).

4.4.5.2 P losses during storage

The addition of oil cakes increased the initial P content of the manure by 25 % at NAPRI and 5 % at INRAN but reduced the initial P content by 26 % at ARI. The amounts of P losses observed during the composting were lower than the N losses at all locations (comparing Figs. 4-35 to 4-37 with Figs. 4-38 to 4-40). At all locations the amounts of P lost were not affected by the addition of oil cakes and the type of facility used for the compost preparation. Covering heaps or lining pits with plastic sheet reduced P losses significantly from 25 - 31% to 7 - 19 % at NAPRI (Fig. 4-38). The compost prepared in heaps at ARI lost higher amount of P during composting than those composted in pits, although these differences were not significant (Fig. 4-39).

A B

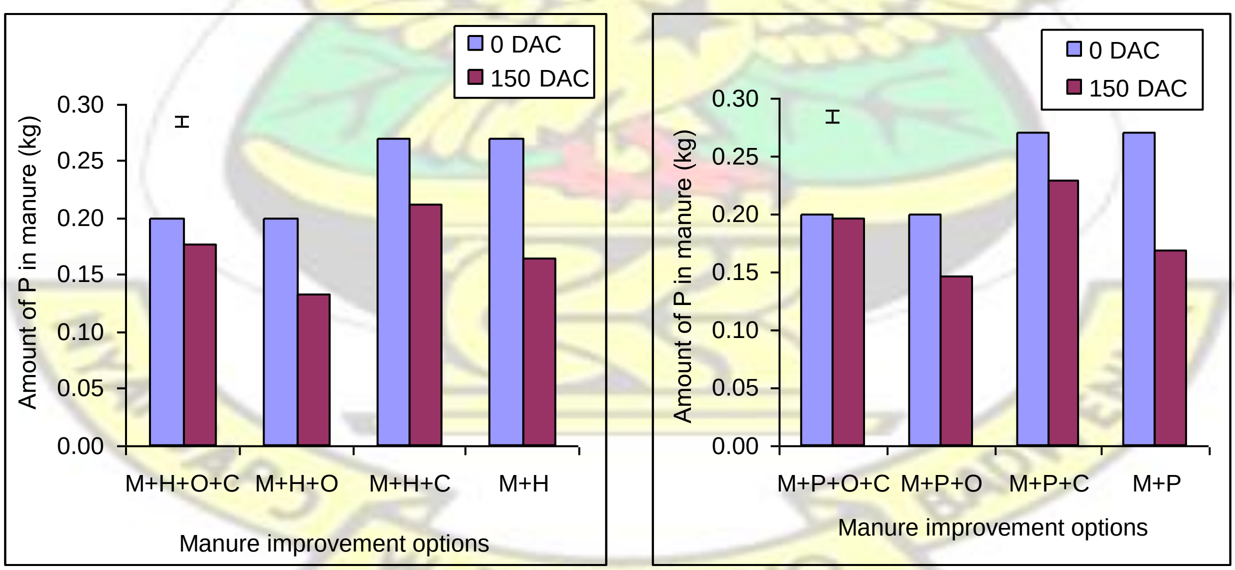


M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet
M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-38: Phosphorus content of compost at NAPRI (A = pit, B = heap).

A B

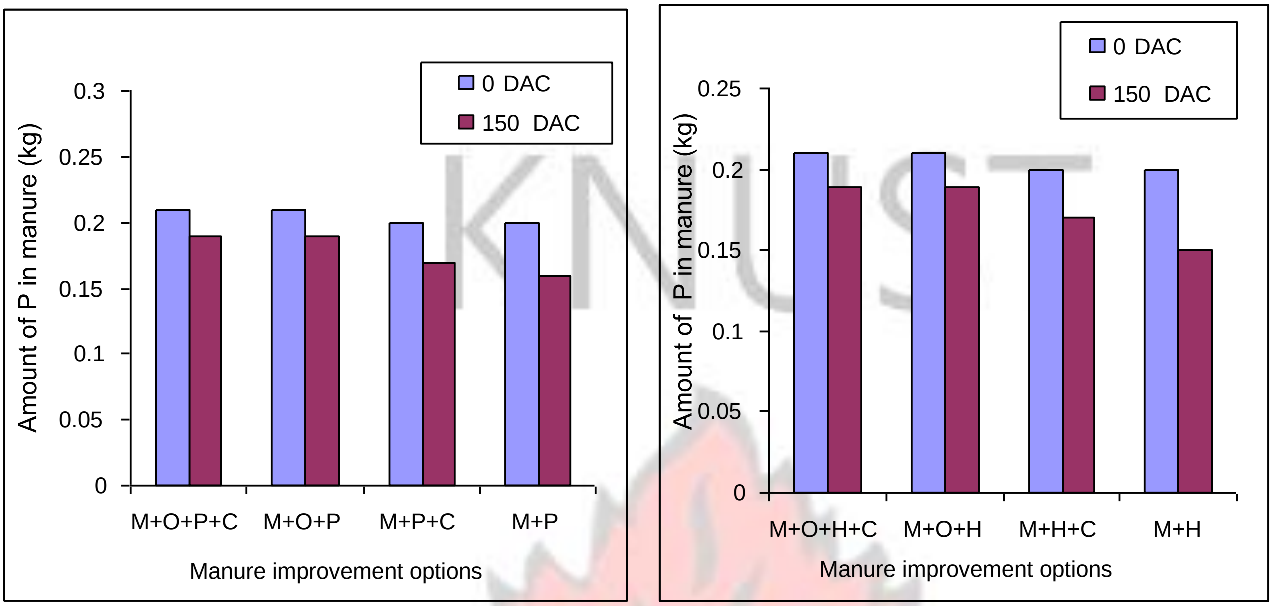


M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet
M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-39: Phosphorus content of compost at ARI (A = pit, B = heap).

A B



M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet
M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet

M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet
M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet

Figure 4-40: Phosphorus content of compost at INRAN (A = pit, B = heap).

Also at ARI, the amount of P lost from materials composted in pits or heaps with plastic sheet covers were significantly lower (3 – 20 %) than those composted in pits or heaps without plastic sheet covers (27 – 38 %). At INRAN, P losses were neither affected by the use of plastic sheets and cotton seed cake, nor storage in heaps or pits (Fig. 4-40).

4.4.6 Cost and returns of manure improvement options

Manure used for the study was obtained at no cost from the ruminant production units of the research institutions in which the study was conducted. This approach mimicked the standard farmer practise of acquiring manure from the livestock unit of their farms. Among the manure improvement options evaluated at ARI, the highest gross benefit accrued from manure fortified with sheanut cake and composted in pits lined with plastic sheets (Table 4-27).

As the sheanut cake used for the study was obtained at no cost, the cost of plastic sheet was found to be the single largest (54 – 100 %) component of the installation cost. The most cost effective option was the standard farmer practise of keeping manure in heaps without any cover or nutrient additive (Table 4-27). Also at NAPRI, the manure– groundnut cake compost prepared in facilities covered or lined with plastic sheet earned the highest gross benefit (Table 4-28). The cost of groundnut cake was the largest (67 – 97 %) component of the installation cost. As a result, the cost incurred in installing these improvement options rendered all the options unprofitable except manure composted in heaps with neither a platic sheet cover nor nutrient additive (Table 4-28).

Table 4-27: Financial analysis of manure improvement option at ARI.

Particulars	Manure improvement options							
	M+P+C	M+O+P+C	M+O+P	M+P	M+H	M+H+C	M+O+H	M+O+H+C
Gross benefit								
Amount of N (kg^{-1} option)	0.97	1.01	0.63	0.63	0.64	0.80	0.56	0.91
Price of N (GH ¢ /kg)	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13
Gross value (GH ¢)	3.03	3.16	1.98	1.97	2.01	2.51	1.77	2.84
Variable inputs cost (GH¢)								
Plastic sheet	1.25	1.25	0.00	0.00	0.00	1.25	0.00	1.25
Oil cake	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transport of oil cakes	0.00	0.08	0.08	0.00	0.00	0.00	0.08	0.08
Pit digging	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Total cost (GH¢)	2.25	2.33	1.08	1.00	0.00	1.25	0.08	1.33
Net value (GH¢)	0.78	0.83	0.90	0.97	2.01	1.26	1.68	1.51

M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet, M+O+P= manure with oilcake in pit, M+P+C = manure in pit linned with sheet, M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet, M+O+H= manure with oilcake in heap, M+H+C = manure in heap covered with sheet.

Table 4-28: Financial analysis of manure improvement option at NAPRI.

Particulars	Manure improvement options							
	M+P+C	M+O+P+C	M+O+P	M+P	M+H	M+H+C	M+O+H	M+O+H+C
Gross benefit								
Amount of N (kg^{-1} option)	0.62	1.58	0.73	0.46	0.44	0.57	0.61	1.49
Price of N (₦ /kg)	195.7	195.7	195.7	195.7	195.7	195.7	195.7	195.7
Gross value (₦)	121.4	308.4	142.7	90.5	86.5	111.3	118.9	291.6
Variable inputs cost (₦)								
Plastic sheet	200.0	200.0	0.0	0.0	0.0	200.0	0.0	200.0
Groundnut cake	0.0	760.0	760.0	0.0	0.0	0.0	760.0	760.0
Transport of oil cakes	0.0	20.0	20.0	0.0	0.0	0.0	20.0	20.0
Pit digging	150.0	150.0	150.0	150.0	0.0	0.0	0.0	0.0
Total cost (₦)	350.0	1130.0	930.0	150.0	0.0	200.0	780.0	980.0
Net value (₦)	-228.6	-821.6	-787.3	-59.5	86.5	-88.7	-661.1	-688.4

M+P = manure in pit, M+O+P+C = manure with oilcake in pit linned with sheet, M+O+P= manure with oilcake in pit, M+P+C = manursheet, M+H = manure in heap, M+O+H+C = manure with oilcake in heap covered with sheet, M+O+H= manure with oilcake in heap, M+H+C = manure in e in pit linned with heap covered with sheet.

4.5 Added benefits derived from integrated use manure and mineral fertiliser

4.5.1 Effect of manure and mineral fertiliser on grain yield

The application of NPK fertiliser and manure-only or in combination significantly ($p<0.05$) increased the grain yield of maize at Nyankpala and Sarauniya (Table 4-29, Figs. 4-41 and 4-42). However, at Maradi grain yield of millet was neither affected by the application of mineral fertiliser nor manure and their combinations (Table 4-29). The use of mineral fertiliser exerted more influence on grain yield than the use of manure.

Table 4-29: Main effects of manure and mineral fertiliser application on grain yield

	Grain yield (kg ha^{-1})		
Mineral Fertiliser (% RR)	Nyankpala (Ferric Luvisol)	Sarauniya (Regosol)	Maradi (Eutric Gleysol)
0	864	278	727
25	1258	653	815
50	1433	1247	773
100	1788	1768	743
Pr	<.001	<.001	0.603
Lsd (0.05)	224.3	217	141.4
Manure (t ha^{-1})			
0	994	776	740
2.5	1325	860	694
5	1478	1014	813
10	1545	1296	811
Pr	0.006	<.001	0.259
Pr fert * man	0.003	0.049	0.651
Lsd (0.05)	224.3	217	141.4
CV%	20.1	26.4	22.2

At Nyankpala (on the Ferric Luvisol), on the average over the four levels of manure use, the application of NPK fertiliser at 25 % of the recommended rate (RR) significantly increased grain yield by 46 %. The magnitude of improvement in grain yield following the application of NPK at 50 %RR (66 %) was similar to the improvement attained at 25 %RR but was significantly ($p<0.05$) lower than the 107 % obtained from the application of 100 %RR (Table 4-29). The increases in grain yield following the application of manure at Nyankpala on the other hand were 33 % by the application rate of 2.5 t ha^{-1}, 49 % by the application rate of 5 t ha^{-1} and 55 % by the application rate of 10 t ha^{-1}. Compared to the improvements in grain yield by mineral fertiliser at Nyankpala, the application of mineral fertiliser at Saurauniya led to higher improvements in grain yield in the order of 135 % by the application of 25 % RR, 349 % by the application of 50 % RR and 534 % by the application of 100 % RR (Table 4-29). Yet, improvements in yield attributable to the application of manure at Sarauniya were only 11 % at the rate of 2.5 t ha^{-1}, 31 % at the rate of 5 t ha^{-1} and 67 % the rate of 10 t ha^{-1}.

Figures 4-41 to 4-43 show the combined effect of NPK fertiliser and manure on grain yields at various locations. As illustrated in Fig. 4-41, the combined use of manure and mineral fertiliser at Nyankpala increased grain yield steadily from 1283 kg ha^{-1} (NPK fertiliser at 25 % RR with manure at 2.5 t ha^{-1}) to 2157 kg ha^{-1} (NPK fertiliser at 100 % RR with manure at 5 t ha^{-1}) and declined to 2032 kg ha^{-1}. A similar trend was observed at Sarauniya (on the Regosol) except that, the combined application of manure and mineral fertiliser increased grain yield sharply from 571.1 kg ha^{-1} by the application of 25 % RR of NPK fertiliser and 2.5 t ha^{-1} of manure to 2376 kg ha^{-1} following the application of

NPK fertiliser at 100 % RR and manure at 10 t ha^{-1} (Fig. 4-42). On the contrary, the conjoint use of mineral fertiliser and manure had no effect on grain yield at Garin Labo (on the Eutric Gleysol) as indicated by Fig. 4-43.

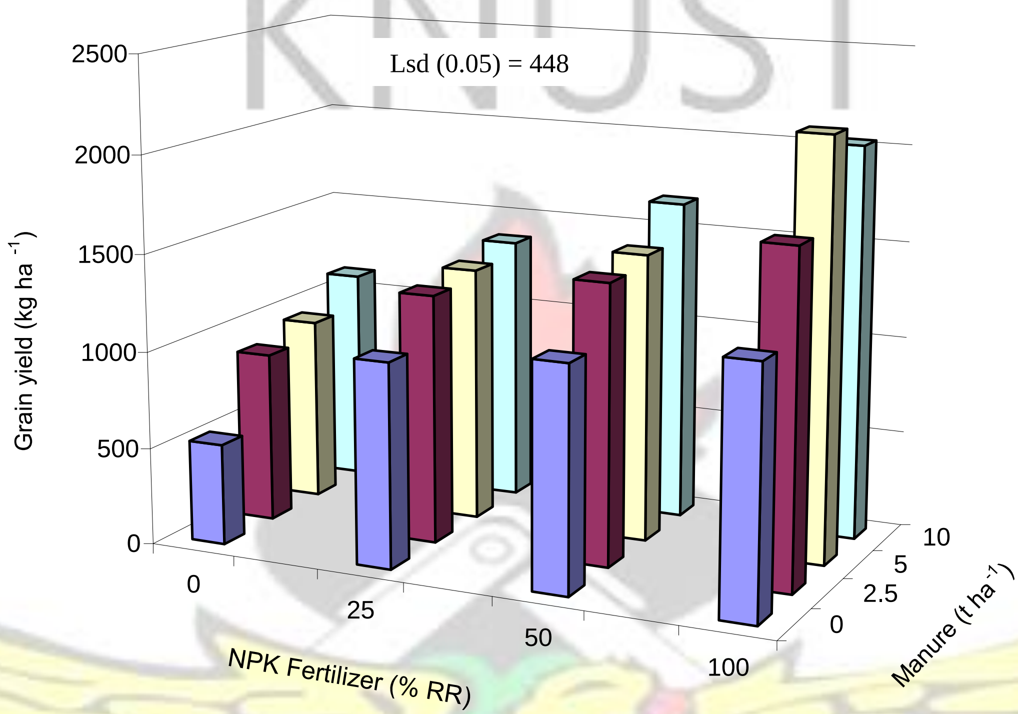


Figure 4-41: Effect of mineral fertiliser and manure on grain yield at Nyankpala.

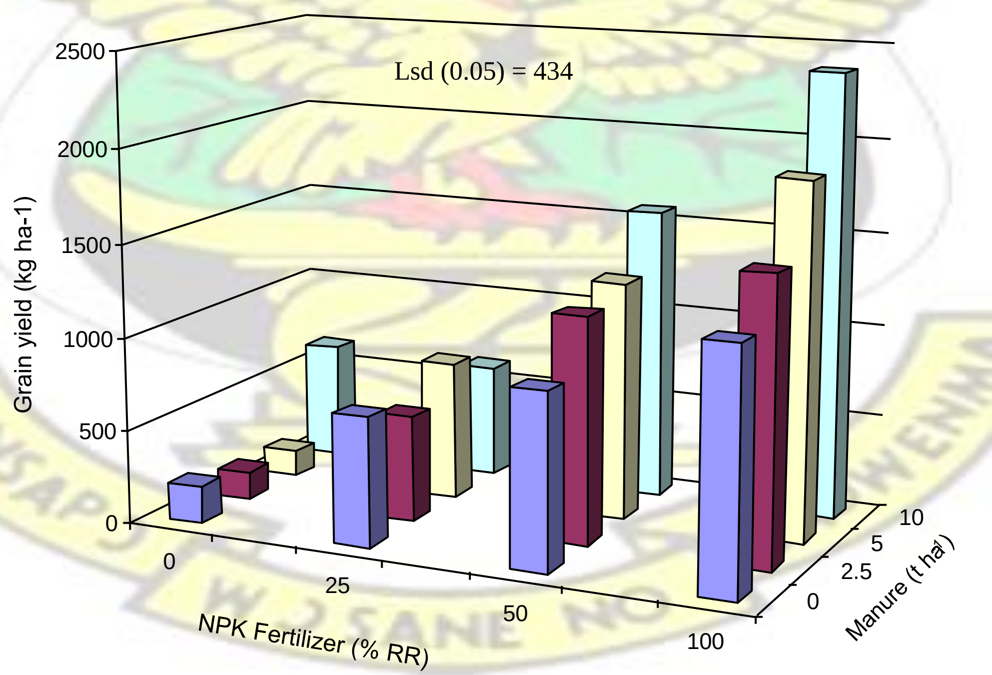


Figure 4-42: Effect of mineral fertiliser and manure on grain yield at Sarauniya.

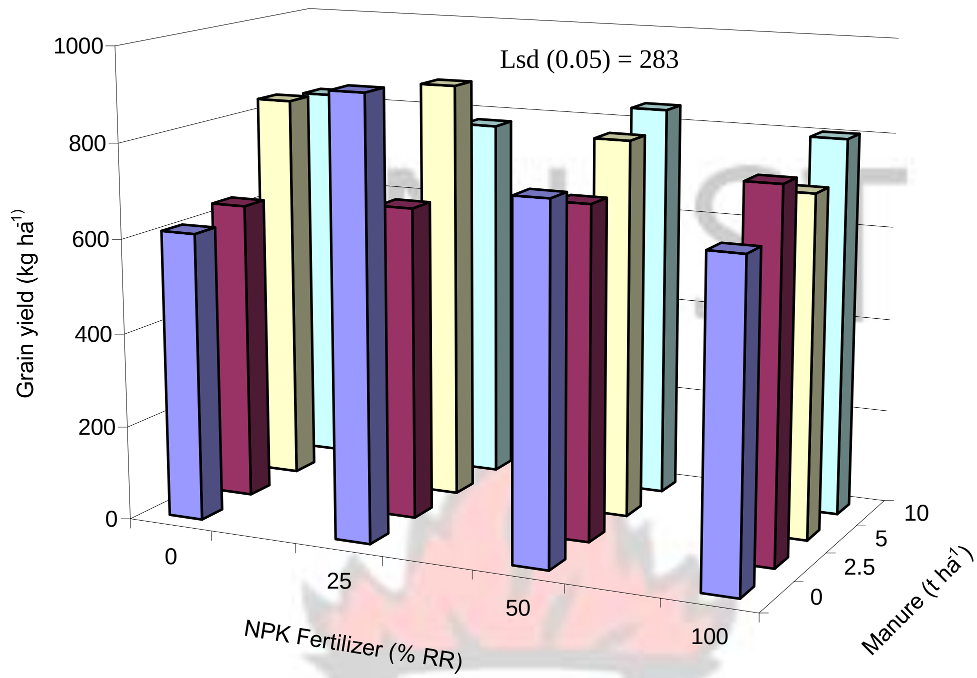


Figure 4-43: Effect of mineral fertiliser and manure on grain yield at Maradi.

4.5.2 Added benefits in grain yield

The changes in grain yield resulting from the interaction of NPK fertiliser and manure at Nyankpala and Sarauniya are shown in Fig. 4-44. The interactive effect of combined NPK fertiliser and manure at Maradi was not significant, hence added benefits or losses were not estimated.

At Nyankpala, regardless of the rate of manure applied the application of NPK fertiliser at a rate less than 50 % of the recommendation resulted in negative interaction with added benefit in grain yield ranging from -68 to -262 kg ha^{-1}. A positive interaction was found only when the recommended rate of NPK fertiliser was applied with manure.

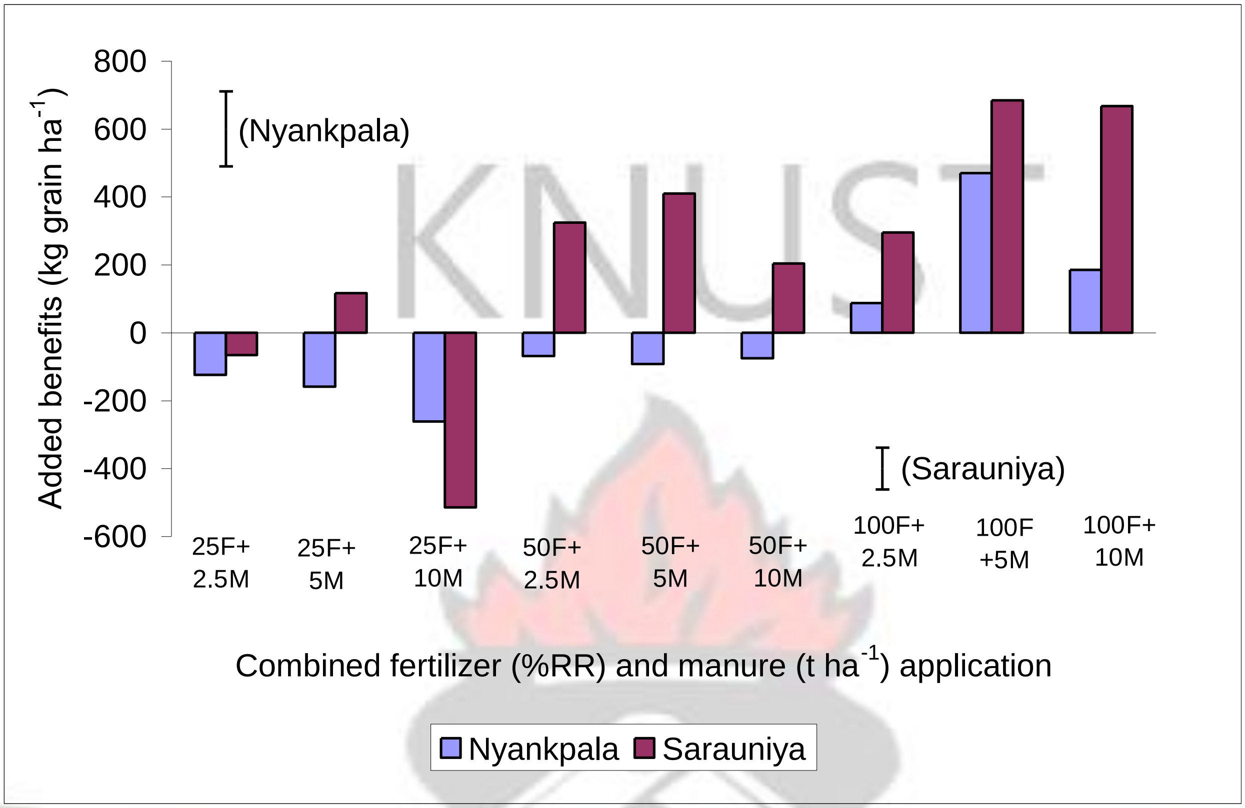


Figure 4-44: Added benefits from manure and mineral fertiliser.

The conjoint application of 100 % RR of NPK and 5 t ha^{-1} of manure recorded the highest added benefits of 470 kg ha^{-1}. However at Sarauniya, the interactions between the NPK fertiliser and manure were generally positive. Negative interactions were only recorded following the application of NPK at 25 % RR and manure at either 2.5 or 10 t ha^{-1}. The conjoint application of 25 % RR of NPK and 10 t ha^{-1} of manure recorded the lowest added benefit of -514 kg ha^{-1} while the application of 100 % RR of NPK and 5 t ha^{-1} of manure recorded the highest added benefits of 684 kg ha^{-1}.

4.5.3 Cost and returns of combined application of mineral fertiliser and manure The returns on investments in mineral fertiliser and manure applications were appraised by the VCR estimates. The application of manure without mineral fertiliser accrued net negative returns at all locations as the VCR estimates were less than 1 (Figs. 4-45 to 447). However, apart from the application of mineral fertiliser at 100 % RR (VCR = 0.6) in Nyankpala, the application of mineral fertiliser alone yielded net positive returns (VCR = 1 – 2.3) in Nyankpala and Sarauniya as indicated by Figs. 4-45 and 4-46.

Furthermore the VCR estimates obtained from the combined application of manure and fertiliser (2.3 – 4.7) were greater than the economic viability threshold. The most economically attractive nutrient management option at Nyankpala was the combined application of NPK fertiliser at 25 % RR and manure at 2.5 t ha^{-1} (Fig. 4-45).

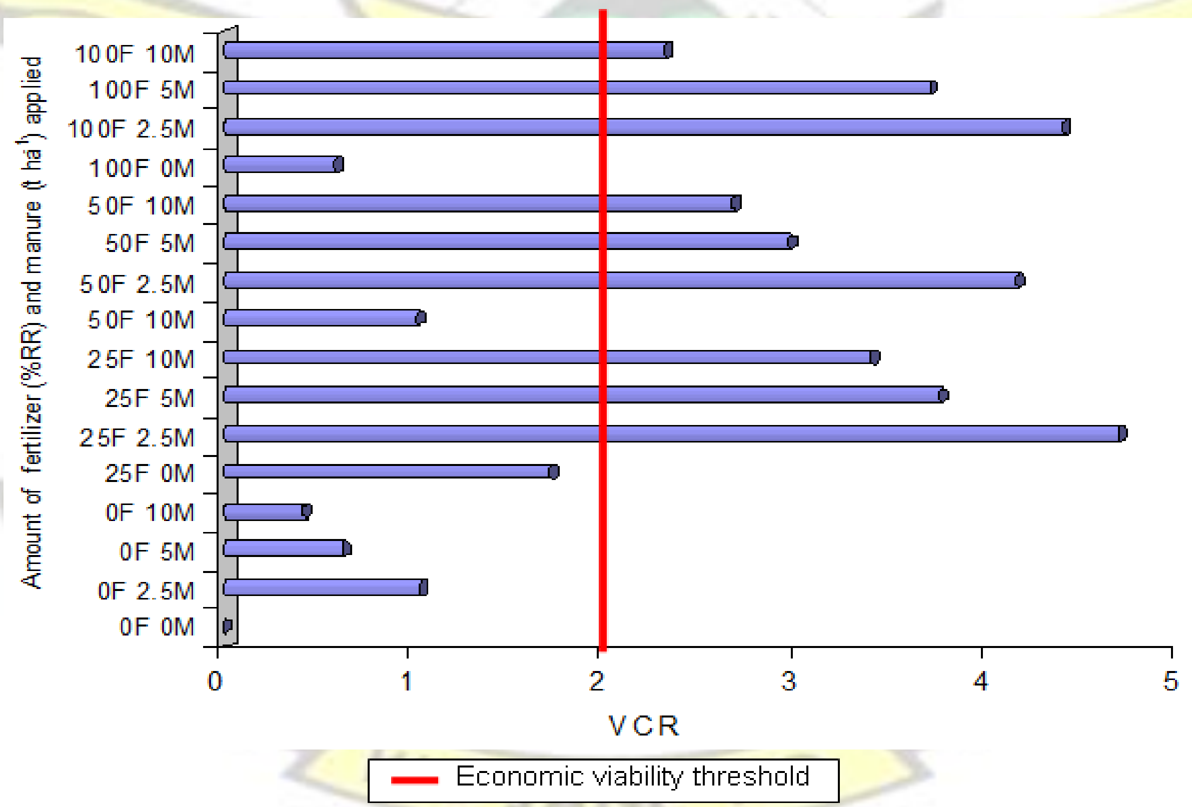


Figure 4-45: Value cost ratios of mineral fertiliser and manure application at Nyankpala.

The sole application of mineral fertiliser at Sarauniya (VCR = 1.3 – 2.3) accrued net positive returns regardless of the application rate. Also at Sarauniya, VCR derived from the combined application of fertiliser and manure (2.4 – 7.7) implied the irrespective of proportions applied the combined mineral fertiliser and manure options were economically attractive (Fig. 4-46). However, the most economically attractive option was the combined application of NPK fertiliser at 100 % RR and manure at 2.5 t ha^{-1}.

At Maradi, the application of NPK fertiliser –only at all rates except 25 % RR recorded net negative returns, Fig. 4-47. Also apart from the combined application of 25 %RR of NPK fertiliser with manure at either 5 or 10 t ha^{-1}, all NPK fertiliser and manure combinations applied at Maradi were not economically attractive.

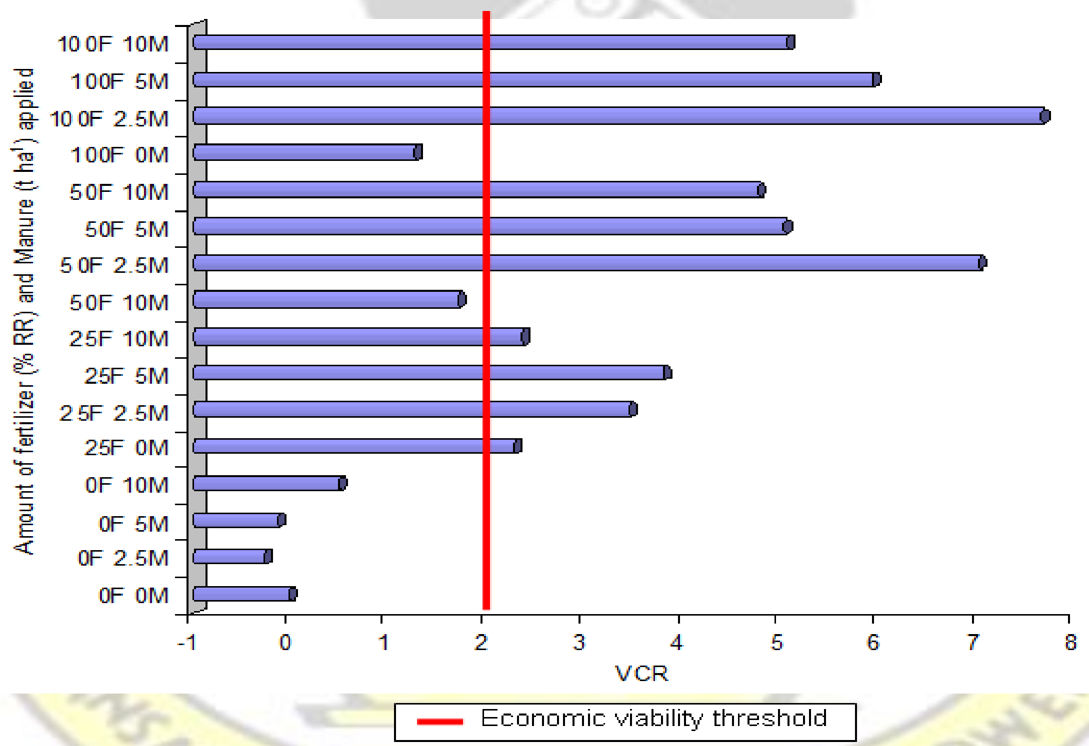


Figure 4-46: Value cost ratios of mineral fertiliser and manure application at Sarauniya.

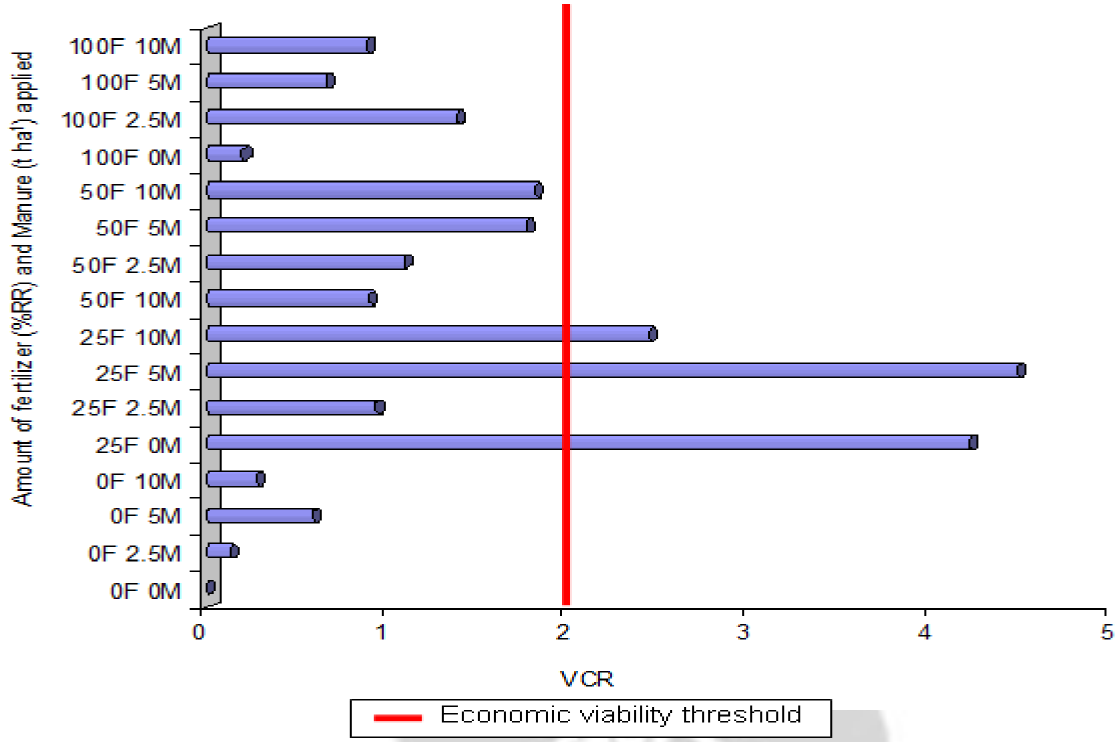


Figure 4-47: Value cost ratios of mineral fertiliser and manure application at Maradi.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Nutrient flows and balances of cereal-legume-livestock systems

5.1.1 Nutrient flows

Nutrient inputs through mineral fertiliser observed in the study far out weighed the amount actually applied by farmers. In contrast to the 23 – 60 kg ha^{-1} of N and 8 – 25 kg ha^{-1} P inputs from mineral fertiliser, a study conducted on Acrisols and Fluvisols in the Nkawie district and on Ferralsols in the Wassa Amenfi district of Ghana, the FAO (2006) reported that farmers supplied only 6 kg ha^{-1} of N and 1.2 kg ha^{-1} of P to maize crops. The chronic low use of mineral fertiliser by smallholder farmers in West Africa is attributed to the high transaction cost and inefficiencies throughout the production – consumption chain (Quinones *et al*., 1997). Furthermore, the quantities of manure applied by the farmers on the Regosol at Sarauniya (537 kg ha^{-1}) and on the Eutric Gleysol at Garin Labo (888 kg ha^{-1}) fell short of the 5000 kg ha^{-1} recommended as the minimium for optimum crop production (Bationo and Mokwunye, 1991) which could be attributed in part to insufficient animals and feed resources to provide the amount of manure required for optimum crop production.

Although the influence of harmattan was more intense at Garin Labo than at Cheyohi (FAO, 2004) the low flux of nutrient through harmattan deposition at Cheyohi was compensated for by the high nutrient inputs through precipitation. Consequently, about 5 – 6 kg ha^{-1} of N and 0.8 – 0.86 kg ha^{-1} of P were obtained from atmospheric deposition at all locations. These nutrient flows agreed with the estimates of 3 – 15 kg N ha^{-1} and 0.2 –

2 kg P ha^{-1} by Stoorvogel and Smaling (1990). The observation that N fixation by groundnut on the Regosol at Sarauniya was significantly higher ($p<0.05$) than cowpea on either the Ferric Luvisol at Cheyohi or the Eutric Gleysol at Garin Labo was consistent with superior N fixing ability of groundnut over cowpea at Nkawie and Wassa Amenfi districts in Ghana as reported by FAO (2004).

Clearly, harvesting of crops produce, removal of crop residues and leaching were the most important pathways for nutrient losses and accounted for about 96 to 100 % of the total nutrient output. In a related study, Elias *et al*. (1998) identified the total removal of crops from the field as a major cause for the predominant negative balances.The observed leaching losses of N (19 – 22 kg N ha^{-1}) were lower than the 24.5 – 30 kg N ha^{-1} losses found by Wortmann and Kaizzi (1998). The marginal contribution of gaseous exchanges to nutrient output could be due to the low pH (5.7 – 6.4) and the well drained nature of these soils which moderated the processes of ammonia volatilization and denitrification (Johnson, 1995).

5.1.2 Nutrient balances

The negative N balance observed at the farms and village levels suggest that annual crop production in these villages rely on soil N stocks to sustain crop production. A depletion of these reserves at the prevailing rate of 7 to 19 N kg $ha^{-1}yr^{-1}$ (Figs. 4-3 and 4-5) may bring crop production to a halt if remedial measures are not used to reverse the trend. The N balances found in this study were better than the average N-balance for sub-Saharan Africa (-22 kg $ha^{-1}yr^{-1}$) reported by Stoorvogel and Smaling (1990) when farmers applied the recommended doses of mineral N fertilisers. In the absence of mineral N fertiliser use, the N balances became worse than average value (Figs. 4-4 and 4-6) confirming the findings of Manyong *et al*. (2002) that more than 80 % of the smallholder farmers in the savannas of West Africa apply mineral fertiliser but at rates lower than recommended dose.

Following the application of the recommended doses of mineral P fertilisers, positive balances were found (Figs. 4-9 and 4-10). The P balances estimated without the use of P fertiliser at Garin Labo (-2.40 kg ha^{-1} yr^{-1}) was consistent with the average P balance for Niger (-2.0 kg ha^{-1} yr^{-1}) reported by Stoorvogel and Smaling (1990) indicating that small holder farmers in Niger may not be using P fertilisers in the cropping systems. Compared to the average balances for Ghana and Nigeria (Stoorvogel and Smaling, 1990), the estimates from this study indicated that small holder farmers use P fertiliser but at a lower rate than recommended. Retention of half of the residues generated on the field supplied higher amount N (8 – 26.3 kg $ha^{-1}yr^{-1}$) than P (0.5 – 2.0 kg $ha^{-1}yr^{-1}$) into the cropping system. Considering that N is the most limiting plant nutrient in the soils of the savannas (Vanlauwe *et al*., 2002a), incorporation of crop residues may improve crop production greatly.

The widespread negative N balance at both farm and village scales can be addressed by devising pragmatic approaches such as pollarding and alley farming to limit the dependency on crop residues for fuel and construction purposes. Secondly, decision made by farmers on the uses of crop residues could be refined by providing them with information on the short and long term benefits of crop residue retention. Furthermore, as poor handling and storage of manure significantly reduced the fertiliser value, cost effective strategies of storing manure such as pits rather than heaps (Kwakye, 1980; Thomsen, 2000), under shed and covering with polyethene film (Rufino *et al*., 2007) and on concrete floors and under roofs (Lekasi *et al*., 1999) should be evaluated and used appropriately. Lastly, the high leaching losses found in this study demand a cost effective land management technique to curb these loses. These measures may include, hill placement of fertiliser (AfNet, 2002), use of nitrification inhibitors (Chaves *et al.,* 2006 and Opoku, 2004) and surface application of mulch (Lal, 1980).

The nutrient stock to nutrient balance ratio gives an indication of time frame a farming system could maintain production at the same level with the available nutrients (Defoer *et al.*, 2000). The estimated NS:NB ratios of 133 at Cheyohi, 27 at Sarauniya and 20 at Garin Labo implied that with application of N fertiliser under the current crop management practices, crop yields could be sustained for 133 years at Cheyohi, 27 years at Sarauniya and 20 years at Garin Labo. Without mineral N fertiliser application however, crop yields may be only maintained for 7 – 15 years. This ratio underscores the fact that a negative nutrient balance *per se* does not necessarily imply a decline in crop production as the soil may contain sufficient stocks of nutrients to maintain productivity for several years. It also addresses the missing link between stocks and balances found in many nutrient balance studies and explains why many studies have pointed to the alarming rate of nutrient mining (Stoorvogel and Smaling, 1990; Smaling *et al*., 1996 and Van den Bosch *et al*., 1998) yet, yields of smallholder farmers are not declining.

5.2 Impact of crop residue allocation on crop and livestock productivities

5.2.1 Effect of crop residues on grain yield and liveweight of livestock

The observation that grain yield of maize increased with increasing amount of crop residues at Cheyohi (Fig. 4-14) affirms the findings of Larbi *et al*. (2002) that along the transect from humid forest to the northern Guinea savanna, grain yield of maize increased with mulching rate. The lack of response of millet and cowpea to crop residue application in the Sahel savanna (Fig. 4-16) while disagreeing with positive effect of crop residue application on the grain yield of millet reported by Franzluebber *et al*. (1994) in the Sahel, supports the conclusion of Giller *et al*. (2009) that crop residue management can result in yield benefits in the long-term, but in the short-term yield losses or no yield benefits may result. In studies where positive responses to crop yield were observed in the short term, they were attributed to the improved rainwater use efficiency through improved infiltration and reduced evaporative water losses (Giller *et al*., 2009) and mobilization of soil P through the release of organic acids from the decomposing residue (Hue, 1991). Nutrient immobilization (Larbi *et al*., 2002), occurrence of residue borne diseases and poor germination (Giller *et al*., 2009) have been cited as factors responsible for the often-observed short-term yield reductions.

The observed weight gain by small ruminants at Cheyohi (15 – 41 g d^{-1}) and Sarauniya (15 – 58 g d^{-1}), compared favourable with 20 – 59 g d^{-1} weight gain reported by Ayetunde *et al*. (2007) by supplementing sheep diet with groundnut haulm as well as other growth rates found by Alli-Balogun *et al*. (2003) and Ngwa and Tawah (2002). The absence of a significant effect of CR on growth rates at Garin Labo suggests that the pasture ingested by grazing on the range land was of equal quality to CR fed (Faftine *et al*., 1998). Although the growth rates attained by animals in Garin Labo (42 – 70 g d^{-1}) were higher than those in Cheyohi and Sarauniya, they fell short of the 187.5 g d^{-1} reported by Hiernaux and Ayantunde (2004). Differences in the breeds of small ruminants and quality of the CR used may account for the discrepancies in these results. The observed increases in weight gain with increasing amount of haulm attest to the assertion that residue from a legume food crop serves as a source of fermentable N and bypass protein which increases the efficiency of utilization of other feed ingredients (Smith *et al*., 1988; Swain and Smith, 1994).

The results further indicated that the application of haulms could be a viable strategy for increasing the grain yield of maize in the northern Guinea savanna (Table 4-13). However, approaches other than crop residue management (eg. improved biological N fixation) may be required to increase the grain yield of cowpea. The strong positive correlation between haulm intake and live weight of livestock found in this study while confirming the findings of Faftine *et al*. (1998) and Ayantunde *et al*. (2007) suggests that mutton production could be increased dramatically by increasing the proportion of haulm fed to small ruminants. In addition, crude protein intake influenced live weight better than neutral detergent fiber. Following the report by Savadogo *et al*. (2000) that the upper part of the cereal stover is more digestible and has a higher concentration of crude protein than the lower part, improvement in live weights could be achieved by selective removal of _stover tops' from the field for livestock feeding, while the less nutritious _stover bottoms' are retained on the field to replenish the organic matter of the soil.

5.2.2 Tradeoff in alternative uses of crop residues

The tradeoff estimated in this study had a strong negative relationship with farm revenue (Fig. 4-19) affirming the fact that the smaller the tradeoff, the better the crop residue allocation option. The legume haulm by virtue of the low C:N ratio, high concentration of crude protein and high digestibility exerted a significant impact on both crop and livestock production units of the farm. The tradeoff indicated that farmers in the northern Guinea savanna where crop–livestock integration is low, obtained the highest farm revenue by allocating lower amount (25 %) of the haulm for livestock feeding and retaining a higher amount (75 %) for soil incorporation. Due to the lack of response to crop residue incorporation in the dry savanna agroecological zones, the highest farm revenue was obtained when more of haulm (75 % in Sudan savanna and 100 % in the Sahel) was fed to livestock rather than incorporating into the soil. In addition to the well known lack of response to crop residue application in the short-term (Giller *et al*., 2009), the poor workability of the soils in savannas during the dry season made manual incorporation of crop residues ineffective and allowed free roaming animals to graze the residues so applied. The current tradeoff for allocating crop residues between the crop and livestock units of the farm may be improved by adopting proactive measures, which would increase the productivity of the two units. First, by planting improved dual purpose legumes in rotation with cereals rather than as intercrop, the water requirement of the legume could be satisfied to supply farmers with quality crop residues for both soil application and livestock feeding. Secondly, as the quantity and distribution of rainfall is a major biophysical constraint to agriculture in the dry savannas, improved soil water conservation practices such as surface mulching and tied ridging are important to improve crop productivity. Lastly, intake of stover in this study was 30 – 52 % as opposed to 80 – 100 % intake of haulm. Considering that stover forms the bulk of the crop residues at the disposal of farmers, strategies such as milling or chopping and treating stover with palatable feed ingredients can enhance stover intake.

Short-term benefits are important to attract farmers to crop residue management yet a significant effect of the application of crop residues on crop yield may require several seasons of continuous practice. Livestock, on the other hand, respond instantaneously to crop residues rations. Besides, while the residual effect of crop residues on the crop yields may last for seasons, no such residual effects were found on the live weights of livestock. The imperative for research on the tradeoff in the alternative uses of crop residues is to determine the appropriate time-frame that would allow the impact of crop residue application on the cropping system to be evaluated in a holistic manner.

5.3 Agricultural Sustainability of crop residue management

5.3.1 Influence of crop residue use on soil quality

The depletion of OM in the Ferric Luvisol at Cheyohi with the removal of CR could be attributed to the decomposition of the native soil OM and root biomass. The relatively higher amount of annual rainfall in the Northern Guinea Savanna (914 mm yr^{-1}), and the large size of the microbial community (1067 – 1100 mg MBC kg^{-1}) recorded in these soils facilitated the rapid break down of the OM. Similarly, many studies have reported of a decline in the OM content of soils under continuous cropping systems over time, especially with the removal of CR from the field (Lal, 2002; Diels *et al*., 2004; Zingore *et al*., 2007). Conversely, on the Regosol at Sarauniya and on the Eutric Gleysol at Garin Labo, the OM contents of soils without CR amendment were similar to the initial OM contents at the onset of the study. The stabilization in soil OM observed at these locations is partly due to the low decomposition rate of OM in the Sudan and Sahel savannas of West Africa as reported by Bationo *et al*. (1995) and Buerkert *et al*. (2000). In a study to evaluate the effect of soil amendments on soil properties, Hati *et al*. (2006) and Du *et al*. (2009) also found the OM of unamended soils to be similar to the initial levels even after 25 years of continuous cropping. These authors explained that the initial OM contents of the soils were so low that the amounts of OM lost during the season were adequately compensated for by the root biomass of crops grown during the season.

It is widely acknowledged that soil OM is not a sensitive indicator of a soil quality as it changes slowly (Woomer *et al*., 1994; Barrios *et al*., 1996 and Garcia-Gil *et al*., 2000). Yet, the results of this study demonstrated marginal increases in soil OM with increasing amount of CR incorporated into the soil. Perhaps, this observation can be explained by the findings of several authors (Samake´ *et al*., 2005; Tittonell *et al*., 2005; Zingore *et al*., 2007; Giller *et al*., 2009) that SOM content of any given soil is determined largely by the amounts and quality of organic matter returned to the soil.

The release of nutrients from CR is governed by the C:N ratio, lignin and polyphenol contents of the CR (Palm *et al*., 2001). According to the decision support system developed by Vanlauwe *et al*. (2002b), the CRs used in this study were of medium quality as they contained low N (< 2.5 %) and lignin (< 15 %) but high polyphenols (> 4 %). Contrary to the recommendation that the use of these organic inputs together with mineral fertilisers builds up nutrient stocks (FAO, 2006; Vanlauwe *et al*., 2002b), the results revealed that the incorporation of CR had no significant (P > 0.05) effect on the N stocks of the soils. Apparently, the key determinant of the effect of medium to high quality residues on N stocks is the time frame for the CR application. Positive effects on

N stocks have been found in long term studies spanning from 4 to 12 years (Kumar and Goh, 2002; Larbi *et al*., 2002, Shafi *et al*., 2007, and Bakht *et al*., 2009). In the short term of 2 years (Makinde *et al*., 2006) or less, however, CR retention exerted a negative or neutral effect on N stocks, attesting to the heretic view of Giller *et al*. (2009) that CR retention could improve nutrient stocks through mineralization but only in the long term.

The observation that the incorporation of stover (480 to 3500 kg ha^{-1}) and haulm (200 to 2100 kg ha^{-1}) did not significantly ($p > 0.05$) affect the bulk density of the top soil corroborates the work of Zeleke *et al*. (2004) in which, the incorporation of maize stover at 6000 kg ha^{-1} for 3 years exerted no significant ($p > 0.05$) effect on bulk density of the surface soil. In constrast, the incorporation or surface application of CR at 5000 to 16,

000 kg ha^{-1} for 11 to 25 years (Singh *et al*., 2007; Mulumba and Lal 2008 and Du *et al*., 2009) significantly reduced the bulk density of the surface soil (0 – 10 cm). Crop residues

have lower density than soil particles and hence their incorporation into a soil lower the bulk density of the soil by diluting the soil matrix with less dense material (Kladivko, 1994) and improving aggregation (Sur *et al*., 1993). In practice, however, the amount of crop residues (0.8 – 2.1 t ha^{-1} of haulm and 1.9 – 3.5 t ha^{-1} of stover) acquired by small holder farmers in the savannas of West Africa may not be large enough to cause detectable difference in bulk density within a short period of time.

The differences in the indigenous microbial community sizes observed at the study sites could be explained by the CR management practised by farmers at these locations. The high microbial biomass C found in the soils at Cheyohi is ascribed to the standard farmer practice of retaining all CR except groundnut haulm on the field (Agyemang *et al*., 1993) which supplies the microorganisms residing in these soils with high amount of organic substrate and promotes their proliferation. On the other hand, the removal of all CR from the field at Sarauniya and Garin Labo (Tarawali, 2002) may account for the low inherent microbial biomass C found in these soils.

Unlike the removal of CR, the use of CR as soil amendment significantly increased (50 – 133 %) soil microbial biomass C of soils at Sarauniya in an order consistent with the amount of CR applied. The increases in microbial C implied a surge in the number of bacteria, fungi, actinomycetes and other microorganisms resident in the soil. The observed proliferation of soil microbes could be ascribed to readily metabolisable C and N in CR (Ladd *et al.*, 1994; Tu *et al*., 2006; Chu *et al*., 2007 and Larkin, 2008) and increased root biomass and root exudates due to better crop growth (Mandal *et al*., 2007). The response of microbial biomass to the retention of CR in this study was not only compatible with the findings of Araujo and Monteiro (2006), Chang *et al*. (2008), Ngosong *et al*. (2010) but also affirmed the popular notion that microbial biomass, is a more sensitive indicator of soil quality than organic carbon (Powlson *et al*., 1987; Leita *et al*., 1999).

The failure of CR retention to influence microbial biomass C significantly at Cheyohi could be attributed to the inability of the low amount of CR (200 – 970 kg ha^{-1} of cowpea haulm compared to 380 – 2100 kg ha^{-1} of groundnut haulm at Sarauniya) applied to provide metabolisable C and N in adequate quantities to support the metabolic activities of large number of microorganisms native to these soils. Besides organic substrates, temperature and moisture predominantly determine the amount of microbial biomass in a soil (Wardle and Parkinson, 1990). Consequently, the high temperature coupled with the low moisture retention of the Sahelian sandy soil (Ikpe and Powell, 2002) may account for the marginal (5 – 22 %) increases in microbial biomass C observed at Garin Labo.

The significant increases in the abundance of AM fungi spore with the incorporation of CR on farm 1 at Garin Labo, corroborates the work done by Bationo *et al*. (1995), in the sahelian zone of Niger in which the application of CR increased AM fungi spore abundance substantially by 40 % relative to the control. Recently, several authors (e.g., Oehl *et al*., 2004; Gosling *et al*., 2006 and Ngosong *et al*., 2010) have also found positive effects of organic amendments on AM fungi spore abundance. The phosphate ion is central to interactions between plants and AM fungi (Smith and Read, 2008).

Presumably, the extremely low content of available P in the soil of Farm 1 at Garin Labo (1.83 mg kg^{-1} compared to the 4.4 to 12.9 mg kg^{-1} on other farms) triggered active colonization of the roots by AM fungi in order to supply the plants with more soluble P (Smith and Read, 2008; Ngosong *et al*., 2010). Mechri *et al*. (2008) established that the partition of carbohydrates to roots decreases as P concentration in the roots increases. Considering that AM fungi are obligate biotrophs which, cannot complete their life cycle without the supply of carbohydrates from their host plant (Smith and Read, 2008), the abundance of AM fungi propagules diminishes with increasing availability of soil P

(Corbin *et al*., 2003; Covacevich *et al*., 2006; Gryndler *et al*., 2006). Another factor moderating the positive effect of CR on AM fungi at Cheyohi and Sarauniya may be the high levels of polyphenols (5.1 – 7.3 % compared to 1.1 to 3.8 % at Garin Labo) in the CR incorporated at these locations as phenolic compounds are known to inhibit the establishment of AM symbioses (Leadir *et al*., 1997).

The revelation that CR incorporation exerted a significant effect on β-glucosidase activity at Cheyohi and Sarauniya, while agreeing with several recent studies which showed increases in β-glucosidase activity in soils amended with CR (e.g., Garcia-Ruiz *et al*., 2008, Rabary *et al*., 2008; Yao *et al*., 2009; Pengthamkeerati *et al*., 2011) accentuates the fact that β-glucosidase activity is a consistent indicator of soil quality, which could be used to differentiate between various soil management systems (Masciandaro and Ceccanti, 1999; Ndiaye *et al*., 2000). β-glucosidase is a critical enzyme for biomass turnover in the soil as it catalyses the rate limiting step in the hydrolysis of cellulose (Garcia *et al*., 1994). In general, the rate of the hydrolysis is limited by the availability of substrate (Knight and Dick, 2004). Accordingly, the reduction in the amount of C supplied into the soil decreased the activities of β-glucosidase when 50 % or less of the stover was incorporated. Lastly, the results proved that the physical and chemical indicators of soil quality monitored were not sensitive enough to track relatively subtle improvements in soil quality following the incorporation of CR. This observation together with the findings of Mijangos *et al*. (2006) and Garcia-Ruiz *et al*. (2008) strengthen the assertion of Parr and Papendick (1997) that physical and chemical soil properties change slowly and hence are not suitable for short-term assessment of soil quality. The observed improvements in soil quality with increasing incorporation rates of CR were mainly due to the response of soil biota to the increase in the supply of metabolisable C and N. In sum, changes in microbial biomass and activity provided early signals of alterations in the soil system and were more responsive indicators of soil quality in the short term than the chemical and physical indicators considered.

5.3.2 Social acceptability of the crop residue uses

The observation that most of the selected farmers at Sarauniya and Garin Labo were engaged in the total removal of CR from the field accords with CR management practices described by Tarawali (2002). Similarly, in line with observations by Agyemang et al. (1993) and Kabo and Agyare (2002), 80 % of famers at Cheyohi left all their CRs on the farm.

The fact that a sizeable number of the farmers were aware of the option of portioning CRs to meet both soil and livestock demands suggests that a technology promoting the dual use of CR could be embraced if farmers are provided with adequate information on the practice and its benefits. However, considering that awareness is short lived and should be constantly recharged (Warner and Murt, 1984), it is imperative that extension officers interact with farmers on the merits of mulching and allied practices at Sarauniya and Garin Labo. There is a need to incorporate CR left on the field into the soil to avert loss due to bush fires, strong winds or grazing by herds of Fulani cattle during the dry season. However, as incorporation of CR was not only alien to farmers but also expensive to practise, it is likely to remain unpopular among farmers for the foreseeable future. The cultivation of crop varieties with high root biomass may be a proactive measure for addressing the technological challenge posed by incorporation of CR.

Farmers are generally risk aversive (Nakhumwa, 2004) and would abandon a technology which is either incompatible with their practice or yields little dividends. The removal of CR for livestock use is saddled with numerous risks (Carsky and Ndikawa, 1998), yet a large majority of the farmers in Sarauniya and Garin Labo were into the practising. Baker

(2003) asserted that the benefit associated with an activity that generates a risk influences an individual's perception of that risk. Hence, the lucrative nature of livestock production at Sarauniya and Garin Labo may explain the commitment of these farmers to supplement the limited biomass on the range lands (Fernández-Rivera *et al*., 2004) with CR. In a previous study, Makokha *et al*. (1999) also observed the perceived risk associated with the use of rock phosphate was not a significant constraint to the adoption of the material as soil amendment.

The lack of consensus on the drudgery associated with incorporation of CR among farmers at various locations could be attributed to the differences in the workability of their soils. The poor workability of the loamy soils at Cheyohi during the dry season compelled most of the farmers to select the incorporation of all crop residues into the soil as the most tiring option. On the other hand, the friability of the sandy soils at Garin Labo made it easier to burry CR under the soil, consequently only smaller number of farmers could anticipate the drudgery associated with incorporation.

As Assefa and Frostell (2007) pointed out, for a technology such as the concomitant use of CR as soil amendment and fodder to be deemed socially sustainable, it should at minimum enjoy wider social acceptance. The massive endorsement of the current uses of CR by farmers as the most acceptable CR management option implies that the concurrent use of CR as a soil amendment and fodder is not socially sustainable. It is of crucial importance that technologies seeking to promote the adoption of CR as soil amendment and fodder devise measures to improve awareness among farmers while moderating the labour requirements and physical stress associated with the practice.

5.3.3 Economic viability of crop residue uses

The results indicated that regardless of the high variable cost of inputs associated with the option of incorporation of all CR, the option yielded the optimum net benefit at Sarauniya and on Farm 1 at Cheyohi. Pressumable, the high amount of nutrients supplied into soil by incorporating all the CR translated into higher yields in these farms and adequately compensated for the high operational cost. Similarly, Opala *et al*. (2007) observed that higher nutrient concentration in farm yard manure defrayed the high handling cost and earned higher net benefit than *Tithonia diversifolia* (Hemsl.) A. Gray at comparable application rates. The high net benefit obtained without the incorporation of CR on Farm 2 at Cheyohi can be attributed to the lack of data on the benefits accrued from cowpea as the farmer harvested the crop earlier than planned. Nevertheless, the high net benefit earned without the incorporation of CR in Farm 1 at Garin Labo was in consonance with the poor response of crops to CR retention observed in the village.

The finding that net benefit from livestock production increased with increasing amount of CR fed to livestock vindicates the *statue quo* farmer practice of feeding all CR to livestock at Sarauniya and Garin Labo. It also reinforces the opinion of Powell and Unger (1998) that livestock farmers would incur huge loses if CR were not used to supplement dry season feeding. The high growth rate attained by livestock at Garin Labo may explain the high net benefits earned by these farmers as low growth rate is a major factor limiting the profitability of livestock production (Ayantunde *et al*., 2007). In general, however, the net benefits obtained in this study were lower than the 6320 FCFA reported by Hiernaux and Ayantunde (2004). To promote growth rate and improve profitability, Ayantunde *et al*. (2007) recommended that feeding of CR to livestock should be augmented with millet bran.

The VCR for incorporating CR into the soil at Cheyohi and Sarauniya (1.7 – 4.5) did not only reflect the net benefits earned but also was within the range of 1.1 – 8.9 estimated for nutrient inputs in West Africa (Vanlauwe and Giller, 2006). A general rule on VCR as an economic indicator stipulates that a VCR of at least 2 (i.e. a return of 100 % above the cost of the nutrient input) is required to make a practice economically attractive to farmers (FAO 2006). Accordingly, the estimated VCR for the concomitant use of CR as soil amendment and fodder on Farm 1 at Cheyohi (2.2 to 2.5) and Farm 2 at Sarauniya (3.3 to 4.5) suggested that use of CR as amendment and fodder concurrently could be attractive to farmers at Cheyohi and Sarauniya.

The overall economic viability of the CR option appraised by the SSI $_{Economics}$ found the *statue quo* management of CR by farmers at Cheyohi and Sarauniya to be the least economically viable options. By virtue of the superior net benefit and VCR accrued from the concurrent use of CR as soil amendment and fodder, this option was the most economically appealing to the farmers at these locations. This observation further underscores the potential of the appropriate allocation of CR to improve the profitability of a crop – livestock system. However, the excellent economic attributes of the current farmer practice of harvesting all CR for livestock use at Garin Labo, affirmed the observation by Delve *et al*. (2001) that feeding CR to livestock yielded immediate benefits and were attractive to farmers. It also implied that farmers may continue with the practice in the foreseeable future unless proactive action plans are developed to increase the returns from CR retention in the Sahel Savanna.

5.3.4 Sustainable crop management options

The appraisal of the agricultural sustainability of the CR management options found the combined use of 75 % of haulm as soil amendment and 25 % of haulm as fodder (Scenario 4) to be the most sustainable option in Farm 1 at Cheyohi. Considering the low social acceptability of the practice, the high sustainability of the option was mainly due to the high ecological benignity and economic viability of the practice. The assessment of agricultural sustainability in Farm 2 at Cheyohi may be disregarded as it was conducted without the contribution of cowpea to crop performance and economic viability. The high sustainability attained by allocating less (25 %) of the haulm into livestock production in the Guinea Savanna questions the sustainability of the practice elsewhere in the ecological zone where more (67 %) of the haulm (Fernandez-Rivera *et al*., 2004) or all of the haulm (Karbo and Agyare, 2002) are used to feed livestock. In general, however, the zone is noted for stubble grazing where all CR are retained on the field and grazed by livestock on the free range. The severe economic limitation associated with the total retention of CR (Scenario 5) observed in this study, brings to the fore the need to diversify CR uses among the various units of the farm. After all, total retention of CR on the field may not translate into increased yields in the short term as a result of nutrient immobilization (Giller *et al*., 2009) and termites attack (Sanginga and Woomer, 2009).

Yet, livestock may lose weight if CR is not used to supplement dry season feeding (Powell and Unger, 1998; Ayetunde *et al*., 2007).

The appraisal of agricultural sustainability at Sarauniya identified the total removal of CR for livestock use (Scenario 1) to be the most sustainable option in Farm 1 but among the least sustainable options in Farm 2. The discrepancy in the sustainability of Scenario1 could be attributed to the difference in the level of ecological benignity attained by the option in the two farms. In Farm 1, the high livestock performances and the moderately high amount of crop yields (1026 kg ha^{-1} of maize, 604 kg ha^{-1} of cowpea) obtained in absence of CR application cumulated in the high level of ecological benignity. Even though in Farm 2, livestock performance was comparably high, the low crop yields (495 kg ha^{-1} maize, 356 kg ha^{-1} cowpea) led to a low grade of ecological benignity. Presumably, the performance of a crop in response to CR management option is a significant factor contributing to the sustainability of the option.

Furthermore, the observation that the use of 25 % of haulm as soil amendment and 75 % of it as fodder (Scenario 2) was the most sustainable option in Farm 2 and among the best options in Farm 1 gives credence to the need for CR to be allocated properly between the crop and livestock units of the farm in the Sudan Savanna. However, in the Sahel savanna, the high ecological benignity, economic viability and social acceptability of total residue removal (Scenario 1) necessitate the need for strategies other than residue retention to address the decline in soil quality and improve crop yields. Such strategies may include improved manure management, better integration of legume crop into cropping systems, improved fallows using coppicing species such as *Gliricidia sepium*, *Leucaena leucocephala*, *Calliandra calothyrsus*, *Senna siamea* (Mafongoya *et al*., 2006). The observation that the trends in the sustainability indexes were consistent with the trends in the tradeoff estimates at all locations strengthens the notion that tradeoff analysis could be used to streamline resource allocation in agricultural systems (Dimes *et al*., 2001; Stoorvogel *et al*., 2004b; Francisco and Ali, 2006; Tittonell *et al*., 2007). Nonetheless, tradeoff analysis being a purely economic concept cannot detect limitations in the ecological and social dimensions of the technology which may impede its scaling up and diffusion among farmers.

The sustainability assessment offered a unique opportunity to identify some of the potential barriers to the adoption of the CR management options. These included the low social acceptability of total removal of CR at Cheyohi, and the dual use of CR as soil amendment and fodder at Sarauniya and Garin Labo. The low economic viability of total retention of CR at all locations also questioned the profitability of the option at Cheyohi where it was practised and highlighted the need for improved management options. Reynolds (1989) cited the failure of biophysical scientists to recognize the contribution of social, economic, institutional and infrastructural forces to agricultural development as a major reason for the widespread non adoption of research findings. Certainly, for improved CR management practices to win the hearts and minds of farmers, the economics and social aspects of the technology should be addressed from the onset. While no measure of sustainability can be perfect (Van Passel *et al*., 2007), the sustainable index adopted for this study can be used to compare and rank the suitability of farming practices. It also highlights aspects of a farming practice which when modified would improve the productivity of the farm. Most of the frameworks for assessing agricultural sustainability presented partial coverage of sustainability with a stronger emphasis on environmental aspects (FAO 1993; De jager *et al*., 2001; Suler *et al*., 2001; Kang *et al*., 2005). Moreover, only few of them appraised sustainability by aggregating the individual indicators into an index. Furthermore, many of these assessments were undertaking at the national scale and could not explicitly establish the impact of management practices at farm level on agricultural sustainability (Dantsis *et al*., 2010). The sustainability index used in this study is designed for farm level assessment based on a holistic set of indicators and therefore can be used to monitor a wide range of agricultural practices on farm.

5.4 The use of oilcakes and polyethene sheet to improve manure quality

5.4.1 Effect of oilcakes and plastic sheet on organic matter loss

The steady loss of OM observed during the early phase of composting (Figs. 4-26 and 428) is largely attributable to rapid degradation of labile organic compounds, such as simple carbohydrates, fats and amino acids (Bernal *et al*., 2009). The reduction in OM subsequently resulted from the mineralization of OC from the more recalcitrant cellulose, lignin, tannins and polyphenols (Gigliotti *et al*., 2002). The OM degraded during composting was low (15 – 54 %) compared to the 55 – 70 % OM loss found by Sellami *et al*. (2008) after composting manure with exhausted olive cake for 70 days. The enhanced decomposition of OM may be due to the use of confectionary wastewater to maintain moisture content at 45 – 60 % during composting as opposed to the low water input approach of humidifying the compost only at the beginning of composting adapted to mimic the standard farmer practice of composting in the dry savannas.

The chemical composition of the raw materials used for composting also influenced the rate of OM degradation. Among the manure improvement options evaluated at NAPRI for instance, the low C:N ratio, lignin and phenol contents of the groundnut cake led to a rapid OM loss when manure was fortified with the oil cake (Table 3-8 and Fig. 4-26). This observation affirmed the high losses in OM reported by Hachicha *et al*. (2006) and Sellami *et al*. (2008) by co-composting manure with olive cakes.

The observation that manure composted in heaps decomposed faster than those composted in pits at ARI (Fig. 4-27) confirmed the notion that manure stored in pits are prone to anaerobic conditions, which slows down their decomposition rates (Thomsen, 2000; Kwakye, 1980). However, the extreme dry conditions during composting period at NAPRI and INRAN prevented the formation of anaerobic pockets in the matrix of compost prepared in pits. Consequently the storage facility used had no effect on decomposition rates (Fig. 4-26 to Fig. 4-28) in these locations.

5.4.2 Effect of oilcakes and plastic sheet on C:N

The continuous decline in C:N ratios observed in all the three locations (Figs. 4-29 to 431) corroborate the findings of Said-Pullicino *et al*. (2007), Tognetti *et al*. (2007) and Sellami *et al*. (2008) that C:N ratio decreases during composting of organic manure due to the mineralization of OC coupled with increased N concentration as a result of dry matter loss. Considering the assertion that stabilization of C:N ratio in time course of composting signals maturation of the compost (Meunchang *et al*., 2005 and Bernal *et al*., 2009), it may be inferred that the compost prepared at NAPRI and ARI matured after 108 days, while those prepared at INRAN failed to mature.

In relation to the 50 to 60 % moisture content recommended by the FAO (2003) for composting, the limited amount of water (40 % only at beginning of composting) used in this study to mimick the farmer practice, made the compost piles at INRAN too dry to adequately support the microbial break down of the compost. The final C:N ratios of 7 to 15 were below the critical C:N ratio of 25 (Whitmore, 1996) highlighting the potential of these compost to release N when applied to the soil.

5.4.3 Effect of oilcakes and plastic sheet on N and P losses

The N concentration of all the manure / and oil cake mixtures increased throughout the composting period. Distinct increases in the N concentration of materials during composting have also been reported by Ruffino *et al*. (2007), Said-Pullicino *et al*. (2007), and Aviani *et al*. (2010). These authors attributed the re-concentration of N in the composting materials to the relatively higher losses of C than N during decomposition.

The re-concentration of N makes the N concentration of finished compost to be higher than that of the starting compost, which may signal gains rather than losses of N in course of the composting. To streamline the quantification of nutrient losses during composting, Bernal *et al*. (2009) indicated that such estimation should be done on mass balance basis to take the dry mass of the compost into consideration instead of just the difference in concentrations of the nutrients as suggested by Paredes *et al*. (1996).

The amount of N lost from the compost (5 – 67 %) although was lower than the 71 – 88 % found by Ogunwande *et al*. (2008), it compared favourably with the 8 to 60 % N losses reported by Tiquia *et al*. (2000). The fortification of manure with groundnut cake increased

N losses from 44 to 67 % in the absence of plastic sheet. The narrowing of the C:N from 24 to 12 (Fig. 4-29) by the addition of the oil cake led to underutilization of N by nitrifying bacteria (FAO, 2003) and triggered emission of NH_3 as asserted by (Tiquia and Tam, 2000). The co-composting of manure and sheanut cake, on the other hand, increased the C:N ratio marginally (18 – 21) and consequently had no effect on N loss.

Lining of pit or covering of heaps with plastic sheet was found to be efficient in moderating N losses through leaching (King, 1990), NH_3 volatilisation (Dewes, 1996) and runoff (Murwira *et al*., 1995). The use of plastic sheets lining or covering reduced N losses by 37 – 51 % at NAPRI and 24 – 35 at ARI. In a related study, Ruffino *et al*. (2007) found that covering manure (C:N ratio >56) heaps with a thin plastic sheet prevented 30 % of initial amount of N from being lost. The differences in the C:N ratios of the starting materials used in these studies may explain the variations in the N losses reduced by the plastic sheet.

The amount of P lost from the compost (2 – 37 %) was lower than the amount of N lost (5 – 67 %). In a compost pile P, unlike N is only lost through leaching (King, 1990) and runoff and hence it may be less vulnerable to losses than N. By moderating P losses via runoff and leaching, the plastic sheet intervention conserved 12 – 18 % of the initial amount of P. Even though co-composting of manure with groundnut cake doubled the N content of the manure, the high cost of the material makes it unprofitable for use as compost material. The standard farmer practice of keeping manure in heaps without any cover or nutrient additive was the most cost efficient option.

5.5 Integrated use of manure and mineral fertilisers and productivity of cereals

5.5.1 Added benefits from combined manure and mineral fertiliser use

It was evident from the study that increases in the application of mineral fertiliser resulted in larger increases (46 – 536 %) in grain yield than manure (11 – 67 %). The superior effect of mineral fertiliser may be ascribed to high nutrient availability of the material (Sanginga and Woomer, 2009) as unlike manure which must decompose and mineralise in order to supply plant nutrients; the chemical constituents of a mineral fertiliser dissolve rapidly to furnish plants with nutrients. The observed rapid response of grain yield to mineral fertiliser concurred with the findings of Lipavsky *et al*. (2008) that application of mineral fertiliser exerted greater (50 %) impact on grain yield than the application of

FYM (27 %). Contrary to suggestion of Mucheru -Muna *et al*. (2007) and Shisanya *et al*. (2008) that at equivalent N rates, the use of manure may sufficiently substitute for the use of chemical fertiliser, the amount N supplied by the application of manure at 10 t ha^{-1} was equivalent to that of the mineral fertiliser rate at Sarauniya (120 kg ha^{-1}) and four times more than the mineral fertiliser rate at Nyankpala (60 kg ha^{-1}) yet the mineral fertiliser effect was superior. Apart from the slow nutrient release, the assertion by Christensen *et al*. (1994) and Edmeades (2003) that higher leaching losses occur on manured soils than chemically fertilized soils may partly account for the inferior effect of manure on grain yield. Indeed, Christensen *et al*. (1994) reported that increases in grain yield following the application of manure (81 %) were lower than mineral fertiliser (164 %) even after 20 years of continuous application at equivalent N rates. The method of manure application is a major factor militating against the efficiency of manure on grain yield. At Karabedji in Niger, AfNET (2002) reported that manure broadcasted at rate of 6 t ha^{-1} increased grain yield of millet by 33 % while hill placement at the same rate led to a substantial increase of 83 %. As the standard practice of broadcasting manure may aggravate nutrient losses, hill placement may be expedient provided labour requirement could be met. The observation that grain yield of millet was neither affected by the application of mineral fertiliser nor manure at Maradi, may be due to the amount and distribution of rainfall during the growing season. Bationo *et al*. (1996) indicated that in semi-arid zones of West Africa, dry periods during the growing season may result in low fertiliser use efficiency, and subsequent negative effect on crop yield. Even though the total annual rainfall of 401 mm in 2008 fell short of the 30 year average of 540 mm (Maman *et al*., 2000), the lack of response in grain yield could be attributed to amount of rainfall per day rather than dry spells. In that, the incorporation of manure coincided with 37 mm rainfall d^{-1}, with similar intensive rainfall event occurring within 2 days after the first and second urea applications as indicated in Appendix 2. Considering the high sand content (84 %) of the soil, such heavy down pours may lead to high nutrients losses through leaching (Smaling, 1993) and render the fertiliser material ineffective. In a similar study to determine the effects of organic and mineral fertiliser inputs on maize yield, MucheruMuna *et al*. (2007) found that uneven distribution of rainfall reduced grain yield drastically and masked the effect of the nutrient inputs.

The observed increases in grain yield with increasing doses of manure and mineral fertiliser applied concurrently at Nyankpala and Sarauniya attest to the general notion that nutrients supplied by the additions of organics are additive to those supplied by inorganic nutrient sources (Palm *et al*., 1997; Giller, 2002). It also implied that the combined application of manure and mineral fertiliser prevented nutrient immobilization of agronomic significance especially at Sarauniya where the C:N ratio of the manure (34) was greater than the critical C:N ratio of 25 as reported by Whitemore (1996).

The assertion of FAO (2006) that antagonistic interactions are caused mainly by imbalanced nutrient supply and suboptimal nutrient ratios may not adequately explain the antagonistic effect on grain yield (added benefits of -76 to -262 kg ha^{-1}) observed at

Nyankpala when manure was combined with low rates of mineral fertiliser. As the correlation between yield and N:P ratio of the materials applied (Appendix 6) revealed that only 18 % (r = 0.42) of the variation in grain yield could be attributed to the N:P ratio of the soil amendments applied. In a related study, Tandon (2004) also found that N:P ratio of the nutrient inputs supplied to maize could only explain 26 % of the variation in added benefits. The mechanism for the negative interaction between manure and mineral fertiliser in the present study is not clear. Perhaps at lower rates of mineral fertiliser, the availability of N was limited by the high level of lignin (24 %) in the manure which together with polyphenols could form humic polymers with amino acids and resist microbial attack (Haynes, 1986). At higher mineral fertiliser rates however, the availability of metabolisable N increased microbial activity and these compounds were in turn degraded leading to added benefits of 88 – 470 kg ha^{-1}.

Both soil factors and manure quality attributes have been cited as probable mechanisms for the mineral fertiliser - manure antagonism in previous studies. Ouedraogo *et al*. (2007) reported an added benefit of -101 kg ha^{-1} following the combined application of sheep dung and urea and attributed the antagonistic effect to low nutrient utilization efficiency induced by moisture stress during grain filling. Mucheru *et al*. (2002) also found negative added benefits in the order of -150 to -250 kg ha^{-1} following the combined application of 30 kg N ha^{-1} of *Leucaena leucocephala* and 30 kg N ha^{-1} of mineral fertiliser. The antagonistic effect of *L. leucocephala* biomass and mineral fertiliser observed by these authors was however attributed to the high polyphenol content of the organic manure and its adverse effect on decomposition rate and N release.

The positive interaction between manure and mineral fertiliser at Sarauniya, as unraveled by the added benefits 117 – 684 kg ha^{-1} was consistent with the body of evidence attesting to the profound synergism between organic and mineral fertilisers (Vanlauwe *et al.,* 2001a; Iwuafor *et al.,* 2002; Gentile *et al.,* 2008; Sanginga and Woomer, 2009; Amusan *et al*., 2011). Sanginga and Woomer (2009) cited the supply of all essential nutrients in suitable quantities and proportions as a possible mechanism underlining the observed synergism. These authors showed that the mineral fertiliser supplied adequate levels of macro nutrients, while micro nutrients absent in the mineral fertiliser were contributed by the manure. Certainly, improvement in the synchrony between nutrient availability and crop demands resulting from the immediate release of nutrient from the mineral fertiliser and delay release from the manure (Palm *et al*., 1997, Jone *et al*., 1997 and Vanlauwe *et al*., 2001a) cannot be ruled out. However, considering the low fertility status of the soil (Table 3-9) it is likely that the combination of inorganic and organic nutrient sources resulted in general improvement in the soil fertility as pointed out by Okalebo *et al*. (2004). Subsequently, nutrient retention, turn over and availability as well as moisture retention (Vanlauwe, 2002a) improved, leading to higher grain yields. In a study to appraise the effect of combined use of cattle manure and ammonium nitrate on maize yield, Nhamo (2001) found added benefits ranging from 663 to 1188 kg grain ha^{-1} and attributed the synergistic effect to supply of cations by the manure to ameliorate the low cation content of the soil. In a later study, improved soil aggregation, reduced P sorption and reduced Al toxicity were found to be responsible for the added benefits (550 kg ha^{-1}) obtained by combining *Tithonia diversifolia* and mineral fertiliser at equivalent rate of 30 kg N ha^{-1} (Mucheru *et al*., 2002).

The synergistic effects of nutrient interactions are of paramount importance to the production output of farmers. Cooke (1982) envisaged that as agricultural production advances, large increases in yield potential would mainly come from interaction effects.

Consequently, the identification of nutrient management strategies which optimize positive interactions will contribute immensely to realization of the African green revolution target of increasing cereal yields from 1 to 3 t ha^{-1} by 2020 (Sanchez, 2010).

5.5.2 Cost and returns of combined use of mineral fertiliser and manure

The findings that returns on investment accruing from the sole application of manure were negative (VCR < 1) support the assertion that nutrient use efficiency of manure is often low (Vanlauwe and Sanginga 1995; Cadisch and Giller, 1997). Consequently, the yields obtained from the use of manure alone could not offset the investment made on its acquisition and application. It further highlights the economic losses suffered by smallholder farmers who rely solely on manure to replenish soil fertility. Williams *et al*. (1995) showed that the application of 5 t ha^{-1} of manure at several locations in Niger yielded VCR ranging from 0.7 to 1.5. Considering that higher VCRs were obtained only when farmers spent less on labour involved in manure acquisition and application, these authors concluded that manure use may be profitable, when labour requirements are minimised.

The positive returns earned from the sole application of mineral fertiliser at Nyankpala and Sarauniya reinforced the role of mineral fertiliser as a key entry point for increasing crop productivity in SSA (Sanginga and Woomer, 2009). Even though, the VCRs of mineral fertilisers (1 - 2.3) reported in this study were consistent with values (1.1 – 4.2) found by, Gerner and Harris (1993), they rarely exceeded the critical value of 2 required to motivate farmers to apply mineral fertilisers. In general, however, the low profitability of mineral fertiliser use in West Africa has been attributed to poor crop response (Dembele and Savadogo, 1996) and unfavorable fertiliser to maize price ratios (Gerner and Harris, 1993). The high profitability of the combined application of manure and mineral fertiliser (VCR of 2.3 -7.7) at Nyankpala and Sarauniya lends credence to the improved agronomic efficiency attained by integrating organic and inorganic nutrient inputs as described by Vanlauwe *et al*. (2001b).

Contrary to the conventional approach of evaluating fertiliser rates on returns per unit area basis, Sanginga and Woomer (2009) proposed returns per unit input as a more efficient way of tailoring fertiliser application to the capacity of cash-poor farmers. Accordingly, the nutrient management options with optimum returns on nutrient inputs were 25 % RR of NPK and 2.5 t ha^{-1} of manure at Nyankpala and 100 % RR of NPK and 2.5 t ha^{-1} of manure at Sarauniya. However, at Sarauniya because the VCRs of 100 % RR NPK and 2.5 t ha^{-1} manure (7.6) and 50 % RR NPK and 2.5 t ha^{-1} manure (7.0), were similar and a farmer makes 50 % saving on fertiliser cost for adopting the latter the use of 50 % RR NPK and 2.5 t ha^{-1} manure would be an appropriate nutrient strategy for optimizing returns on nutrient inputs at a reasonable cost. Due to the general lack of response to nutrients inputs at Maradi, none of the application rate was found to be economically attractive.

CHAPTER SIX

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The study has contributed to the general objective of increasing the productivity of small holder crop–livestock farmers without depleting the resource base of the soil by:

i) quantifying the nutrient balances and identifying pathways of redressing imbalances in cereal–legume–livestock systems at both farm and village levels. ii) quantifying tradeoff in using crop residues as either fodder or soil amendments.

iii) evaluating the sustainability of using crop residues as fodder or soil amendment in cereal–legume–livestock systems.

iv) evaluating the effect of storage methods, oilcakes and plastic sheets on nutrient losses during composting.

v) assessing the added benefits from the combined application of manure and mineral fertiliser.

By quantifying nutrient balances, crop residue and leaching were found to be the most important outflows which, when managed pragmatically could reverse the negative balances. Nitrogen balances were negative even with the use of mineral N fertiliser at the recommended rates. The application of recommended rates of P fertiliser on the other hand, led to positive P balances. The nutrient stock : nutrient balance ratio connected soil N stocks with N balances and revealed that even though N balances were negative, a farmer using mineral fertilisers at the recommended rate could maintain crop yields at current level with current crop management practices for 20 – 133 years. This observation added onto the existing knowledge on nutrient balance assessment and explained why crop yields in West Africa have stagnated over the last two decades on soils with alarming rate of nutrient mining.

The incorporation of crop residue significantly increased grain yield of maize on the Ferric Luvisol at Cheyohi but had no effect on cowpea, groundnut and millet at all locations. Increasing the amount of haulm fed increased live weight of livestock significantly ($P<0.05$) at Cheyohi and Sarauniya but had no effect on live weight at Garin Labo. The tradeoff favoured the incorporation of more haulm into the soil at Cheyohi. At Sarauniya and Garin Labo, however, the assessment supported the allocation of more haulm into livestock production. The tradeoff assessment bridged the knowledge gap on the quantities of crop produce a farmer sacrificed by allocating more crop residues into livestock production but fell short of being a tool for refining decisions made by farmers on crop residues allocation as there were no significant differences among the tradeoff estimates.

The formulation of the agricultural sustainability index addressed a pertinent research challenge of integrating the biophysical, social and economic dimensions of agricultural technology. The application of this index led to the identification of crop residue management options which were environmentally friendly, economically viable and socially acceptable at the farm scale. It also identified the potential weaknesses of an option which could be addressed to boost the efficiency of the option.

The evaluation of nutrient losses during composting of manure established that about 67 % of N and 37 % of P losses occur during the storage of manure by smallholder farms in the dry savannas of West Africa. It also showed that plastic sheet can control nutrient losses. Furthermore, the study indicated that fortification of manure with other organics may not be economically feasible unless the material is obtained at a moderate cost. The assessment of the interactive effects of mineral fertiliser and manure on crop yield confirmed the occurrence of both antagonistic and synergistic effects. It also identified cost effective application rates of mineral fertiliser and manure for smallholder cereal farmers.

6.2 Conclusions

On the basis of the outcomes of the five studies conducted to address some of the challenges associated with crop residue and manure management in cereal-legumelivestock systems, the follwing conclusions were drawn:

i) Amount of N supplied through mineral fertiliser at recommended rates, organic fertiliser, BNF and atmospheric deposition fell short of the amount required to counterbalance the nutrient losses caused by removal of crop produces and residues, leaching and gaseous losses and led to negative N balances at both farm and village levels on the Ferric Luvisols, the Regosols and the Eutric Gleysols. Likewise, the positive P balances recorded at both the farm and village levels implied that inputs of P supplied mainly through mineral fertilisers out-weighed losses of P. These outcomes contravene the null hypothesis that amount of nutrients supplied into a cereal–legume–livestock system does not differ from the amount of nutrients lost from the system. Furthermore, these findings point out that whereas the P requirements for crop production could be supplied by mineral fertilisers at the recommended rates, the amount of N required for sustainable crop production could only be met by the judicious use of mineral fertilisers, crop residues, manure and biological N fixation together with proactive measures to control leaching.

ii) Feeding of crop residues to livestock had immediate benefits on live weight at Cheyohi and Sarauniya but not at Garin Labo. The incorporation of crop residues on the other hand, had no effect on crop productivity at all locations except maize on the Ferric Luvisol at Cheyohi. The strong correlation between farm revenue and the tradeoff indicates that tradeoff estimate is a good indicator of the profitability of crop residue uses. However, the crop residue management scenarios had no significant effect on tradeoff at all locations. This confirmed the null hypothesis that re-allocation of crop residues from crop production into livestock production does not affect the quantity of crop produce a farmer forgoes to gain more livestock produce. The study identified the use of improved dual purpose legumes to increase legume biomass yield, and processing of stover to enhance its palatability and intake as potential pathways for improving the prevailing tradeoffs.

iii) The most sustainable crop residue management options were the use of 75 % of haulm and 25 % of stover as soil amendment in Farm 1 on the Ferric Luvisol at Cheyohi, total removal of crop residues in Farm 1 on the Regosol at Sarauniya and on the Eutric Gleysol at Garin Labo, and the use of 25 % of haulm and 75 % of stover as soil amendment in Farm 2 at Sarauniya. This refuted the null hypothesis that the ecological benignity, economic viability and social acceptability of crop residue management is not affected by its use as either fodder or soil amendment. Furthermore, to motivate farmers to use crop residues as soil amendment and fodder concurrently, limitations on the social acceptability of the option with regards to knowledge on its merits, high labour requirement and drudgery should be addressed.

iv) Co-composting of manure with oil cakes in either pits or heaps had no significant effect on the amount of N and P lost during storage. However, the use of plastic sheet to cover compost heaps or line compost pits reduced N and P losses significantly. This flouted the null hypothesis that nutrient loss during composting is not influenced by the use of plastic sheets. Although the fortification of manure with either groundnut cake or cotton seed cake increased the nutrient content of the manure substantially, the high cost of these oilcakes precludes their use as compost additives. On the other hand, the low cost of acquiring shea nut cake makes it suitable for co-composting. In all, composting manure in heaps with any oil cake or plastic sheet covering was the most cost effective method.

v) Both added benefits and losses in grain yield were obtained following the combined application of manure and mineral fertiliser at Sarauniya and Nyankpala. Consequently, the study rejects the null hypothesis that the combined effect of mineral fertilisers and manure is additive and concludes that the appropriate combinations of mineral fertiliser and manure induce synergistic effect on crop production. Futhermore, the most cost effective application rates were 2.5 t ha^{-1} of manure complemented with either 25 % of the fertiliser recommendation at Nyankpala or 50 % of the fertiliser recommendation at Sarauniya.

6.3 Recommendation for further study

Although this study has adequately addressed some of the pertinent issues in the management of crop residues and manure, the following aspects are worthy of further research:

i) Long-term evaluation of tradeoff is warranted to capture the residue effect of CR incorporation on crop productivity. The corresponding feeding trials should use CR to supplement grazing in order to prolong the feeding trial and amplify livestock productivity.

ii) Future assessment of social acceptability should cover a sample size larger enough to be true representative of the target population. As the negative effect of some technologies may be only observed in the long term, both *ex-ante* and *expost* evaluation of agriculture sustainability is recommended.

iii) Studies are required to map out locally available organic materials which could be acquired at moderate cost to improve the profitability of manure composting. iv) Additional studies to unravel the mechanisms for the antagonistic and synergistic effects of combined mineral fertiliser and manure application is required to streamline nutrient management schemes.

REFERENCES

AfNet (The African Network for Soil Biology and Fertility). (2002). *Network Research Progress Report.* 46 pp. AfNet Tropical Soil Biology and Fertility (TSBF) Institute of CIAT, Nairobi, Kenya.

Agbede, T. M. and Ojeniyi, S. O. (2009). Tillage and poultry manure effects on soil fertility and sorghum yield in southwestern Nigeria. Soil Tillage Res. doi:10.1016/j.still.2008.12.014.

Agboola, A. A. and. Kintomo, A. A. (1995). Nutrient recycling in pastures, rangeland, fallow and cut-and-carry systems in sub-Saharan Africa Pages 243 – 257 *in* Livestock and sustainable nutrient cycling in mixed farming systems of subSaharan Africa. Volume II, J. M. Powell, S. Fernandez-Rivera, T. O. Williams, and C. Renard (Eds.). International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Agyenim-Boateng, S., Zickermann J. and Kornahrens M. (2006). Poultry manure effect on growth and yield of maize. West Africa Journal of Applied Ecology 9: 12 -18.

Ahn, J. H., Elliot, R., and Norton, B. W. (1997). Oven drying improves the nutritional value of *Calliandra calothyrsus* and *Gliricidia sepium* as supplement for sheep given low-quality straw. Journal of the Science of Food and Agriculture 75: 503510.

Alli-Balogun, J. K., Lakpini, C. A. M., Alawa, J. P., Mohammed, A. and Nwanta, J. A. (2003). Evaluation of cassava foliage as a protein supplement for sheep. Nigerian Journal of Animal Production 30: 37–46.

Amusan, A. O., Adetunji, M. T., Azeez, J. O., Bodunde, J. G. (2011). Effect of the integrated use of legume residue, poultry manure and inorganic fertilisers on maize yield, nutrient, uptake and soil properties. Nutr Cycl Agroecosyst 90: 321– 330

Anderson, J. M. and Ingram, J. S. I. (1993). Tropical Soil Biology and Fertility: A Handbook of Methods. CAB International, Oxon, UK.

Andrews, S. S., Flora, C. B., Mitchell, J. P. and Karlen, D. L. (2003). Growers‘ perceptions and acceptance of soil quality indices. Geoderma 114: 187– 213.

AOAC. (1990). Official Methods of Analysis. Association of Official Analytical Chemists, (AOAC) 15th edition. Washington DC, USA, pp. 69 - 88.

Araujo, A. S. F. and Monteiro, R. T .R. (2006). Microbial biomass and activity in a Brazilian soil plus untreated and composted textile sludge. Chemosphere 64: 1043–1046.

Assefa, G. and Frostell, B. (2007). Social sustainability and social acceptance in technology assessment: A case study of energy technologies. Technology in Society 29: 63–78.

Atuahene, C. C., Donkoh, A. and Asante, F. (1998). Value of sheanut cake as a dietary ingredient for broiler chicken. Animal Feed Science and Technology 72: 133– 142.

Aviani, I. Laor, Y., Medina, S., Krassnovsky, A. and Raviv, M. (2010). Co-composting of solid and liquid olive mill wastes: Management aspects and the horticultural value of the resulting composts. Bioresource Technology 101: 6699–6706.

Ayantunde, A. A., Delfosse, P., Fernandez-Rivera, S., Gerard, B. and Dan-Gomma, A. (2007). Supplementation with groundnut haulms for sheep fattening in the West African Sahel. Tropical Animal Health Production 39: 207–216.

Bado, B. V. (1985). Amelioration de l'efficacite des phosphates naturelles par l'utilisation des matieres organiques. Memoire de fin d'Etude. Universite de Ouagadougou, Ouagadougou, Burkina Faso. 124 pp.

Baker, G.A. (2003). Food safety and fair: factors affecting consumer response to food safety risk. Paper presented to the International Food and Agribusiness Management Association (IAMA) and Agribusiness Institute in the Leavey School of Business 2003. Santa Clara University, 500 El. Camino Real, Santa Clara, CA 93053, USA.

Bakht, J., Shafi, M., Jan, M. T and Shah, Z. (2009). Influence of crop residue management, cropping system and N fertiliser on soil C and N dynamics and sustainable wheat (*Triticum aestivum* L.) production. *Soil and Tillage Research* 104(2): 233-240.

Barrios E., Buresh R.J., Sprent J.I. (1996). Organic matter in soil particle size and density fractions from maize and legume cropping systems. *Soil Biol. Biochem*.28 (2): 185-193.

Bationo, A. and Mokwunye, A. U. (1991). Role of manures and crop residues in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. Fertiliser Research 29: 117–125.

Bationo, A., Buerkert, A., Sedogo, M. P., Christianson, B. C. and Mokwunye, A. U. (1995). A critical review of crop residue use as soil amendment in the West African semi-arid tropics. *In* Powell, J. M. S., Fernandez-Rivera, T. O. Williams and C. Renard. (Eds.) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp 305–322.

Bationo, A., Christianson, C. B. and Klaij, M. C. (1993). The effect of crop residues and fertiliser use on pearl millet yields in Niger. Fertiliser Research 34: 251–258.

Bationo, A., Nanadwa, S. M., Kinetu, J. M., Kinyangi, J. M., Bado, B. V., Lompo, F., Kimani, S., Kihanda, F. and Koala, S. (2004). Sustainable intensification of crop – livestock systems through manure management in eastern and western Africa: Lessons learned and emerging research opportunities. *In* Williams, T. O., Tarawali, S. A., Hiernaux, P. and Fernandez-Rivera, S. (Eds.) Sustainable croplivestock production for improved livelihoods and natural resource management in West Africa. Proceedings of an international conference held at the International Institute of Tropical Agriculture, Ibadan, Nigeria, pp 173-198.

Bationo, A., Rodes, E., Smaling, EMA. and Visker, C. (1996) Technologies for restoring soil fertility. In: Mukwunye AU, Jager A, Smaling EMA (eds) Restoring and maintaining the productivity of West Africa soils: key to sustainable development. Miscellaneous fertiliser studies No 1. LEI-DLO, SC-DLO, IFDC Africa, pp 61–72 .

Bayu, W., Rethman, N. G. and Hammes P. S. (2004). The role of animal manure in sustainable soil fertility management. J. Sus Agric 25(2): 113-136.

Bedingar, T. and Degefa, G. (1990). Trends in agro-byproducts and their feeding potential in sub-Saharan Africa. Working document no. 14. Livestock Economics Division (LED) International Livestock Centre for Africa, Addis-Ababa, Ethiopia.

Bernal, M. P., Alburquerque, J.A. and Moral,R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review Bioresource Technology 100: 5444–5453.

Biederbeck, V. O., Campbell, C. A., Bowren, K. E., Schnitzer, M. and Mclver, R. N. (1980). Effect of burning cereal straw on soil properties and grain yields in Saskatchewan, Soil Sci Soc. Am. J. 44:103.

Blake, G. R., and Hartge, K. H. (1986). Bulk Density. *In* Klute, A. (Ed.) Methods of Soil Analysis, Part I. Physical and Mineralogical Methods: Agronomy Monograph no. 9 (2nd ed.), pp. 363-375.

Bliimmel, M., Makkarb, H. P. S., Chisanga, G., Mtimuni, J. and Beckerb, K. (1997). The prediction of dry matter intake of temperate and tropical roughages from in vitro digestibility/gas-production data, and the dry matter intake and in vitro digestibility of African roughages in relation to ruminant live weight gain. Animal Feed Science Technology 69: 131-141.

Bloem, J., Schouten, T., Sørensen, S. and Breure, A.M. (2003). Application of microbial indicators in ecological approaches to monitor soil quality. Ambio, (in press).

Boateng, S. A. and Dennis, E. A. (2001). Contribution of crop residues to soil fertility restoration. Journal of Ghana Science Association 3 (1): 51-59.

Bogale, S., Melaku, S. and Alemu, Y. (2008). Potential use of crop residues as livestock feed resources under smallholder farmers‘ conditions in bale highlands of Ethiopia. Tropical and Subtropical Agroecosystems 8: 107 – 114.

Bonsi, M. L. K., Osuji, P. O., Tuah, A. K. and Umunna, N. N. (1995). *Vernonia amygdalina* as a supplement to teff straw (*Eragrostis* tef) fed to Ethiopian Menz sheep. Agroforestry System 31: 229-241.

Bouyoucos, G. J. (1963). Hydrometer method improved for making particle size analysis of soils. Agronomy Journal 53: 464-465.

Brussaard, L. and Van Faassen, H. G. (1994). Effects of compaction on soil biota and soil biological processes. In: Soane, B.D., Van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Elsevier, New York, USA. pp. 215–235.

Budelman, A. and Defoer, T. (2000). PLAR and resource flow analysis in practice. Case studies from Benin, Ethiopia, Kenya, Mali and Tanzania (Part 2). In: Defoer, T. and Budelman, A. (Eds) (2000) Managing soil fertility in tropics. A Resource Guide for participatory learning and action research. Amsterdam, The Netherlands: Royal Tropical Institute.

Buerkert, A. and Stern, R. D. (1995). Crop residue and P application affect the spatial variability of non-destructively measured millet growth in the Sahel. Exp. Agric. 31: 429–449.

Buerkert, A., Bationo, A. and Doss, K. (2000). Mechanisms of residue mulch-induced cereal growth increases in West Africa. Soil Sci. Soc. Am. J. 64: 346–358.

Bunemann, E. K. (2008). Enzyme additions as a tool to assess the potential bioavailability of organically bound nutrients. Soil Biology and Biochemistry 40: 2116–2129.

Cadisch, G. and Giller, K. E. (1997). (eds). Driven by Nature: Plant litter quality and decomposition. CAB International, Wallingford, UK.

Carsky, R. J. and Ndikawa, R. (1998). Screening multiple-use cover crops for the Sudan savanna of northern Cameroon. Pp. 179–187. *In* D. Buckles *et al*. (Eds.) Cover crops in West Africa: Contributing to sustainable agriculture. IDRC, Ottawa, Canada.

Chang, E. H Chung, R. S and Wang F.N (2008). Effect of different types of organic fertilisers on the chemical properties and enzymatic activities of an Oxisol under intensive cultivation of vegetables for 4 years. *Soil Science and Plant Nutrition* 54: 587–599

Chapman, D. F., Kenny, S. N., Beca, D. and Johnson, I. R. (2008). Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. Agricultural Systems 97: 108–125.

Chaves, B., Opoku, A., De Neve, S. Boeckx, P., Van Cleemput, O. and Hofman, G. (2006). Influence of DCD and DMPP on soil N dynamics after incorporation of vegetable crop residues. Biol Fertil Soils 43: 62–68.

Chen, G., Zhu, H. and Zhang, Y. (2003). Soil microbial activities and carbon and nitrogen fixation. Research in Microbiology 154: 393–398.

Chesson, A. (1997). Plant degradation by ruminants: parallels with litter decomposition in soils. *In*: Cadisch, G. and Giller, K. E. (Eds.), Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp. 47–66.

Christensen, B. T., Petersen, J., Kjellerup, V. and Trentemøller, U. (1994). The Askov long-term experiments on animal manure and mineral fertilisers: 1894–1994. SP Report No 3, April 1994. Danish Institute of Plant and Soil Science, Skovbrynet, Lyngby, Denmark.

Chu, H., Lina, X., Fujiib,T., Morimotob, S., Yagib, K., Hua, J. and Zhang, J. (2007) Soil microbial biomass, dehydrogenase activity, bacterial community structure in response to long-term fertiliser management. Soil Biology & Biochemistry 39: 2971–2976.

CIMMYT. (1988). From agronomic data to farmer recommendations: An economics training manual. International Wheat and Maize Improvement Centre (CIMMYT) Mexico, D. F. 33 pp 16-26.

Coleman, S. W. and Moore, E. J. (2003). Feed quality and animal performance. Field crops research 84(1): 17-29.

Coleman, S. W., Hart, S. P., Sahlu, T. (2003). Relationships among forage chemistry, rumination and retention time with intake and digestibility of hay by goats. Small Ruminant Research 50: 129–140.

Cooke, G. W. (1982). *Fertilizing for maximum yield*. 3rd edition. London, Granada. 465 pp.

Corbin, J. D., Avis, P. G. and Wilbur, R. B. (2003). The role of phosphorus availability in the response of soil nitrogen cycling, understory vegetation and arbuscular mycorrhizal inoculum potential to elevated nitrogen inputs. Water Air Soil Poll. 147: 141–161.

Covacevich, F., Marino, M. A. and Echeverriá, H. E. (2006). The phosphorus source determines the arbuscular mycorrhizal potential and the native mycorrhizal colonization of tall fescue and wheatgrass. Eur. J. Soil. Biol. 42: 127–138.

Crissman, C. C., Espinosa, P., Ducrot, C., Cole, D. C. and Carpio, F. (1998). The Case Study Site: Physical, Health and Potato Farming Systems in Carchi Province. *In*: Crissman, C. C., Antle, J. M. and Capalbo, S. M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production, Kluwer Academic Publishers, Boston, pp. 85–120, Chapter 5.

Dalal, R. C., Lawrence, P., Walker, J., Shaw, R. J., Lawrence, G., Yule, D., Doughton, J. A., Bourne, A., Duivenvoorden, L., Choy, S., Moloney, D., Turner, L., King, C. and Dale, A. (1999). A framework to monitor sustainability in the grains industry. Australian Journal of Experimental Agriculture 39: 605–620.

Dalal, R. C. (1998) Soil microbial biomass—what do the numbers really mean? Australian Journal of Experimental Agriculture. 38: 649–665

Dalal, R. C., Eberhard, R., Gratham, T. and Mayer, D. G. (2003). Application of sustainability indicators, soil organic matter and electrical conductivity, to resource management in northern grain region. Australian Journal of Experimental Agriculture 43: 253-259.

Danso, S. K. A. (1992). Biological nitrogen fixation in tropical agroecosystems: twenty years of biological nitrogen fixation research in Africa. *In* Mulongoy, K., Gueye M and Spencer D.S.C. (Eds.) Biological nitrogen fi xation and sustainability of tropical agriculture. John Wiley & Sons Ltd, Chichester, UK.

Dantsis, T., Caterina Douma C., Giourga, C., Loumou, A. and A. Polychronaki, E. A. (2010). A methodological approach to assess and compare the sustainability level of agricultural plant production systems. Ecological Indicators 10: 256–263.

De Jager, A., Nandwa, S. M. and Okoth, P. F. (1998.) Monitoring nutrient flows and economic performance in African farming systems (NUTMON). 1. Concepts and methodologies. Ag., Ecosys. Env 71: 37-48.

De Jager, A., Onduru, D., Van Wijk, M. S., Vlaming, J. and Gachini, G. N. (2001). Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Ag. Sys 69: 99-118.

De Willigen, P. (2000). An analysis of the calculation of leaching and denitrification losses as practised in the NUTMON approach. Report 18. Plant Research International. Wageningen, The Netherlands.

Defoer, T., Budelman, A., Toulmin, C. and Cater, S. (2000). Building common knowledge: participartory learning and action research (part 1). *In*: Defoer T. Budelman A., Toulmin C. and Cater S. Managing soil fertility in the tropics. A resource guide for participatory learning and action research. Royal Tropical Institute, Amsterdam, The Netherlands.

Delve, R. J., Cadisch, G., Tanner, J. C., Thorpe, W., Thorne, P. J. and Giller, K. E. (2001). Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agric. Ecosyst. Environ 84: 227 – 243.

Delve, R. J., Tanner, J. C., Kimani, S. K., Giller, K. E., Cadisch, G. and Thorne, P. J. (1999). Effects of dietary nitrogen source fed to steers on faecal nitrogen, its mineralisation, and the vegetative responses in maize to the incorporation of the faeces in soil. 1999. *In*: CIMMYT and EARO 1999. Maize production Technologies for the future: Challenges and Opportunities. Proceedings of the 6th Regional maize conference for Eastern and Southern Africa. Addis Ababa, Ethiopia, September 21-25, 1998. pp. 282-285.

Dembele, N. N. and Savadogo, K. (1996), The need to link soil fertility management to input/output market development in West Africa: key issues, In:The Key to Sustainable agriculture in West Africa" Seminar, Lomé, November 19-22, 1996.

Devendra, C. (1982). Perspectives in the utilization of rice straw by ruminants in Asia. *In*: P. T. Doyle (Ed). The Utilization of fibrous agricultural residues in animal feeds. (School of Agriculture and Forestry, University of Melbourne, Australia

Dewes, T. (1996). Effect of pH, temperature, amount of litter and storage density on ammonia emissions from stable manure. Journal of Agricultural Science 127: 501–509.

Diels, J., Vanlauwe, B., Van der Meersch, M. K., Sanginga, N., Merckx, R., (2004). Longterm soil organic carbon dynamics in a subhumid tropical climate: 13C data in mixed C3/C4 cropping and modeling with RothC. Soil Biol. Biochem 36: 1739–1750.

Dimes, J., Muza, L., Malunga, G. and Snapp, S. (2001). Tradeoff between investiments in Nitrogen and weeding: on-farm experimentation and simulation analysis in Malawi and Zimbabwe. 7th Eastern and Southern Africa regional maize conference. Pp 452-456.

Dixon, J., Gulliver, A. and Gibbon, D. (2001). Global farming systems study: Challenges and priorities to 2030. Synthesis and global overview. FAO (Food and Agriculture Organization of the United Nations), Rome, Italy. 98 pp.

Doran, J. W. (1980). Soil microbial and biochemical changes associated with reduced tillage. Soil Sci Soc Am J 44: 765–771.

Doran, J. W. (2002). Soil health and global sustainability: translating science into practice Agriculture, Ecosystems and Environment 88: 119–127.

Doran, J. W. and Zeiss, M. R. (2000). Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15: 3–11.

Doran, J. W., and Parkin T. B. (1994). Defining and assessing soil quality pp. 3–21. *In* J.W. Doran *et al*. (Ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. No. 35. SSSA, Madison, WI, USA.

Du, Z., Liu, S., Li, K and Ren, T. (2009). Soil organic carbon and physical quality as influenced by long-term application of residue and mineral fertiliser in the North China Plain.

Edmeades, D. C. (2003). The long-term effects of manures and fertilisers on soil productivity and quality: a review *Nutrient Cycling in Agroecosystems* 66: 165–180.

Eghball, B., Power, J. F., Gilley, J. E. and Doran, J. W. (1997). Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. Journal of Environmental Quality 26: 189-193.

Eivazi, F. and Tabatabai, M. A. (1988). Glucosidases and galactosidases in soils. Soil Biol Biochem 20 (5): 601-606.

Elias, E., Morse, S., and Belshaw, D. G. R. (1998). Nitrogen and phosphorus balance of Kindo Koisha farms in southern Ethopia. Agriculture, Ecosystems and Environment 71: 5-8.

Ellis, J. R.. (1998). Post flood syndrome and vesicular–arbuscular mycorrhizal fungi. J. Prod. Agric. 11, 200-204.

Faftine, O., Muir, J. P. and Massaete, E. (1998). Dry season supplementation of goats tethered on range supplemented with cowpea or groundnut residues with or without fresh *leucaena* leaves. Animal Feed Science Technology. 76: 1-8.

FAO (1993). FESLM: An international framework for evaluating sustainable land management. (http://www.fao.org/docrep/T1079E/t1079e00.HTM).

FAO (2003). Assessment of soil nutrient balance: Approaches and methodologies Fertiliser and Plant Nutrition Bulletin No.14. 101 pp, Rome, Italy.

FAO (2004). Scaling soil nutrient balances: Enabling mesolevel applications for African realities. Fertiliser and Plant Nutrition Bulletin No.15, 150 pp Rome, Italy.

FAO (2006). Plant nutrition for food security, a guide for integrated nutrient management. FAO Fertiliser and Plant Nutrition Bulletin. No.16, 121pp. Rome, Italy.

FAO and UNESCO. (1994). Soil map of the world, revised legend. World Resources Report 60. FAO, Rome, Italy.

FAOSTAT. (2009). FAO statistical database online, accessed in 2009 (available at http://faostat.fao.org).

Fening, J. O., Adjei-Gyapong, T., Yeboah, E. Ampontuah, E. O., Quansah, G. and Danso, S. K. A. (2005). Soil fertility status and potential organic inputs for improving smallholder crop production in the interior Savanna zone of Ghana. Journal of Sustainable Agriculture 25(4): 69-92.

Fernandez-Rivera, S., Okike, I., Manyong, V., Willams, T. O., Kruska, R. L. and Tarawali, S. A. (2004). Classification and description of the major farming systems incorporating ruminants livestock in West Africa Lessons learned and emerging research opportunities. Pages 89-122 in Sustainable crop-livestock production for improved livelihoods and natural resource management in West Africa. Proceedings of an international conference held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 19-22 Nov 2001 edited by Williams, T. O., Tarawali, S. A., Hiernaux, P. and Fernandez-Rivera, S.

Fernández-Rivera, S., Williams, T.O., Hiernaux, P. and Powell, J. M. (1995). Faecal excretion by ruminants and manure availability for crop production in semi-arid West Africa Pages 149–170 *in* Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II. Powell, J. M. Fernandez-Rivera, S. Williams, T. O. and Renard, C (Eds). International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Francisco, S. R. and Ali, M. (2006). Resource allocation tradeoffs in Manila‘s peri-urban vegetable production systems: An application of multiple objective programming. Agricultural Systems 87: 147–168.

Franzluebbers, K., Juo, A. S. R. and Manu, A. (1994). Decomposition of cowpea and millet amendments to a sandy Alfisol in Niger. Plant and Soil 167: 255-265.

Garcia, C., Hernandez, M. T., Costa, F. and Ceccanti, B. (1994). Biochemical, parameters in soil regenerated by addition of organic wastes. *Waste Manage. Res*., 12: 457–466.

Garcia, C., Hernandez, T. and Costa, F. (1994). Microbial activity in soils under Mediterranean environmental conditions. Soil Biol Biochem 26 (9): 1185–1191.

Garcıa-Gil, J. C., Plaza, C., Soler-Rovira, P. and Polo, A. (2000). Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. Soil Biology & Biochemistry 32: 1907–1913.

Garcia-Ruiz, R. Ochoa, V., Hinojosa, M.B. and Carreira, J. A. (2008). Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems, Soil Biology & Biochemistry 40: 2137–2145.

Gentile, R., Vanlauwe, B., Chivenge, P. and Six, J. (2008) Interactive effects from combining fertiliser and organic residue inputs on nitrogen transformations. Soil Biology and Biochemistry 40: 2375–2384.

Gerner H. and Harris G. (1993) The Use and Supply of Fertilisers in Sub-Saharan Africa. In :The Role of Plant Nutrient for Sustainable Food Crop Production in Subaharan Africa. Reuter, H. van,. Prins, H., W, eds The Dutch Association of Fertiliser Producers.

Gigliotti, G., Kaiser, K., Guggenberger, G. and Haumaier, L. (2002). Differences in the chemical composition of dissolved organic matter from waste materials of different sources. Biology and Fertility of Soils 36: 321–329.

Giller K. E., Witter, E., Corbeels, M. and Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics‘ view. Field Crops Research 114: 23–34.

Giller, K. E. (2001). Nitrogen fixation in tropical cropping systems. 2nd edition. CABI Publishing. Wallingford, UK,

Giller, K. E. (2002). Targeting management of organic resources and mineral fertilisers: Can we match scientist fantasies with farmers realities? *In*: Vanlauwe B., Diels, J., Sanginga, N. and Merckx, R. (Eds), Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice. CAB International, Wallingford Oxon, UK, pp. 155-172.

Giller, K. E. and Wilson, K. J. (1991). Nitrogen fixation in tropical cropping systems. CAB International, Wallingford, Oxon, UK,

Giller, K. E., Rowe, E., de Ridder, N. and van Keulen, H. (2006). Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric. Syst. 88: 8–27

Gosling, P., Hodge, A., Goodlass, G. and Bending, G.D. (2006). Arbuscular mycorrhizal fungi and organic farming. Agriculture, Ecosystem and Environment 113: 17–35.

Gregorich, E. G., Carter, M. R., Angers, D. A., Monreal, C. M. and Ellert, B. H. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74: 367-385.

Gryndler, M., Larsen, J., Hrselova , H., Rezacova, V., Gryndlerova, H. and Kubat, J. (2006). Organic and mineral fertilization, respectively, increase and decrease the development of external mycelium of arbuscular mycorrhizal fungi in a long-term field experiment. Mycorrhiza 16: 159–166.

Hachicha, S., Chtourou, M., Medhioub, K. H. and Ammar, E. (2006). Compost of poultry manure and olive mill wastes as an alternative fertiliser. Agron. Sustain. Dev. 26: 135–142.

Hafner, H., George, E., Bationo, A. and Marschner, H. (1993). Effect of crop residues on root growth and nutrient acquisition of pearl millet in an acid sandy soil in Niger. Plant and Soil 150:117–127.

Handayanto, E., Cadisch, G. and Giller, K. E. (1997). Regulating N mineralization from plant residues by manipulation of quality. In: Cadisch, G., Giller, K. E. (Eds.), Driven by Nature - Plant Litter Quality and Decomposition. CAB International, Wallingford, Oxon UK. pp. 175–186.

Harris, F. (1996). Intensification of agriculture in semi-arid areas: Lessons from the Kano close-settled zone, Nigeria. Gatekeeper Series No. SA59. International Institute for Environment and development, London, UK.

Harris, F. (1999). Nutrient Management Strategies of Small-Holder Farmers in a ShortFallow Farming System in North-East Nigeria. The Geographical Journal, Vol.
165 (3): 275-285.

Harris, F. (2002). Management of Manure in Farming system in semi-arid West Africa. Experimental Agriculture 38: 131-148.

Harris, F. and Yusuf, M. A. (2001) Manure management in the Kano close settled zone. Experimental Agriculture 36: 1-14.

Hartemink, A. E. (2001). Soil fertility in the tropics with case studies on plantation crops. PhD. thesis, The University of Reading, Reading, UK.

Hati, K. M., Swarup, A., Singh, D., Misra, A.K. and Ghosh, P. K. (2006). Long-term continuous cropping, fertilization, and manuring effects on physical properties and organic carbon content of a sandy loam soil. Australian Journal of Soil Research 44: 487–495.

Haynes, R. J. (1986). The decomposition process: Mineralization, immobilization, humus formation and degradation. *In:* Mineral nitrogen in the plant-soil system. Haynes, R.J. (Ed), pp 52-109. Academic Press, Orlando, FL, USA.

Herrero, M., Gonzalez-Estrada, E., Thornton, P. K., Quiros, C., Waithaka, M. M., Ruiz, R. and Hoogenboom, G. (2007). IMPACT: Generic household-level database and diagnostics tools for integrated crop-livestock systems analysis. Agricultural Systems 92: 240-265.

Hiernaux, P. and Ayantunde, A. A. (2004). The Fakara: a semi-arid agro-ecosystem under stress, Report of research activities of International Livestock Research Institute (ILRI) in Fakara, South-western Niger, between 1994 and 2002 (Desert Margins Programme, ICRISAT, Niamey, Niger).

Hue, N. V. (1991). Effects of organic acids/anions on P sorption and phytoavailability in soils with different mineralogies. Soil. Sci. 152: 463–471.

Ibekwe, A. M., Paiernik, S. K., Gan, J., Yates, S. R., Yang, C. H. and Crowley, D. (2001). Impact of fumigants on soil microbial communities. Appl. Environ. Microbiol. 67: 3245–3257.

Ikpe, F. N and Powell, J. M (2002). Nutrient cycling practices and changes in soil properties in the crop-livestock farming system of western Niger Republic of West Africa. Nutrient Cycling in Agroecosystems 62: 37-45.

Iwuafor, E. N. O., Aihou, K., Jaryum, J. S., Vanlauwe, B., Diels, J., Sanginga, N., Lyasse, O., Deckers, J. and Merckx, R. (2002). On-farm evaluation of the contribution of sole and mixed applications of organic matter and Urea to maize grain production in the Savanna. *In*: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (Eds), Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice. CAB International, Wallingford Oxon, UK, pp. 185197.

Jeffries, P., Gianinazzi, S., Perotto, S., Turnau, K. and Barea, J. M. (2003). The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. Biol. Fert. Soils 37: 1–16.

Jenkins, W. R. (1964). A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Dis. Rep. 48:692.

Johnson W. J. (1995). Nitrification inhibitors potential use in Ohio. AGF-201-95 (http://ohioline.osu.edu/agf-fact/0201.html).

Jones R. B., Snapp, S. S. and Phombeya, H. S .K. (1997). Management of leguminous leaf residue to improve nutrient use efficiency in the sub-humid tropics. P. 239250. In G. Cadisch and K.E Giller (eds). Driven by Nature: Plant litter quality and decomposition. CAB International, Wallingford, UK.

Jones, R. B., Wendt, J. W., Bunderson, W. T. and Itimu O. A. (1996). *Leucaena* + maize alley cropping in Malawi: 1. Effects of N, P, and leaf application on maize yields and soil properties. Agrofor. Syst. 33: 281-294.

Kaitho, R. J., Umunna, N. N., Nsahlai, I. V., Taminga, S. and van Bruchem, J. (1998). Utilization of browse supplements with varying tannin levels by Ethiopian Menz Sheep. 1. Intake digestibility and live weight changes. Agroforestry Systems 39: 145-159.

Kang, G. S., Beri, V., Sidhu, B. S. and Rupela, O. P. (2005). A new index to assess soil quality and sustainability of wheat-based cropping systems Biol Fertil Soils 41: 389–398.

Karbo, N. and Agyare, W. A. (2002). Crop-livestock systems in northern Ghana. *In*: Tarawali, G. and P. Hiernaux (Eds). Improving crop-livestock systems in the dry savannas of West and Central Africa. Reports from the Workshop on Croplivestock

Systems in the Dry Savannas of West and Central Africa, 22–27 November 1998, IITA, Ibadan, Nigeria.

Karlen, D. L. and Stott, D. E. (1994). A framework for evaluating physical and chemical indicators of soil quality. *In* Doran, J. W., Coleman, D. C., Bezdicek, D. F. and Stewart B. A. (Eds.), Defining soil quality for a sustainable environment (pp. 53–72). SSSA Special Publication No 35, ASA and SSSA Madison, WI, USA.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., and Schuman, G. E. (1997). Soil quality: a concept, definition and framework for evaluation. Soil Science Society of America Journal 61: 4–10.

Kasim, A. B. and Edwards, H. M. (1998). The analysis for inositol phosphate forms in feed ingredients. J. Sci. Food Agric. 76: 1-9.

Kassa, H., Gibbon, D. and Tamir, B. (2003). Use of livestock feed balance as a potential indicator of sustainability of tropical smallholder mixed farms-prevailing knowledge gap: A case study from the Harar Highlands of Eastern Ethiopia. Journal of Sustainable Agriculture 22(4): 31-48.

Kelly, K.W. and Sweeney, D. W. (1998). Effects of wheat residue management on double cropped soybean and subsequent crops. J. Prod. Agric. 11: 452–456.

Kihanda, F. M. and Gichuru, M. (2000). Manure management for soil fertility improvement. Tropical Soil Biology and Fertility Institute (TSBF), Nairobi, Kenya. 16 pp.

Kimani, S. K. and Lekasi, J. K. (2004). Managing manures throughout their production cycle enhances their usefulness as fertilisers: a review. *In*: Bationo, A. (Ed.). Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa. Academy Science Publishers, Nairobi, pp. 187–197.

King, L. D. (1990). Soil nutrients management in the United States. *In* Edwards, C..A., Lal, R., Madden, P., Miller, R. H. and House, G. (Eds). Sustainable agricultural systems. Soil and water conservation society. Ankeny Iowa, pp 89-106.

Kladivko, E. J. (1994). Residue effect on soil physical properties. *In* Unger P. W. (Ed.) Managing agricultural residues. Lewis Publ., Boca Raton, Florida, USA. pp 448.

Knight T. R. and Dick, R. D. (2004). Differentiating microbial and stabilized bglucosidase activity relative to soil quality. Soil Biology & Biochemistry 36: 2089–2096

Kouame, C., Hoefs, S., Powell, J. M., Roxas, D. and Renard, C.

(1992). Intercrop *Stylosanthes* effect on millet yields and animal performance in the Sahel. In: Proc. Joint Feed Resources Networks Workshop. ILCA, Gaborone, 4-8 March, pp. 137-146.

Kristensen, P. K. (1996). The mineralization of faeces nitrogen in relation to the feed and faeces composition. MSc thesis, The Royal Veterinary and Agricultural University, Copenhagen Denmark.

Kulling, D. R., Menzi, H., Krober, T. F., Neftel, A., Sutter, F., Lischer, P. and Kreuzer, M. (2001). Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. J. Agric. Sci. 137: 235–250.

Kumar, K., and Goh, K. M. (2002). Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. European Journal of Agronomy 16: 295–308

Kumar, R. (1992). Anti-nutritional factors. The potential risks of toxicity and methods to alleviate them. *In:* Legume trees and other fodder trees as protein sources for livestock (Speedy, A. and Pugliese, J. L. Eds.) FAO Animal Production and Health Paper 102 pp 145-160, Rome, Italy.

Kwakye, P. K. (1980). The effects of method of dung storage and its nutrient (NPK) content and crop yield in the north east savanna zone of Ghana. Paper 20. Organic recycling in Africa. FAO Soils Bulletin 43, Rome, Italy.

Ladd, J. N., Amato, M., Li-Kai, Z., Schultz, J. E. (1994). Differential effects of rotation, plant residue and nitrogen fertiliser on microbial biomass and organic matter in a Australian alfisol. Soil Biology and Biochemistry 26: 821–831.

Lal, R. (1980). Losses of plant nutrients in runoff and eroded soil. *In:* T. Rosswall (Ed.). Nitrogen cycling in West African Ecosystems, Proc SCOPE/UNEP, held at IITA, 11-15 December 1978, pp. 32-38.

Lal, R. (2002) Soil carbon dynamics in cropland and rangeland. Environmental Pollution 116: 353–362.

Larbi, A., Smith, J. W., Adekunle, I. O., Agyare, W. A., Gbaraneh, L. D., Tanko, R. J., Akinlade, J., Omokaye, A. T., Karbo, N. and Aboh, A. (2002). Crop residues for mulch and feed in crop-livestock systems: Impact on maize grain yield and soil properties in the west African humid forest and savanna zones. Expl Agric. 38: 253-264.

Larkin, R. P. (2008), Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato. Soil Biology & Biochemistry 40: 1341–1351

Leadir, L., Fries, M., Pacovsky, R. S., Safir, G. R. and Siqueira, J. O. (1997). Plant growth and arbuscular mycorrhizal fungal colonization affected by exogenously applied phenolic compounds. Journal of Chemical Ecology 23: 1755–1767.

Leita, L. Nobili, M. D., Mondini, C. (1999): Influence of inorganic and organic fertilization on soil microbial biomass, metabolic quotient and heavy metal bioavailability. Biol. Fertil. Soils 28: 371–376.

Lekasi, J. K. (2000). Manure management in the Kenya highlands: collection, storage and utilisation to enhance fertiliser quantity and quality. Doctoral Thesis. Coventry University, UK.

Lekasi, J. K., Tanner, J. C., Kimani, S. K. and Harris, P. J. C. (1999). Manure management in Kenya Highlands. Practices and potential. 2nd edn. Henry Doubleday Research Association (HRDA) Publication, Coventry, UK. 35 pp.

Linn, D. M. and Doran, J. W., (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48: 1267–1272.

Lipavský, J., Jaromir, K. and Jiri, Z. (2008). Long term effects of straw and farmyard manure on crop yields and soil properties. Archives of Agronomy and Soil Science, 54(4): 369 - 379.

Lo´pez-Ridaura, S., van Keulen, H., van Ittersum, M. and Leffelaar, P. (2005). Multiscale methodological framework to derive criteria and indicators for sustainability evaluation of peasant natural resource management systems. Environ. Dev. Sustain. 7: 51–69.

Lompo, F. (1984). Problématique de la matière organique dans la zone du plateau Mossi. Etude de la disponibilité des résidus culturaux et de leur mode de transformation. Mémoire de fin d'études. ISP/Université de Ouagadougou, Burkina Faso. 108 pp.

Lynam, J. K. and Herdt R. W. (1989). Sense and sustainability, sustainability as an objective in international agricultural research. Agricultural Economics 3: 381–398.

Mafongoya, P. L. Bationo, A. Kihara, J. and Waswa, B. S. (2006) Appropriate technologies to replenish soil fertility in southern Africa. Nutr Cycl Agroecosyst 76: 137–151.

Makinde, E. A., Oluwatoyinbo F. I. and Ayoola. (2006). Intercropping and Crop Residue Incorporation: Effects on Soil Nutrient Status Journal of Plant Nutrition 26: 235244.

Makokha, M., Odera, H., Maritim, H. K., Okalebo, J. R., and Iruria, D. M. (1999). Farmers' perceptions and adoption of soil management technologies in western Kenya. African Crop Science Journal 7(4): 549-558.

Maman, N., Mason, S.C., and Sirifi, S. (2000). Influence of variety and management level on pearl millet production in Niger: I. Grain yield and dry matter accumulation. African Crop Science Journal 8(1): 25-34.

Mandal, B., Majumder, B., Bandyopadhyay, P. K., Hazra, G. C., Gangopadhyay, A., Samantaray, R. N., Mishra, A. K., Chaudhury, J., Saha, M. N. and Kundu, S. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Global Change Biol. 13: 357–369.

Mando, A., Ouattara, B., Somado, A. E., Wopereis, M. C. S., Stroosnijder, L. and Breman, H. (2005). Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under SudanoSahelian conditions. Soil Use Manage. 21: 25–31.

Manyong, V. M. (2002). Economic research at IITA for the improvement of agriculture in the subhumid and humid zones of West Africa. *In*: Sakurai T., Furuya J. and Takagi, H. (Eds), Economic analyses of agricultural technologies and rural institutions in West Africa: Achievements, challenges, and application to rice farming research. Proceedings of JIRCAS international workshop, 12–13 July 2001, Tsukuba, Japan. Japan International Research Centre for Agricultural Sciences (JIRCAS). Working Paper Report 25. pp. 37–58.

Manyong, V. M., Makinde, K. O. and Ogungbile, A. G. O. (2002). Agriculture transformation and fertiliser use in cereal-based systems of northern Guinea savanna of Nigeria. *In:* Vanlauwe B., Diels, J., Sanginga, N., and Merckx, R., (Eds.), Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice. CAB International, Wallingford, Oxon, UK, pp. 75-85.

Masciandaro, G. and Ceccanti, B. (1999). Assessing soil quality in different agroecosystems through biochemical and chemico-structural properties of the humic substances. Soil Till. Res. 51: 129-137.

Masto, R. E., Chhonkar, P. K., Singh, D. and Patra, A. K. (2008). Alternative soil quality indices for evaluating the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils of India. Environ Monit Assess 136: 419–435.

McMeniman, N. P., Elliot, R. and Ash, A. J. (1988). Supplementation of rice straw with crop by-products. I. Legume straw supplementation. Animal Feed Science and Technology 19: 43-53.

Mechri, B., Mariemb, F. B., Bahamb, M., Elhadjc, S. B. and Hammamia, M. (2008). Change in soil properties and the soil microbial community following land spreading of olive mill wastewater affects olive trees key physiological parameters and the abundance of arbuscular mycorrhizal fungi. Soil Biology and Biochemistry 40: 152–161.

Meunchang, S., Panichsakpatana, S. and Weaver, R.W. (2005). Co-composting of filter cake and bagasse; by-products from a sugar mill. Biores. Technol. 96: 437–442.

Mijangos, I., Perez, R., Albizu, I. and Garbisu, C., (2006). Effects of fertilization and tillage on soil biological parameters. Enzyme and Microbial Technology 40: 100–106.

Moran, J. B., Satoto, K. B. and Dawson, J. E. (1983). The utilization of rice straw fed to zebu cattle and buffalo as influenced by alkali treatment and *Leucaena* supplementation. Australian Journal of Agricultural Research 34: 73-84.

Morgan, D. E. and Trinder, H., (1980). The composition and nutritional value of some tropical and subtropical by-products. ADAS Regional Nutrition Chemistry Department, Wolverhampton, Newcastle-Upon-Tyne, UK.

Mubarak, A. R., Rosenani, A. B., Anuar, A. R. and Zauyah, D. (2002). Decomposition and nutrient release of maize stover and groundnut haulms under tropical field conditions of Malaysia. Commun. Soil Sci. Plant Anal., 33(3&4): 609–622.

Mubarak, A. R., Rosenani, A. B., Anuar, A. R. and Zauyah, D. S. (2003). 'Effect of Incorporation of Crop Residues on a Maize-Groundnut Sequence in the Humid

Tropics. II. Soil Physical and Chemical Properties', Journal of Plant Nutrition, 26(12): 2343-2364.

Mubarak, A. R., Rosenani, A. B., Zauyah, S. D. and Anuar, A. R. (1999). Decomposition and nutrient release from maize (*Zea mays* L.) residues and N uptake by groundnut (*Arachis hypogaea*) in a crop rotation system. Malaysian J. Soil Sci. 3: 93–107.

Mucheru, M., Mugendi, D. N., Micheni, A., Mugwe, J., Kungu J., Otor, S., and Gitari, J. (2002). Improved food production by use of soil fertility amendments strategiesin the central highlands of Kenya, in: Bationo A., and Swift M. J. (Eds), Proceedings of the 8th meeting of the African Network for Soil Biology and Fertility research, Nairobi, Kenya.

Mucheru-Muna, M., Mugendi, D., Kung'u, J., Mugwe, J. and Bationo, A. (2007). Effects of organic and mineral fertiliser inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. Agroforest Syst 69:189–197

Mulumba, L. N., Lal, R. (2008). Mulching effects on selected soil physical properties. Soil & Tillage Research 98: 106–111.

Murwira, H. K. (1995). Ammonia losses from Zimbabwean cattle manure before and after incorporation into soil. Trop. Agric. 72: 269–273.

Murwira, H. K., Swift, M. J. and Frost, P. G. H. (1995). Manure as a key resource in sustainable agriculture. Pages 131–148 *in* Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II, edited by Powell, J. M.,Fernandez-Rivera, S., Williams T.O. and Renard, C. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Nahed, J., Castel, J. M., Mena, Y. and Caravaca, F. (2006). Appraisal of the sustainability of dairy goat systems in Southern Spain according to their degree of intensification. Livestock Science 101: 10–23.

Nakhumwa, T.O. (2004). Dynamic Costs of Soil Degradation and Determinants of Adoption of Soil Conservation Technologies by Smallholder Farmers in Malawi. Doctoral Thesis. University of Pretoria, South Africa.

Nambiar, K. K. M, Gupta, A. P, Fu, Q. and Lic, S. (2001). Biophysical, chemical and socioeconomic indicators for assessing agricultural sustainability in the Chinese coastal zone Agriculture, Ecosystems and Environment 87: 209–214.

Ndiaye, E. L., Sandeno, J. M., McGrath, D., and Dick, R. P. (2000). Integrative biological indicators for detecting change in soil quality. Am. J. Altern. Agric. 15: 26–36.

Nelson, D. W. and Sommers, L. E. (1975). A rapid and accurate method for estimating organic carbon in soil. Proc. of the Indiana Academy of Science 84: 456-462.

Nelson, D. W. and Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. *In:* Page, A. L., Miller, R. H, and Keeney, D. R. (Eds.) Methods of Soil Analysis, part 2. American Society of Agronomy, Madison, USA, pp. 539 -579.

Ngosong, C. Jarosch, M. Raupp, J. Neumann, E. and Ruess, L. (2010), The impact of farming practice on soil microorganisms and arbuscular mycorrhizal fungi: Crop type versus long-term mineral and organic fertilization. Applied Soil Ecology 46: 134–142.

Ngwa, A. T. and Tawah, C. L. (2002). Effect of supplementation with leguminous crop residues or concentrates on the voluntary intake and performance of Kirdi sheep. Tropical Animal Health and Production 34: 65–73.

Ngwa, A.T. and Tawah, C. L. T., (1992). Effect of legume crop residues and concentrate supplementation on voluntary intake and performance of Kirdi sheep fed a basal diet of rice straw. In: Proc. Joint Feed Resources Networks Workshop. ILCA, Gaborone, 4-6 March, pp. 239-248.

Nhamo, N. (2001). An evaluation of the efficacy of organic and inorganic fertiliser combinations in supplying nitrogen to crops. M Phil thesis, University of Zimbabwe, Harare, Zimbabwe.

Novozamsky, I., Houba, V. J. G., van Eck, R. and van Vark, W. (1983). A novel digestion technique for multi-element plant analysis. Communications in Soil Science and Plant Analysis, 14 (3): 239 – 248.

Nyamangara, J., Piha, M. I. and Kirchmann, H. (1999). Interactions of aerobically decomposed manure and nitrogen fertiliser applied to soil. Nutr. Cycl. Agroecosyst. 54: 183–188.

Nye, P. H. and Greenland, D. J. (1960). The soil under shifting cultivation. Technical Communication 51, Commonwealth Bureau of Soil, Harpenden, UK.

Odongo, N. (1999) Effects of Rock P fed to cattle as supplement and the resultant manure quality. PhD thesis. University of Guelph, Canada.

Oehl, F., Sieverding, E., Mäder, P., Dubois, D., Ineichen, K., Boller, T. and Wiemkem, A. (2004). Impact of long-term conventional and organic farming on the diversity of arbuscular mycorrhizal fungi. Oecologia 138: 574–583.

Ogle, R. B. (2001). The need for socio-economic and environmental indicators to monitor degraded ecosystem rehabilitation: a case study from Tanzania. Agriculture, Ecosystems and Environment 87: 151–157.

Ogunwande, G.A., Osunade, J.A., Adekalu, K.O. and Ogunjimi, L.A.O. (2008). Nitrogen loss in chicken litter compost as affected by carbon to nitrogen ratio and turning frequency. Bioresour. Technol. 99, 7495–7503.

Okalebo, J. R, Palm, C. A., Lekasi, J. K., Nandwa, S. M., Othieno, C. O., Waigwa, M. and Ndungu, K. W. (2004). Use of organic and inorganic resources to increase maize yields in some Kenyan infertile soils: A five-year experience. *In* Bationo A. (Ed.) Managing nutrient cycles to sustain soil fertility in sub-Saharan Africa. Academy Science Publishers (ASP), Nairobi, Kenya, pp. 359-371.

Opala, P. A., Jama, B. A Othieno, C. O. and Okalebo, J. R. (2007). Effect f phosphate fertiliser application methods and nitrogen sources on maize in Western Kenya: an agronomic and economic evaluation. Expl Agric. 43: 477–487.

Opoku, A. (2004). The use of nitrification inhibitors to reduce nitrate leaching after incorporation of crop residues. M.Sc thesis, University of Ghent, Ghent, Belgium. Ørskov, E. R. (1992). Protein Nutrition in Ruminants. Academic Press, London, UK.

Osuji, P. O. and Odenyo, A. A. (1997). The role of legume forages as supplements to low quality roughages – ILRI experience. Animal Feed Science Technology 69: 27-38.

Ouedraogo, E., Stroosnider, L. Mando, A., Brussaard, L. and Zougmore, R. (2007). Agroecological analysis and economic benefit of organic resources and fertiliser in till and no-till sorghum production after a 6-year fallow in semi-arid West Africa. Nutr Cycl Agroecosyst 77: 245–256.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G. and Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83: 27–42.

Palm, C. A., Myers, R. J. K. and Nandwa, S. M. (1997). Organic–inorganic nutrient interactions in soil fertility replenishment. *In*: Buresh, R. J., Sanchez, P. A., Calhoun, F. (Eds.) Replenishing soil fertility in Africa. Soil Science Society of America, Madison, WI, pp 193–218, Special publication No. 51.

Parr, J. F. and Papendick, R. I. (1997). Soil quality: relationship and strategies for sustainable dryland farming system. Annals Arid Zone 36: 181–191.

Payne, R. W., Murray, D. A., Harding, S. A., Baird, D. B. and Soutar, D. M. (2009). GenStat for Windows (12th Edition) Introduction. VSN International, Hemel Hempstead, UK pp 310.

Pengthamkeeratia, P., Motavallib, P. P. and Kremerc, R.J. (2011). Soil microbial activity and functional diversity changed by compaction, poultry litter and cropping in a claypan soil. Appl. Soil Ecol. doi:10.1016/j.apsoil.2011.01.005

Powell, J. M. and Mohamed-Saleem, M. A. (1987). Nitrogen and phosphorus transfers in a crop livestock system in West Africa. Agricultural Systems 25: 261–277.

Powell, J. M. and Unger, P. W. (1998). Alternative to crop residues for sustaining agricultural productivity and natural resource conservation. Journal of Sustainable Agriculture.11 (2/3): 59 - 84.

Powell, J. M. and Williams, T. O. (1993). Livestock, Nutrient Cycling and Sustainable Agriculture in the west African Sahel. Gatekeeper Series 37. International Institute for Environment and Development, London, UK.

Powell, J. M., Pearson, R. A. and Hiernaux, P. H. (2004). Crop-livestock interaction in the West African drylands. Agron J. 96: 469-483.

Powlson D. S., Brookes P. C. and Christensen B. T. (1987). Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biology & Biochemistry 19: 159-164**.**

Quinones M. A., Borlaugh, N. E. and Dowswell, C. R. (1997). A fertilize-based green revolution for Africa. In: Buresh, R. J., Sanchez, P. A. and Calhoun, F. (eds). Replenishing Soil Fertility in Africa. Soil Science Society of America Special Publication 51, Madison, USA. Pp 81-95.

Rabary B. Sall, S. Letourmy, P., Husson, O. Ralambofetra, E. Moussa, N. and Chotte, J. L. (2008), Effects of living mulches or residue amendments on soil microbial properties in direct seeded cropping systems of Madagascar. Applied Soil Ecology 39: 236-243.

Rasul, G. and Thapa, G. B. (2004). Sustainability of ecological and conventional agricultural systems in Bangladesh: an assessment based on environmental, economic and social perspectives. Agricultural Systems 79: 327–351.

Reynolds, L. and de Leeuw, P. N. (1995). Myth and manure in nitrogen cycling: A case study of Kaloleni Division in Coast province, Kenya. *In*: Powell, J. M., Ferna´ndez-Rivera, S., Williams, T. O., Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Proceedings of ILCA, 22–26 November 1993, Addis Ababa, Ethiopia, pp. 509–521.

Reynolds, S. G. (1989). Possible reasons for non-adoption of pasture and forage crop research findings at farmer level. In: Grasslands and Forage Production in Southeast Asia (ed. Halim R.A.). Proceedings First Meeting Regional Working Group on Grazing and Feed Resources of South-east Asia 27 Feb.-3 March 1989, Serdang, Malaysia, 181–191.

Robertson J. G. and Lyttleton P. (1984). Division of peribacteriod membranes in root nodules of white clover, J. Cell Sci. 69: 147–157.

Rolda´n, A., Salinas-Garc, J. R., Alguacil, M. M., Caravaca, F. (2007). Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil and Tillage Research 93: 273–282.

Ruben, R. and Pender, J. (2004). Rural diversity and heterogeneity in less favoured areas: the quest for policy targeting. Food Pol. 29: 303–320.

Rufino, M. C., Rowe, E. C., Delve, R. J. and Giller, K. E. (2006). Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. Agriculture, Ecosystems and Environment 112: 261–282.

Rufino, M. C., Tittonell, P., van Wijk M. T., Castellanos-Navarrete, A., Delve, R. J., de Ridder, N. and Giller, K. E. (2007). Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livestock Science 112: 273–287.

Sakala, W. D., Cadisch, G. and Giller, K. E. (2000). Interactions between residues of maize and pigeonpea and mineral N fertilisers during decomposition and N mineralization. Soil Biology and Biochemistry 32: 679–688.

Samaké, O., Smaling, E. M. A., Kropff, M. J., Stomph, T. J., Kodio, A. (2005). Effect of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. Agr. Ecosyst. Environ. 109 (3-4): 335-345.

Sanchez, P. (2010). Tripling crop yields in Tropical Africa. Nature Geoscience 3: 299300.

Sanchez, P. A., Izac, A. M. N., Valencia, I. and Pieri, C. (1996) Soil fertility replenishment in Africa. In: Breth, S.A. (Ed.) Achieving Greater Impact from Research Investments in Africa. Sasakawa Africa Association, Mexico City.

Sangaré, M., Fernández-Rivera, S., Hiernaux, P. and Pandey, V. S. (2003). The effect of supplementation with fresh browse of *Ziziphus mauritiana* or *Combretum aculeatum* on feed intake, nitrogen utilization and growth of grazing range sheep. Tropical Animal Health and Production 35: 465-476.

Sanginga, N. and Woomer, P. L. (eds.). (2009). Integrated Soil Fertility Management in Africa: Principles, Practices and Development Process. Tropical Soil Biology and Fertility Institute of the International center for Tropical Agriculture. Nairobi 263 pp.

Savadogo, M. (2000). Crop residue management in relation to sustainable land use. Ph.D. Thesis, Wageningen Agricultural University, The Netherlands.

Schloter, M., Dilly, O. and Munch, J. C. (2003). Indicators for evaluating soil quality. Agriculture, Ecosystems and Environment 98: 255–262.

Sellami, F., Jarboui, R., Hachicha, S., Medhioub, K. and Ammar, E., (2008). Cocomposting of oil exhausted olive-cake, poultry manure and industrial residues of agro-food activity for soil amendment. Bioresource Technol. 99: 1177–1188.

Seo, S. N. and Mendelsohn, R. (2006). Climate change impacts on animal husbandry in Africa: A Ricardian analysis. CEEPA Discussion Paper No. 9, Centre for Environmental Economics and Policy in Africa, University of Pretoria, South Africa.

Shafi, M., Bakht, J., Jan, M. T. and Shah, Z. (2007). Soil C and N dynamics and maize (Zea may L.) yield as affected by cropping systems and residue management North-western Pakistan. Soil & Tillage Research 94: 520–529.

Shisanya, C. A., Mucheru, M. W., Mugendi, D. N. and Kung'u, J. B. (2008). Effect of organic and inorganic nutrient sources on soil mineral nitrogen and maize yields in central highlands of Kenya. Soil Tillage Res. doi:10.1016/j.still.2008.05.016.

Singh, G., Jalota, S. K. and Singh, Y. (2007). Manuring and residue management effects on physical properties of a soil under the rice–wheat system in Punjab, India. Soil & Tillage Research 94: 229–238.

Smaling, E. M. A. (1993). An Agroecological Framework for Integrated Nutrient Management with Special Reference to Kenya. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Smaling, E. M. A., Fresco L. O. and de Jager, A. (1996). Classifying, monitoring and improving soil nutrient stocks and flows in Africa agriculture. Ambio 25(8): 492–496.

Smaling, E. M. A., Stoorvogel, J. J. and Windmeijer, P. N. (1993). Calculating soil nutrient balances in Africa at different scales. II District scale. Fert. Res. 35: 237–250.

Smith, S.E. and Read, D.J (2008). Mycorrhizal Symbiosis. Springer, Berlin

Smith, T., Manyochi, B., Mikayiri, S. (1988). Legume supplementation of maize stover. In: Proc. First Joint Workshop on Utilization of Research Results on Forage and Agricultural Byproducts Material as Animal Feed Resource in Africa. Lilongwe, 5±6 December 1988, ILCA, 302 pp.

Stepniewski, W., Glinski, J. and Ball, B. C. (1994). Effects of compaction on soil aeration properties. *In*: Soane, B. D., Van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Elsevier, New York, USA. pp. 167–169.

Stevenson, F. J. (1994). Humus chemistry: genesis, composition, reactions. John Wiley and Sons, New York, USA.

Stoorvogel, J. J. and Smaling, E. M. A. (1990). Assessment of soil nutrient depletion in sub Saharan Africa, 1983–2000. Report 28. The Winand Centre for Integrated Land, Soil and Water Research (SC- DLO) Wageningen, The Netherland.

Stoorvogel, J. J., Antle, J. M. and Crissman, C. C. (2004 b). Tradeoff analysis in the Northern Andes to study the dynamics in agricultural land use. Journal of Environmental Management 72: 23–33.

Stoorvogel, J. J., Antle, J. M., Crissman, C. C. and Bowen, W. (2004 a). The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. Agricultural Systems 80: 43–66.

Strobel, H. (Ed.) 1987. Fertiliser use recommendation project final report. Annex III. Description of the first priority sites in various districts. Vol. 1-32 MoA (Ministry of Agriculture)/NARL (National Agricultural Research Laboratory), Nairobi, Kenya.

Suler T. B., Duryea M. L., Frolich L. M. and Guevara-Cuaspud E., (2001). A field practical approach for assessing biophysical sustainability of alternative agricultural systems. Agricultural Systems 68: 113-135.

Sur, H. S., Sidhu, A. S., Singh, R., Aggarwal, G. C., and Sandhu, K. S. (1993). Longterm effect of green manuring on soil physical properties and production potential in green manure–maize–wheat sequence. Annals of Agriculture Research 14: 125–131.

Swain, T.L., Smith, A. (1994). Cowpeas (Vigna unguiculata) as a planted pasture. Bull. Grassland Soc. Southern Africa 5: 34.

Sydorovych, O. and Wossink, A. (2008). The meaning of agricultural sustainability: Evidence from a conjoint choice survey. Agricultural Systems 98: 10–20.

Tabatabai, M. A. (1994). Soil enzymes. *In*: Weaver, R. W., Angel, J. S. and Bottomley (Eds.). Methods of soil analysis, Part 2. Microbiological and biochemical properties – SSSA Book Series 5: 775–826.

Tandon, H. L. S. (2004). Fertilisers in Indian agriculture – from 20th to 21st century. New Delhi, Fertiliser Development and Consultation Organisation. 239 pp.

Tanimu, J., Iwuafor, E. N. O., Odunze, A. C. and Tian, G. (2007). Effect of incorporation of leguminous cover crops on yield and yield components of maize. World Journal of Agricultural Sciences 3 (2): 243-249.

Tanner, J. C., Holden, S. J., Owen, E., Winugroho, M. and Gill, M. (2001). Livestock sustaining intensive smallholder crop production through traditional feeding practices for generating high quality manure-compost in upland Java. Agriculture, Ecosystems and Environment 84: 21–30.

Tarawali, G. (2002). A synthesis of the crop-livestockproduction systems of the dry savannas of West and Central Africa. *In:* Tarawali, G. and P. Hiernaux (Eds). 2002. Improving crop-livestocksystems in the dry savannas of West and Central Africa. Reports from the Workshop on Crop-livestockSystems in the Dry Savannas of West and Central Africa, 22–27 November 1998, IITA, Ibadan, Nigeria.

Thomsen, I. K. (2000). C and N transformations in ^{15}N cross-labelled solid ruminant manure during anaerobic and aerobic storage. Bioresour. Technol. 72, 267–274.

Tian, G., Badejo, M. A., Okoh, A. I., Ishida, F., Kolawole G. O., Hayashi Y. and Salako F. K. (2007). Effects of residue quality and climate on plant residue decomposition and nutrient release along the transect from humid forest to Sahel of West Africa. Biogeochemistry 86: 217–229.

Tian, G., Brussaard, L. and Kang, B. T. (1995). An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. Appl Soil Ecol 2: 25–32.

Tian, G., Kang, B. T. and Brussaard, L. (1993). Mulching effect of plant residues with chemically contrasting compositions on maize growth and nutrient accumulation. Plant Soil 153: 179–187.

Tiquia, S.M. and Tam, N.F.Y. (2000). Fate of nitrogen during composting of chicken litter. Environmental Pollution 110: 535–541.

Tiquia, S.M., Richard, T.L. and Honeyman, M.S. (2000). Effect of windrow turning and seasonal temperatures on composting of hog manure from hoop structures. Environ. Technol. 21: 1037–1046.

Tisdell, C. (1996). Economic indicators to assess the sustainability of conservation farming projects: an evaluation. Agriculture, Ecosystems and Environment 57: 117–131.

Tittonell, P., van Wijk, M. T., Rufino, M. C., Vrugt, J. A. and Giller, K. E. (2007). Analysing tradeoffs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. Agricultural Systems 95: 76–95.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E. C., Giller, K.E., (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110: 149–165.

Tognetti, C., Mazzarino, M. J. and Laos, F. (2007). Cocomposting biosolids and municipal organic waste: effects of process management on stabilization and quality Biol Fertil Soils 43: 387–397.

Tu, C., Ristaino, J. B., Hu, S. (2006). Soil microbial biomass and activity in organic tomato farming systems: Effects of organic inputs and straw mulching Soil Biology & Biochemistry 38: 247–255.

Turner, L. B., Paphazy, J. M., Haygarth, M. P. and Mckelvie, D. I. (2002). Inositol Phosphates in the Environment Phil. Trans. R. Soc. Lond. B 357 (1420), 449-469.

Turner, M.D., and Hiernaux, P. (2002). The use of herders‘ accounts to map livestock activities across agropastoral landscapes in semi arid Africa. Landscape Ecol. 17: 367–385.

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Cidad, V. G., Hermy, M., Mathijs, E., Muys, B., Reijnders, J., Sauvenier, X., Valckx, J., Vanclooster, M., Van der Veken, B., Wauters, E. and Peeters, A. (2007). SAFE – a hierarchical framework for assessing the sustainability of agricultural systems. Agriculture, Ecosystems and Environment 120 (2–4): 229–242.

Van den Bosch, H., Gitari, J.N., Ogaro, V.M., Maobe, S. and Vlaming, J. (1998). Monitoring nutrient flows and economic performance in Africa farming systems (NUTMON). III. Monitoring nutrient flows and balances in the districts in Kenya. Agric Ecosyst. Environ. 71: 63–80.

Van der Heijden, M. G. A., Klironomos, J. N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A. and Sander, I. R. (1998). "Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity." Nature 396 (6706): 69-72.

van der Pol, F. (1993) Analysis and evaluation of options for sustainable agriculture, with special reference to southern Mali. *In*: van Reuler,H. and Prins, W.H. (Eds). The role of plant nutrients for sustainable food crop production in sub-Saharan Africa. VKP. Liedschendam, The Netherlands.

Van Passel, S., Nevens, F., Mathijs, E., and van Huylenbroeck, G., (2007). Analysis: measuring farm sustainability and explaining differences in sustainable efficiency. Ecol. Econ. 62 (1): 149–161.

van Soest, P. J. and Robertson, J. B. (1985). Analysis of Forages and Fibrous Foods. A Laboratory Manual for Animal Science, 613. Cornel University, Ithaca. New York, USA. pp. 202.

Vanlauwe, B., Aihou, K., Aman, S., Iwuafor, E. N. O., Tossah, B. K., Diels, J., Sanginga, N., Lyasse, O., Merckx, R. and Deckers, J. (2001 b). Maize yield as affected by organic inputs and urea in the West African moist savanna. Agronomy Journal 93: 1191–1199.

Vanlauwe, B.and Giller K.E. (2006).Popular myths around soil fertility management in sub- Saharan Africa. Agriculture, Ecosystems & Environment 116: 34-46.

Vanlauwe, B., Diels, J., Aihou, K., Iwuafor, E. N. O., Lyasse, O., Sanginga, N. and Merckx, R. (2002 a). Direct interactions between N fertiliser and organic matter: evidence from trials with ^{15}N-labelled fertiliser. *In*: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa: from Concept to Practice. CAB International, Wallingford, Oxon, UK. pp. 173–184.

Vanlauwe, B., Palm, C. A., Murwira, H. K., and Merckx, R. (2002 b). Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system. Agronomie 22: 839 – 846.

Vanlauwe, B., and Sanginga N. (1995). Efficiency of use of N from pruning and soil organic matter dynamics in Leucaena Leucocephala alley cropping in Southwestern Nigeria. In: Dudal, R. and Roy, R. N. (eds). Integrated Plant Nutrition Systems. FAO, Rome. Pp 279-292.

Vanlauwe, B., Wendt, J. and Diels, J. (2001 a). Combined application of organic matter and fertiliser. *In*: Tian, G., Ishida, F., Keatinge, J.D.H. (Eds.), Sustaining Soil Fertility in West Africa. Soil Science Society of America and American Society of Agronomy, Madison, WI, USA. pp. 247–279.

von Wiren-Lehr, S. (2001). Sustainability in agriculture – an evaluation of principal goaloriented concept to close the gap between theory and practice. Agriculture, Ecosystems and Environment 84: 115–129.

Wahed, R.A., Owen, E., Naate, M. and Hosking, B.J. (1990). Feeding straw to small ruminants: effect of amount offered on intake and selection of barley straw by goats and sheep. Anim. Prod. 51: 283–289.

Walker, J. and Reuter, D. G. (1996). _Indicators of Catchment Health: A Technical Perspective.‘ (CSIRO Publishing: Collingwood, Vic. Australia).

Warambwa, A. R. and Ndlovu, L. R. (1992). Use of whole sunflower seeds and urea as supplements to crop residue based diets for goats. *In*: Proc. Joint Feed Res. Networks Workshop. ILCA, Gaborone, 4 - 8 March 1991, pp. 197-205.

Wardle, D. A., and Parkinson, D. (1990). Comparison of physiological techniques for estimating the response of the soil microbial biomass to soil moisture. Soil Biology and Biochemistry 22: 817–23.

Warner, K.E. and Murt, H. (1984). Economic incentive for health. American Review of Public Health 5: 107–133.

Watson, C. A., Oborn, I., Eriksen, J. and Edwards, A. C. (2005). Perspectives on nutrient management in mixed farming systems. Soil Use und Management. 21: 132-140.

Webb, K. E. and Bergman, E. N. (1991). Amino acid and peptide absorption and transport across the intestine. *In*: Tsuda, T., Sasaki, Y., Kawashima, R. (Eds.), Physiological Aspects of Digestion and Metabolism in Ruminants, Academic Press, San Diego, California, USA.

Whitemore, A. P. (1996). Modelling the release and loss of nitrogen after vegetable crops. NI J. Agric Sci. 44: 73-86.

Wijnhoud, J. D., Konboon, Y. and Lefroy, R. D. B. (2003). Nutrient budgets: sustainability assessment of rainfed lowland rice-based systems in northeast Thailand. Agriculture, Ecosystems and Environment 100: 119–127.

Williams, P. H. and Haynes, R. J. (2000). Transformations and plant uptake of urine N and S in long and short-term pastures. Nutr. Cycl. Agroecosyst. 56: 109–116.

Williams, T. O., Hiernaux, P. and Fernández-Rivera, S. (2000). Crop-livestock systems in sub-Saharan Africa: Determinants and intensification pathways. *In*: McCarthy, N., Swallow, B., Kirk, M. and Hazell, P. (Eds), Property rights, risks, and livestock development in Africa. International Food Policy Research Institute, Washington, DC, USA, and International Livestock Research Institute, Nairobi, Kenya. pp. 132–149.

Williams, T. O., Powell, J. M. and Ferna´ndez-Rivera, S. (1995). Manure utilisation, drought cycles and herd dynamics in the Sahel: implications for cropland productivity. *In:* Powell, J. M., Ferna´ndez-Rivera, S., Williams, T. O. and Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Proceedings of ILCA, 22–26 November 1993, Addis Ababa, Ethiopia, pp. 393–409.

Wong, J. W. C., Fung, S. O. and Selvam, A. (2009). Coal fly ash and lime addition enhances the rate and efficiency of decomposition of food waste during composting. Bioresour. Technol. doi:10.1016/j.biortech.2009.01.063

Woomer, P. L., Martin, A., Albrecht, A., Resck, D. V. S. and Scharpenseel, H. W. (1994) The importance and management of soil organic matter in the tropics. In: P.L.

Woomer and M.J. Swift (Eds) The biological management of tropical soil fertility. John Wiley and Sons, New York. Pp 47-80.

World Bank (2001). World development indicators. The World Bank, Washington, DC, USA. CD-ROM.

World Bank (2006). World development indicators database, April 2006; http://www .worldbank.org.

World Bank (2007). World development report, 2008. Agriculture for development. Washington, D C, USA. CD-ROM.

Wortmann, C. S. and Kaizzi, C. K. 1998. Nutrient balances and expected effects of alternative practices in the farming systems of Uganda. Agriculture, Ecosystems and Environment 71: 117-131.

Yang, Y., Yao, J., Hu, S. and Qi, Y. (2000). Effects of agricultural chemicals on the DNA sequence diversity of microbial communities. Microbiol. Ecol. 39: 72–79.

Yao, H., Bowma, D., Rufty, T. and Shi, W. (2009). Interactions between N fertilization, grass clipping addition and pH in turf ecosystems: Implications for soil enzyme activities and organic matter decomposition. Soil Biology and Biochemistry 41: 1425–1432.

Young, A., Chynoweth, D. and Hurst, T. (2000). What feedstocks work best in high carbon compost mix? Biocycle 9: 51–53.

Zeleke, T.B., Grevers, M.C.J., Si, B.C., Mermut, A.R. and Sheleme Beyene (2004). Effect of residue incorporation on physical properties of the surface soil in the South Central Rift Valley of Ethiopia. Soil & Tillage Research 77: 35–46.

Zhen, L. and Routray, J. K. (2003). Operational Indicators for Measuring Agricultural Sustainability in Developing Countries. Environmental Management. 32(1): 34–46.

Zingore, S., Murwira, H. K., Delve, R. J., Giller, K. E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric. Ecosyst. Environ. 119: 112–126.

Zucconi, F., Forte, M., Monac, A. and Beritodi, M. (1981). Biological evaluation of compost maturity. Biocycle 22, 27–29.

APPENDICES

Appendix 1: Questionnaire for social acceptability survey

Name: Location:

Occupation: Date:

Instructions

Please tick the appropriate answers using a black or blue ink pen. For 'open' questions, please write only in the space provided under each question.

Indicator (1): knowledge. (What does the farmer know and practice?)

Study focus: Soil application of crop residues

1) Which of the following crops do you cultivate?

1) Cowpea	☐	2) Groundnut	3) ☐	Soya beans	☐
4) Maize	☐	5) Millet	6) Rice ☐		☐
7) Sorghum	☐	8) Any	other ☐	……………………..	

2) Which of these crop residues do you leave on your fields after harvest?

1) Cowpea	☐	2) Groundnut	3) ☐	Soya beans	☐
4) Maize	☐	5) Millet	6) Rice ☐		☐
7) Sorghum	☐	8) Any	other ☐	……………………..	

3) Which of these crop residues do you incorporate into your fields after harvest?

1) Cowpea	☐	2) Groundnut	3) ☐	Soya beans	☐
4) Maize	☐	5) Millet	6) Rice ☐		☐
7) Sorghum	☐	8) Any	other ☐	……………………..	

Study focus: Feeding of crop residue to livestock

4) Which of the following livestock do you rear?

1) Goat ☐ 2) Sheep ☐ 3) Cattle ☐ 4) Donkey ☐

5) Which of these crop residues to you take home after harvest?

1) Cowpea	☐	2) Groundnut	☐	3) Soya beans	☐
4) Maize	☐	5) Millet	☐	6) Rice	☐
7) Sorghum	☐	8) Any other	☐	……………………..	

6) Which of these crop residues to you feed to your livestock after harvest?

1) Cowpea	☐	2) Groundnut	☐	3) Soya beans	☐
4) Maize	☐	5) Millet	☐	6) Rice	☐
7) Sorghum	☐	8) Any other	☐	……………………..	

7) Which of these crop residue management options are you aware of?

Crop residue management	
Leaving all crop residues on field after harvest	☐
Incorporating all crop residues into the soil	☐
Harvest all crop residues and feeding it to livestock	☐
Sharing the crop residues for both livestock feeding and soil improvement	☐

8) Which of these crop residue management options do you practice?

Crop residue management	
Leaving all crop residues on field after harvest	☐
Incorporating all crop residues into the soil	☐
Harvest all crop residues and feeding it to livestock	☐
Sharing the crop residues for both livestock feeding and soil improvement	☐

Indicator (2): perceived constraints – (What farmers think are barriers to the adoption of the innovation?).

Study focus: Soil application of crop residues

9) What is the main reason why you would not like to leave crop residues on the field and incorporate them into the soil?

1) It makes crop residue for 2) reduces supply of plant materials ☐ ☐ livestock feeding scarce for construction purposes

3)Requires high amount of labour ☐ 4) Any other ……………………….. ☐

5) None of the above ☐

10) Do you suffer any health risk or illness by incorporating crop residue into the soil? 1) No ? 2) Yes ? If yes please state it ………………………...

Study focus: Feeding of crop residue to livestock

11) What is the main reason why you would not like to collect crop residues from farm after harvest and feed to ruminant livestock?

1) It leaves the soil surface bare ? 2) reduces plant materials for construction purposes ?

3)Requires high amount of labour ? 4) Any other …………………………... ?

5) None of the above ☐

12) Do you suffer any health risk or illness by gathering crop residues and feeding it to livestock?

1) No ? 2) Yes ? If yes please state it ………………………

Indicator (3): Physical Stress (The drudgery associated with the innovation)

Study focus: Soil application of crop residues

13) Can you please rank these methods of crop management in decreasing order of tiredness (3- most tiring, 1 – least tiring).

Crop residue management	Preference
Incorporating none of the crop residues	
Incorporating 50% of the crop residues	
Incorporating all of the crop residues	

14) Can you please rank these methods of crop management in decreasing order of time consumption (3- most time demanding, 1 – least time demanding).

Crop residue management	Preference
Incorporating none of the crop residues	
Incorporating 50% of the crop residues	
Incorporating all of the crop residues	

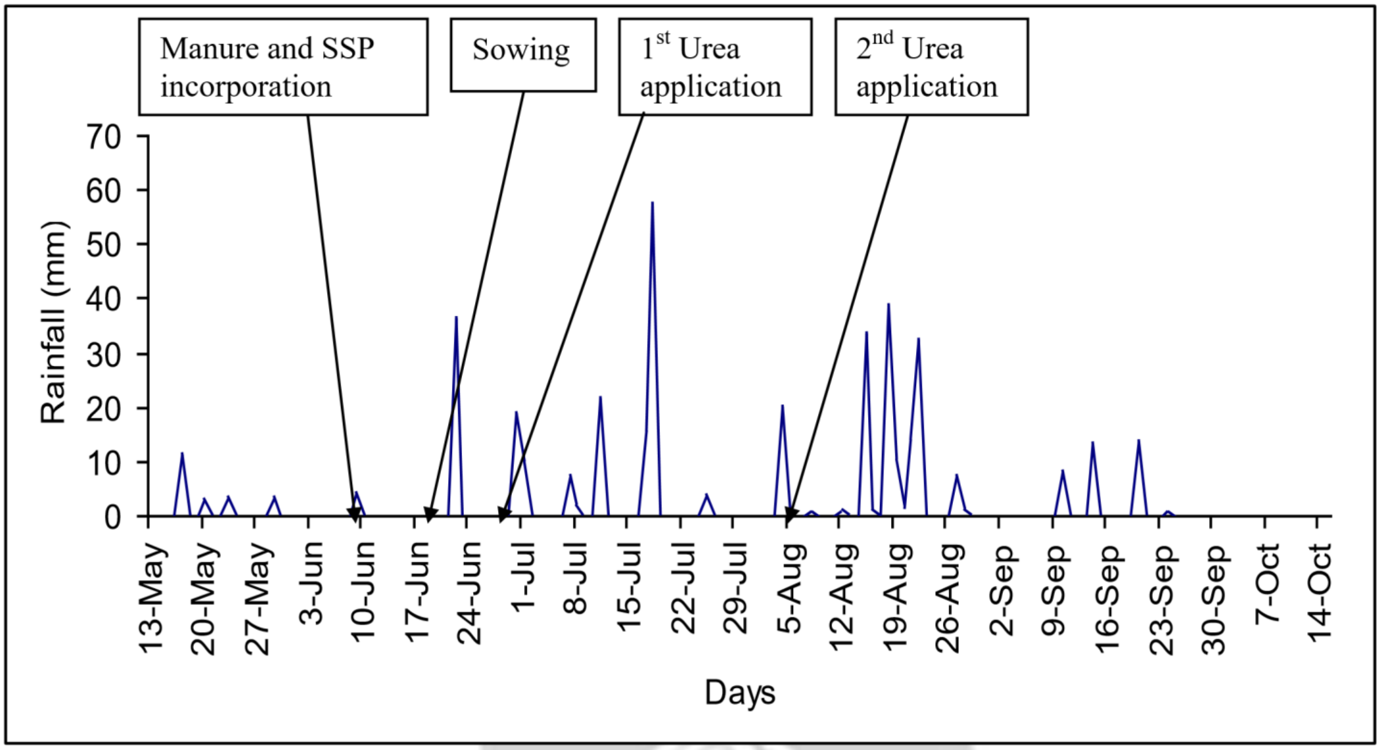
Study focus: Feeding of crop residue to livestock

15) Can you please rank these methods of livestock feeding in decreasing order of tiredness (3- most tiring, 1 – least tiring).

Feeding system	Preference
Free range grazing	
Controlled grazing on communal graze land	
Cut and carry	

16) Can you please rank these methods of livestock feeding in decreasing order of time consumption (3- most time demanding, 1 – least time demanding).

Feeding system	Preference
Free range grazing	
Controlled grazing on communal graze land	
Cut and carry	



Appendix 2: Rainfall distribution at Maradi in 2008

Appendix 3: Application rates of crop residue

Location	Crop Residue	Application rate (kg/ha)				
		0H 0S	25H 75S	50H 50S	75H 25S	100H 100S
Sarauniya						
Farmer 2	Groundnut haulms	0.0	375.0	750.0	1125.0	1500.0
	Maize stover	0.0	1755.0	1170.0	585.0	2340.0
Farmer 3	Groundnut haulms	0.0	525.0	1050.0	1575.0	2100.0
	Maize stover	0.0	2648.3	1765.5	882.8	3531.0
Cheyohi						
Farmer 2	Cowpea haulms	0.0	201.6	403.2	604.8	806.4
	Maize stover	0.0	1458.0	972.0	486.0	1944.0
	Maize husk	0.0	216.0	144.0	72.0	288.0
Farmer 3	Cowpea haulms	0.0	243.6	487.2	730.8	974.4
	Maize stover	0.0	1966.2	1310.8	655.4	2621.6
	Maize husk	0.0	326.3	217.5	108.8	435.0
Garin Labo						
Farmer 2	Cowpea haulms	0.0	266.7	533.3	800.0	1066.7
	Millet stover	0.0	2400.0	1600.0	800.0	3200.0
Farmer 3	Cowpea haulms	0.0	250.0	500.0	750.0	1000.0
	Millet stover	0.0	2250.0	1500.0	750.0	3000.0

Appendix 4: Score values of Social indicators

Cheyohi

Scenario	CR applied (%)	CR fed (%)	Knowledge	Perceive Constraints	Physical stress	SSI $_{social}$
1	0C 0M	100C 100M	1.0	6.7	5.3	4.3
2	25C 75M	75C 25M	7.1	3.1	3.6	4.6
3	50C 50M	50C 50M	7.1	3.1	3.6	4.6
4	75C 25M	25C 75M	7.1	3.1	3.6	4.6
5	100C 100M	0C 0M	10.0	5.9	4.4	6.8

Sarauniya

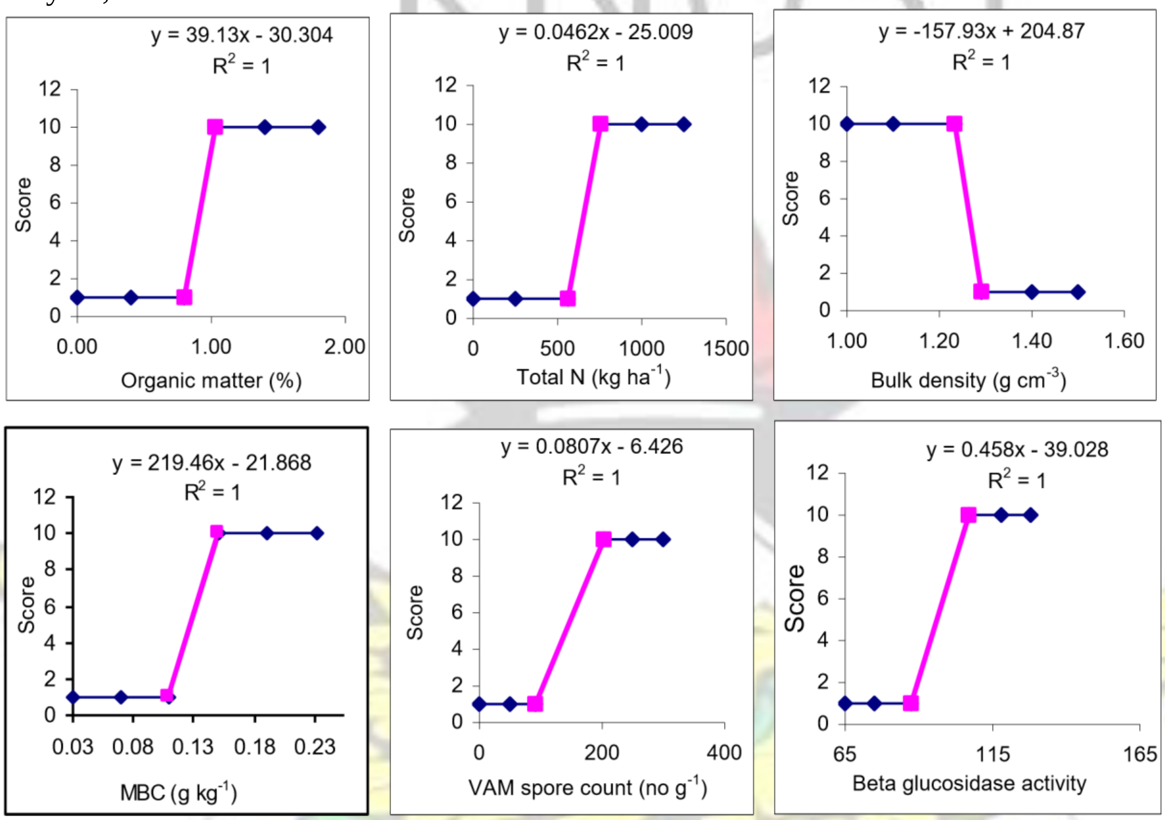
Scenario	CR applied (%)	CR fed (%)	Knowledge	Perceive Constraints	Physical stress	SSI $_{social}$
1	0C 0M	100C 100M	10.0	6.2	5.0	7.1
2	25C 75M	75C 25M	6.5	3.0	3.0	4.2
3	50C 50M	50C 50M	6.5	3.0	3.0	4.2
4	75C 25M	25C 75M	6.5	3.0	3.0	4.2
5	100C 100M	0C 0M	3.0	5.6	6.0	4.9

Garin Labo

Scenario	CR applied (%)	CR fed (%)	Knowledge	Perceive Constraints	Physical stress	SSI $_{social}$
1	0C 0M	100C 100M	10.0	7.1	5.5	7.5
2	25C 75M	75C 25M	4.3	3.1	2.6	3.3
3	50C 50M	50C 50M	4.3	3.1	2.6	3.3
4	75C 25M	25C 75M	4.3	3.1	2.6	3.3
5	100C 100M	0C 0M	1.0	5.4	7.1	4.5

Appendix 5: Scoring functions for indicators of soil quality

Cheyohi, Farm 1



Appendix 6: Correlation (r) between grain yield and N:P ratios at Nyankpala

	Grain Yeild	Added Effect	N	Applied P	Applied N	Biomass P	Biomass N:P	Applied N:P Biomass
Grain Yield	1.00							
Added Effect	0.92	1.00						
Applied N	0.83	0.56	1.00					
Applied P	0.73	0.42	0.98	1.00				
Biomass N	-0.07	0.16	-0.36	-0.47	1.00			

Biomass P	-0.53	-0.45	-0.49	-0.46	0.58	1.00		
Applied N:P	0.42	0.62	0.00	-0.20	0.58	-0.03	1.00	
Biomass N:P	-0.47	-0.49	-0.30	-0.24	0.11	0.84	-0.19	1.00