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Effects of tillage on greenhouse gas emission and nitrogen mineralization under *Tephrosia* fallows in Nyabeda, Western Kenya

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Nitrogen availability was measured in two improved fallows (*Tephrosia candida*, *Crotolaria paulina*), natural fallows, and continuously cropped fertilized and unfertilized maize (*Zea mays*) in Nyabeda, Siaya District, Western Kenya. Nitrogen availability was high following incorporation of their residues. N availability in all the treatments declined over time during the cropping season indicating that the soil N capital is not adequate. Tillage did not significantly ($P>0.05$) affect N availability and gaseous emissions. No tillage, however, reduced total N_2O and CO_2 emissions by 152 g N_2O-N ha^{-1} and 317 kg CO_2-C ha^{-1} respectively indicating its potential in reducing greenhouse effect. The findings of this study will be important in developing practices that increase N-use efficiency and reduce greenhouse gas emissions.

Key words: *Tephrosia candida*, *Crotolaria paulina*, tillage greenhouse gas emission and nitrogen mineralization.

Introduction

Because of the high incidences of soil fertility depletion in Western Kenya, improved fallow farming systems are being promoted for soil fertility improvements using nitrogen fixing trees/shrubs that are also capable of recycling of other nutrients through litter fall or pruning (Baggs *et al.*, 2001). Despite these efforts, there are increasing concerns regarding low crop N recovery from added pruning (Giller and Cadisch, 1995) because of lack of synchrony between N release and crop demand, and the potential for substantial N losses (Baggs *et al.*, 2001). Loss vectors in the field include nitrate leaching, erosion and gaseous emission (Mosier, 1998). The gaseous losses, as emphasized by recent research, are of particular concern due to their detrimental effect on the atmospheric environment. To date however, there are few reports of trace gas emissions from the tree-based tropical agricultural systems (Palm *et al.*, 2002, Millar *et al.*, 2003a). The effect of the various species pruning to the emissions of greenhouse gas is therefore necessary. Although Nair and Nair (2002), state that improved fallows have the potential for carbon sequestration, however, considerable effort is still required to assess the magnitude of this potential.

Many factors are involved in the regulation of nitrification and denitrification including climatic conditions, soil characteristics, and cropping practices and their interactions (Mills and Jones, 1996). Denitrification and nitrification processes are also linked to mineralization of SOM. Significant amount of soil organic N is mineralised during the growing season. Most crops require substantial quantity of N early in the growing season

(Keeney, 1982). Traditionally nitrate has been the primary N form absorbed by plants due to rapid conversion of ammonium in the soil to the nitrate. Higher plants and microorganisms compete for N in soils. Since the microorganisms are more efficient in intercepting N, the availability of N for plant growth depends on the soil C: N ratio. When C: N>30:1, N is immobilized in the decomposition process of organic residue by soil microbes, while at 20:1<C: N<30:1, there is limited immobilization and release of N into soil environment occurs. Nitrogen is available for plant uptake at C: N<20:1 form (Mills and Jones, 1996).

In the study, N availability were measured prior to and following cutting of improved fallow species. Comparisons were made with natural fallow and continuous maize (fertilized and unfertilised) cropping systems. Knowledge of the contribution of these systems to atmospheric loading of greenhouse gasses will contribute to the development of appropriate organic matter management practices to mitigate emissions and to increase nutrient use efficiency in these systems. The beneficiaries will be the farmers whose crop yields would be improved with increased nutrient use efficiency. The mitigation of gaseous losses would also reduce global warming. The objective of this study was to determine N availability during the cropping season under different fallows and continuous farming systems as affected by chemical composition of the fallow residues and method of tillage.

Materials and methods

Study site

The field study was conducted in Western Kenya highlands at an existing KEFRI/ICRAF smallholder experimental farm at Nyabeda in Yala Division, Siaya District in Nyanza Province. The area lies on coordinates $0^{o}07'N$, $34^{o}24'E$ at 1330 metres above see level (Soil Survey Staff, 1999). The area experiences bimodal rainfall pattern with two growing seasons. The first (long) rains season starts in March to July and the second (short) rain season starts from August to November. Annual rainfall ranges between 1500 to 1900-mm with an annual mean temperature of 24 ^{o}C (Rommelse, 2000). Despite the total high rainfall, dry spells occur during the growing seasons, negatively affecting crop production. The predominant soils in the area are P-sorbing alfisols and oxisol originally quite fertile but now quite depleted of N and P. Declining soil fertility has therefore been found as main factor limiting crop production (Hoekstra, 1988). The soils are silty clay loam, slightly acidic (pH 5.4) with low total cabon and N contents, and frequent P deficiencies (Nyambati, 2000).

The area is densly populated (500-1200 people Km^{-2}) with smallholder farms (0.2 – 2.5 Ha per household). Maize is preferred staple food and is often intercropped with beans, with low yields ranging between 700 -2000 Kg ha^{-1} for maize and 100 - 500 Kg ha^{-1} for beans. Other common food crops are bananas, cassava, sweet potatoes, sorghum, groundnuts, cowpeas and kales. In spite of the extreme land pressure, about 52 % of the farmers leave their farms under natural fallow (Swinkels *et al.,* 1997), while others are increasingly adopting improved fallow farming systems (Sanchez *et al.,* 1997).

Experimental treatments

Tillage and no-tillage practices were tested on *Tephrosia candida* fallow because of its ability to suppress weeds. The experiment was a randomized complete block design with three replicates comparing two treatments: *Tephrosia candida* (conventional till) and *Tephrosia candida* (no till). Each main plot measured 9 x 18m, and were subdivided into two equal sub-plots measuring (4.5 x 9m), where one of the sub-plots was either tilled or not tilled. The main plots were separated by 1m strips. *Tephrosia candida* had previously been seeded directly through intercropping into a growing maize crop. Fallows were harvested, and together with litter fall collected during fallow growth together, were incorporated by conventional till to 15cm depth or by no-tillage where residues remained on the surface three days later. Uniform broadcasts of inorganic P (Triple Superphsophate, 100 kg P ha^{-1}) and K (Muriate of Potash fertilizer, 100 kg K ha^{-1}) were also done over all the plots thereafter on 15-16 March 2002. Maize was planted at 53,333 plants per hectare over a period of three days from 16 – 18 March 2002. Emissions of N_2O, CO_2 and CH_4 were measured prior to and periodically following fallow biomass additions. This was done concurrently with estimates of available soil N. Measurements were made between February - June 2002.

Sampling was carried out before, and after harvesting mulch from the fallow tree species, land preparation and incorporation of mulch biomass into the soil. Gas sampling was then carried out 3, 6, 10, 13, 17, 24, 38, 60 and 88 days after mulch incorporation into the soil between February and June 2002. Nitrous, methane and carbon dioxide gases emitted from the soil were sampled using gas tight syringes into evacuated 12 ml gas vials from closed flux chambers (0.2 m height by 0.3m diameter) installed into the soil as described by Smith *et al.* (1995). Two chambers per plot (treatment) were inserted to a soil depth of 50 mm, 12 days prior to biomass incorporation. Care was taken during insertion to minimize disruption to the soil especially to soil inside the chambers. The chambers were reinstalled after biomass incorporation after which, they remained *in situ* until the end of the experiment. The chambers were closed for one hour before sampling.

In order to minimise effects of diurnal variation in gas emissions, all gas sampling was done between 10 am – 12.00 noon on each occasion (Baggs *et al.,* 2000). The vials containing sampled gas were kept under refrigeration up to the time they were sent to Wye College in the United Kingdom for analysis using gas chromatography method. The gas samples were analysed for N_2O, CO_2 and CH_4 in an Agilent 6890 gas chromatograph fitted with an electron capture detector, flame ionisation detector and a methaniser. Column and detector temperatures were 50 and 250 ^oC, respectively. Gas chromatography using electron capture detector was used for N_2O analysis. The method is highly sensitive for N_2O analysis. Flame ionisation detector is highly sensitive and selective for organic gases and was used for the determination of CO_2 and CH_4.

Soil sampling and analysis

Bulk soil samples from six auger holes were taken at depth of 0 – 15cm at the same time of gas sampling for the purpose of determinating gravimetric soil water contents. A sub sample of thoroughly was immediately put into a prewieghed and labeled moisture tins. This was used for determination of soil water content. A second sub sample of about 20 g was then collected from the remaining soil in the bucket and placed in a plastic bag, labeled and sealed with sisal twine. The soil in the bags were analysed for mineral N and were stored in the refrigerator between collection and extraction (Dorich and Nelson, 1984).

During fallow growth, litter traps were installed in each fallow plot. These were used to quantify litter fall from each fallow treatment. Litter falls from the improved- and natural-fallow treatments were collected every two weeks for determination of chemical composition (or quality) and quantities of biomass incorporated. The fallow species were harvested at the onset of the long rains in March 2002. Harvesting was done between 1st and 4th March 2002. At fallow harvest the aboveground biomass was separated into woody biomass (main trunk and branches), foliage (leaves, small twigs) and pods. The woody material were removed from the plots and fresh weight of other plant components was determined and a sub sample taken to the laboratory for dry matter determination. The samples were oven dried at 40 ^{o}C for 72 hours. Dried sub samples were ground and passed through 20-mesh screen for further determination of chemical composition of residues.

Soil water content was determined gravimetrically. Fresh soil sample was weighed before being dried in an oven at 105 ^{o}C for 48 hours after which it was reweighed (Dorich and Nelson, 1984). Assessment of residue quality was done at Wye College in UK. Sub-samples of litter fall were analysed for dry-matter yield, total N and total C content using a C/N analyser coupled to a Europa 20/20 isotope ratio mass spectrometer. Lignin content was measured in an Ankom 220 fiber analyser. Total extractable polyphenol content were determined using Folin-Ciocalteu reagent in a method adapted from Anderson and Ingram (1993). All data was subjected to ANOVA using Genstat 5 Release 3.2 statistical program ($p<0.05$). Treatment means were separated using least significant differences test (LSD). Correlation of parameters were determined using excel data analysis tool.

Results and discussion

Effect of tillage and non-tillage on greenhouse gas emissions and N release in soil

Daily fluxes

Daily CO_2 and CH_4 fluxes did not differ significantly ($P>0.05$) between the treatments throughout the sampling period (Figure 1). Carbon dioxide and N_2O fluxes were, however, generally higher in the tilled treatment while, CH_4 fluxes were higher in the non-tilled treatment. Nitrous oxide fluxes from no-till treatment were only higher than from tilled treatment on day 3 after residue incorporation. Carbon dioxide fluxes from no-tilled treatment were higher than those from tilled treatment on day 3, 10 and 24 after residue incorporation. Nitrous oxide and CO_2 fluxes peaked on day 10 after residue application in both treatments. Daily fluxes of CH_4 were negative from non-tilled treatment on day 6, 10, 60 and 88 after biomass addition while, were only were negative on day 60 and 88 from the tilled treatment (Fig. 1). This indicates that there was greater production than consumption of CH_4 in the non-tilled treatment.

Total emissions

There was no significant difference ($P>0.05$) between treatments in the amount of total N_2O, CO_2 and CH_4 over 14,28, 48, 60 and 88 days after incorporation of residues (Appendix 10a, 10b and 10c). Total N_2O, CO_2 and CH_4 emitted over the sampling period

(99 days) were still not significantly different ($P > 0.05$) among the treatments. Higher total N_2O emissions were measured from non-tilled than tilled *Tephrosia* treatment over the first 14 days after residue incorporation; however, cumulative N_2O emissions over 99 days were lower from non-till treatment (432 N_2O-N Kg ha^{-1}) than from tilled treatment (584 N_2O-N Kg ha^{-1}) (Appendix 10a). Higher cumulative CO_2 and CH_4 emissions were measured from tilled than from non-tilled *Tephrosia* treatment throughout the sampling period. Cumulative CH_4 emissions reduced between 48th up to 88th day indicationg greater consumption than production of CH_4 in these treatments (Fig. 2).

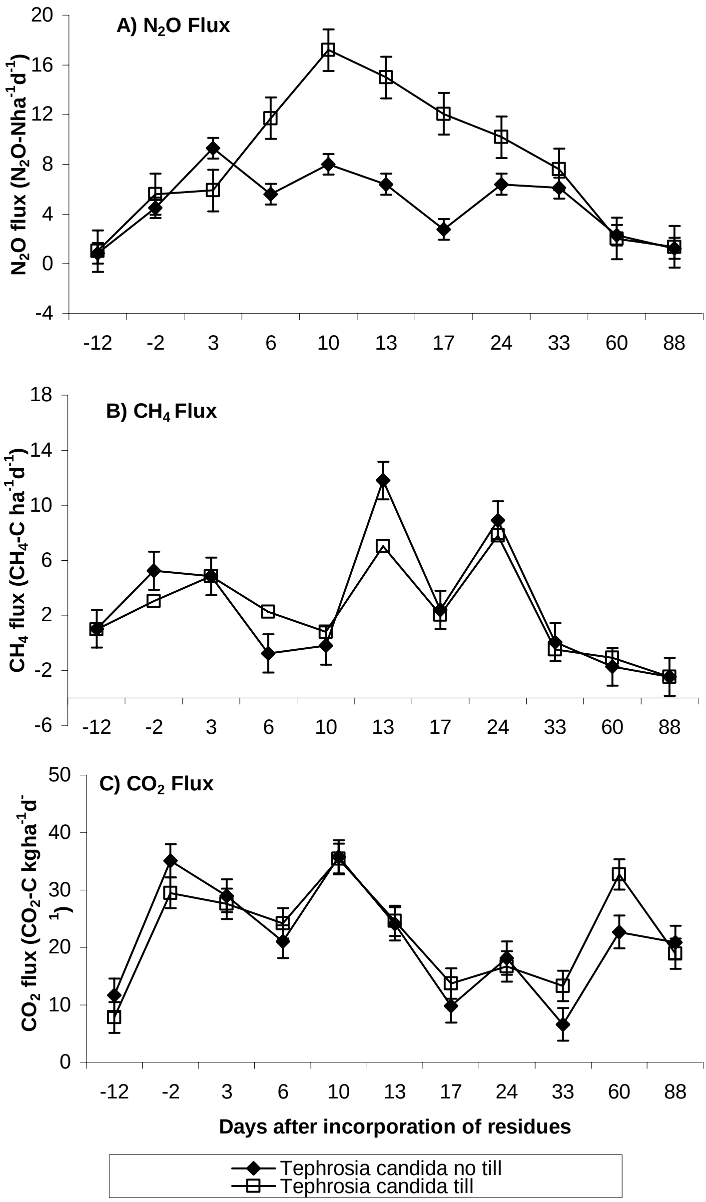

Fig. 1: Daily greenhouse gaseous emissions

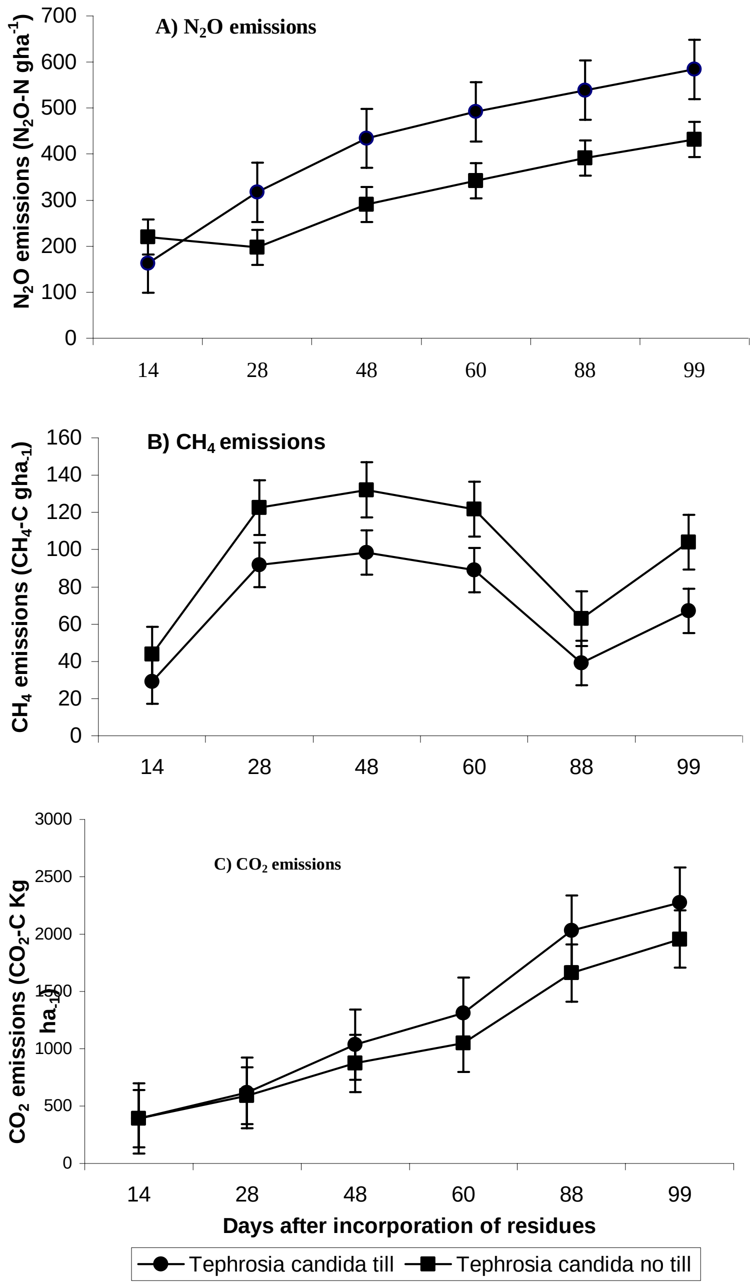

Fig. 2: Cumulative greenhouse gas emissions

Effect of tillage and non-tillage on N release after biomass incorporation

There was no significant difference ($P>0.05$) in the amounts of available total N, NO_3^- and NH_4^+ measured from tilled and untilled *Tephrosia* treatments throughout the sampling period (Figure 3). Total N measured was generally higher in the non-tilled treatment in the first 13 days after residue incorporation. Thereafter high total N was measured from tilled treatment. The dominant forms of N measured from non-tilled and tilled treatments were NH_4^+ and NO_3^-, respectively (Fig. 3).

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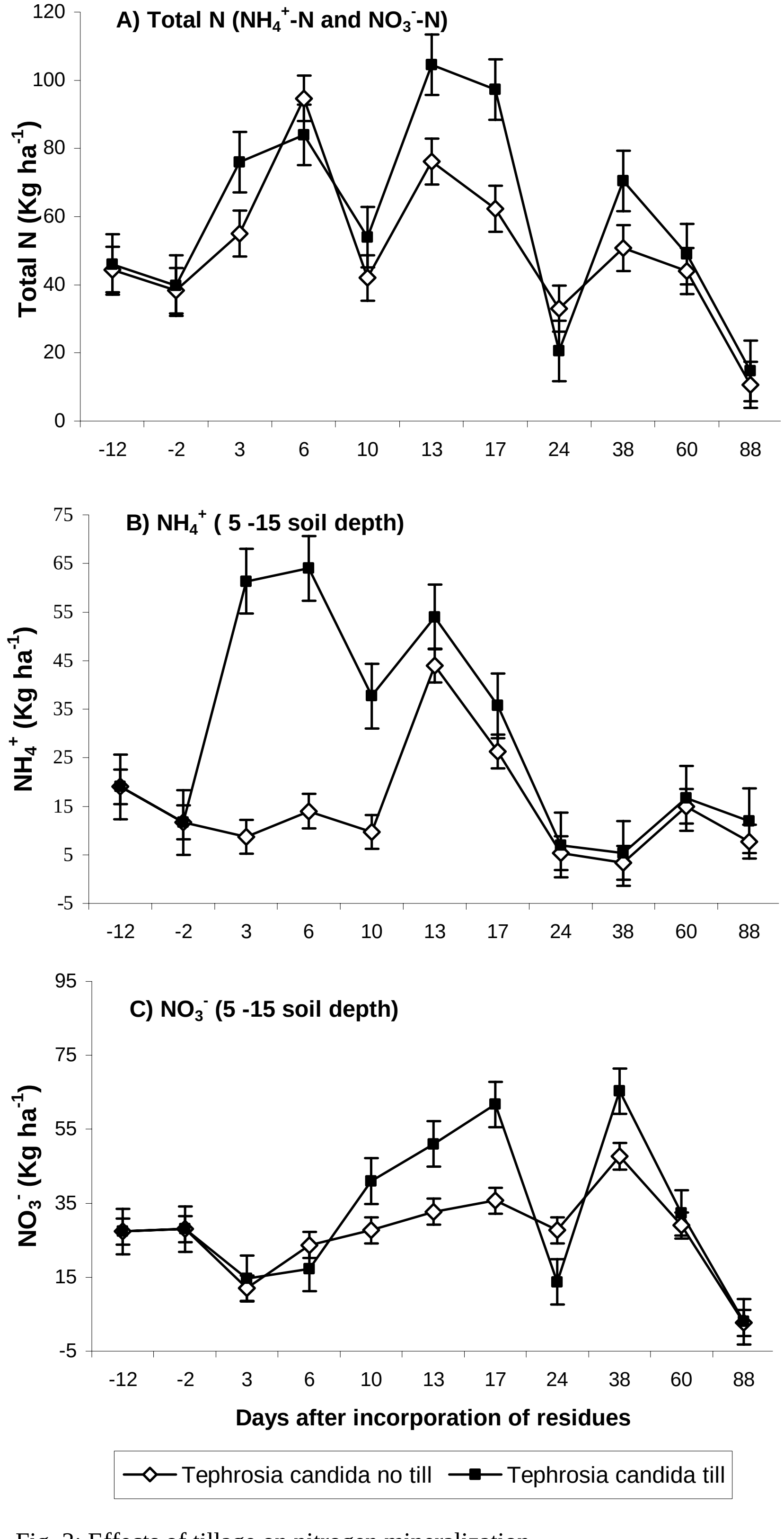

Fig. 3: Effects of tillage on nitrogen mineralization

Total N measured in soils did not differ significantly ($P>0.05$) between the treatments throughout the days of observation except on 17^{th} day after residue incorporation (Appendix 11a). On 17^{th} day total N from tilled *Tephrosia* was the highest over the sampling period and it was significantly higher ($P<0.05$) than from *Tephrosia* no-till treatment (Appendix 11a). There was no significant difference ($P>0.05$) in the amounts of NO_3^- in the tilled and non-tilled treatments throughout the experimental period (Appendix 11b). Tilled treatment had significantly higher ($P<0.05$) NH_4^+ amounts only on day 3 and 6 after residue incorporation (Appendix 11c). Generally higher total N, NO_3^- and NH_4^+ were measured from tilled than non-tilled treatment (Fig. 10). Nitrogen release at 5-15cm depth was also generally higher than from 0-5cm in both treatments

Effect of tillage on gaseous emissions

Aulakh *et al.* (1991), found that surface-placed residues resulted in lower initial rates of denitrification. This is in contrast with the results of this study where N_2O fluxes from no-till treatment were higher than from tilled treatment on day 3 after residue incorporation. Denitrification potential and rates in soils are controlled by amount of NO_3^- and C susceptible to mineralization (Aulakh *et al.,* 1991). Tillage accelerates decomposition of SOM with consequent increases in both available SOC and nitrate, which enhances denitrification. Tillage also temporary lowers soil moisture content, which affects decomposition rates and anaerobic state of soil (Li *et al.,* 1994). Available NO_3^- was higher and dominant N form in the tilled treatment thus enhancing denitrification potential and hence increased N_2O emissions. Higher available NO_3^- resulted from increased rate of nitrification. Nitrification is the biological oxidation of ammonia to nitrate. The process requires molecular oxygen and hence would readily take place in well –aerated soils in the tilled treatment (Tisdale and Nelson, 1975).

In well-drained neutral to slightly acid soils the rate of oxidation of NO_2^- to NO_3^- is higher than NH_4^+ to NO_2-. If the rate of NO_2^- formation is equal to or greater than that of NH_4^+, nitrate is the form that therefore accumulates (Tisdale and Nelson, 1975). The results of the study agree with this since NO_3^- was the dominant form of N in the tilled treatment. Higher initial CO_2 fluxes from non-tilled treatment could have occurred due to activity of soil microbes, which probably were disturbed on the tilled treatment. A significant proportion of soil microbial biomass may be directly killed by soil disturbances. Microbial activity was, however, short lived. Aulakh *et al.* (1991) also found that with surface placed residues initial CO_2 production was greater than corresponding incorporated residue treatments due to the activity of epiphytic fungi, while denitrification rates showed an opposite trend.

Methane (CH_4)fluxes were generally higher from non-tilled than tilled treatment, probably due to enhanced anaerobic conditions in the non-tilled treatment. In the non-tilled treatment, CH_4 may have been microbially produced through methanogenesis process. The major pathways of CH_4 production in anaerobic conditions involve: (i) the reduction of CO_2, with H_2, fatty acids, or alcohols being the hydrogen donors; and (ii) the transmethylation of acetic acid or methyl alcohols by methane-producing bacteria (Verchot *et al.,* 2004). In the tilled treatment where aerobic conditions were enhanced, CH_4 may have been oxidised by bacteria through methanotrophy process. Methanotrophy is a biochemical process, which is dominant in aerobic soils or upland soils. In these soils, oxidation generally exceeds production and there is a net uptake by the soil of CH_4 atmosphere (Verchot *et al.*, 2004).

Initial higher emissions in the non-tilled treatment could have been due to N_2O produced near the surface diffusing readily out of the soil into the atmosphere, where as N_2O produced after cultivation, may have taken longer to diffuse from the soil providing more opportunity for reduction to N_2, before reaching the atmosphere (Arah *et al.*, 1991). N_2O emissions from the study contrasts emissions of N_2O from the temperate systems that have been generally reported to be higher from undisturbed, no till, than from cultivated soils (Baggs *et al.*, 2002).

Higher initial CO_2 emissions in the tilled treatment could have been caused by immediate creation of anaerobic conditions conducive for denitrification and methanogenesis under the residues by increased water content (Aulakh *et al.*, 1991). Anaerobic conditions enhance anaerobic decomposition, which leads to the formation of methane and carbon dioxide gases (Tan, 1994). Thereafter the aerobic conditions in the tilled treatment lead to the oxidation of CH_4 to CO_2. Higher CH_4 emissions could have been produced microbially in the anaerobic conditions under no-tilled treatment. Microbial oxidation of CH_4 to CO_2 was very likely reduced by anaerobic conditions in the non-tilled treatment and hence increased accumulation of CH_4. The margins between CH_4 emissions from non-tilled and tilled treatment were higher between 28th and 60th day. This could have been caused by higher rainfall (445mm) experienced during this period, which enhanced anaerobic conditions in the non-tilled treatment and hence reduced oxidation of CH_4 to CO_2.

No-tillage of *Tephrosia* resulted in an estimated reduction in emissions of 919 g N_2O-Nha^{-1}yr^{-1} and 318 Kg CO_2-Cha^{-1}yr^{-1} and increased CH_4 emissions of 144 g CH_4-Cha^{-1}yr^{-1}. Chikowo *et al.* (2003) also measured lower N_2O emission from non-tilled than from tilled *Sesbania* residues over four weeks in an improved fallow system in Zimbabwe. Although tillage increased emissions of N_2O and CO_2 there was no significant difference between tillage and no-tillage practices. This may have been due to the fact that the no-till treatment had not been established long enough to cause significant accumulation of organic matter on the soil surface (Six et *al.*, 2002). Similarly Millar, (2002) found no significant effect of tillage following application of *Macroptilium atropurpureum* residues to an oxisol in Western Kenya. Aulakh *et al.* (1991) also found that cumulative CO_2 and N_2O losses were not significantly different with respect to crop residue placement.

Effects of tillage effect on N release

Tilled treatment had generally higher NO_3^--N pools at 0-5 cm soil depth compared with non-tilled treatment. This indicates that net nitrification rates were higher in the tilled treatment, which resulted in higher cumulative N_2O emissions. The results of the study are in agreement with findings of Neill *et al.* (1995), that depth affects the net nitrification rates and these rates are higher at 0-5 cm depth. On the other hand, the soil NH_4^+ remained relatively high at soil depth 0–5 cm for non-tilled treatment, which indicates that nitrification potential was low and hence reduced denitrification potential. In 5-15 cm depth there was no dominant form of mineral N in the tilled treatment, which indicates that net mineralization and nitrification were more or less equal. In the no-till treatment NH_4^+ form dominated. This resulted from reduced soil aeration, which reduced nitrification potential. Nitrification normally takes place under oxygenated conditions.

In the study, tillage did not affect significantly nitrogen availability both at 0- 5 and 5-15 cm depth; however, N levels were generally higher at 5 –15 cm soil depth. At 15 cm higher N availability was most likely due to reduced denitrifier activity. Soil organic matter, especially easily decomposable fraction, is an important source of soluble carbon and nitrate for denitrification (Li *et al.*, 1994). As fertilizers are applied deeper into the soil, they become less available to denitrifying bacteria, which are active near the surface where carbon substrate is more abundant and saturated conditions are more frequent.

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References

Anderson, J.M. and Ingram J.S.I. (eds) (1993). Tropical Soil Biology and Fertility: A handbook of methods, second edition. CAB International, United Kingdom, 1-89.

Arah, J.R.M., Smith, K.A., Crichton, I.J. and Li, H.S. (1991). Nitrous oxide production and denitrification in Scottish soils. *Journal of Soil Science* 42, 351-367.

Aulakh, M.S. and Doran J.W. (1991). Effectiveness of acetylene inhibition of N_2O reduction for measuring denitrification in soils of varying wetness. *Communications in Soil Science and Plant Analysis* 21, 2233-2243.

Aulakh, M.S., Doran, J.W., Walters, D.T., Mosier, A.R. and Francis, D.D. (1991). Crop residue type and placement effects on denitrification rates in conventional and zero-tilled soils. *Soil Science Society of America Journal* 48, 790-794.

Baggs, E. M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G. (2003). Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant Soil* 254, 361-370.

Baggs, E.M., Cadisch, G., Verchot, L.V., Millar, N. and Ndufa, J.K. (2002). Environmental impacts of tropical agricultural systems: N_2O emissions and organic matter management. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok.

Baggs, E. M., Millar, N., Ndufa, J. K. and Cadisch, G. (2001). Effect of residue quality on N_2O emissions from tropical soils. In: Rees, R. M., Ball, B. C., Campbell, C. D. and Watson, C. A. (Eds). Sustainable Management of Soil Organic Matter. CAB International, 120-125.

Baggs, E.M., Rees R.M., Smith, K.A. and Vinten, A.J.A. (2000). Nitrous oxide emission from soils after incorporating crop residues. *Soil use and Management* 16, 82 –87.

Baldwin, J.T., Olson, R. K. and Reiners, W. A. (1983). Protein binding phenolics and the inhibition of nitrification in subalpine balsam fir soil. *Soil Biology and Biochemistry* 15, 419-423.

Barbara, L. N. (1994). The effect of temperature, oxygen and salinity and nutrients enrichment on estuarine denitrification rates measured with modified nitrogen gas flux techniques. *Environmental Abstracts*, Volume. 24, numbers 1 – 12, 94 – 03195.

Beauchamp, E.G. (1997). Nitrous oxide emission from agricultural soils. *Canadian Journal of Soil Science* 77,113-132.

Bremner, J.M. and Blackmer, A.M. (1982). Composition of Soil Atmosphere. In: Page, A.L., Miller, R.H. and Keeney, D.K. (eds). Methods of Soil Analysis: Part 2: Chemical and Microbiological properties, 2nd edition. Madison, Wisconsin, USA.

Bormann, F.H. and Likens, G.E. (1979). Pattern and process in a forested ecosystem. New York, USA: Springer-Verlag.

Bouwman, A.F. (1996). Direct emission of nitrous oxide from agricultural soils. *Nutrient Cycling in Agroecosystems* 46, 53-70.

Bouwman, A.F. (1990). Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman, A.F. (ed). Soils and the greenhouse effect. John Wiley and Sons, New York. 61-127.

Bouwman, A.F., Fung, L., Mathews, E. and John, J. (1993). Global analysis of the potential for N_2O production in natural soils. *Global Biogeochemical Cycles* 7, 557-597.

Buresh, R.J. and Tian, G. (1997). Soil improvement by trees in sub-Saharan Africa. *Agroforestry Systems* 38, 51-76.

Cabrera, M. L. (1994). Water content effect on denitrfication and ammonia volatilisation in poultry litter. *Environmental extracts* 1994, Volume 24, numbers 1 –12, 94 – 16765.

Castro, M. S., Peterjohn, W.T., Melillo, J.M. and Steudler, P.A. (1994). Effects of nitrogen fertilization on the fluxes of N_2O,CH_4 and CO_2 from soils in a Florida slash pine plantation. *Canadian Journal of Forest Research* 24, 9-13.

Chikowo, R., Mapfumo, P., Nyamugafata, P. and Giller, K .E. (2003). Mineral N dynamics, leaching and nitrous oxide losses following two-year improved-fallows on a sandy loam soil in Zimbabwe. *Plant and Soil*.

Crill, P.M., Keller, M., Weitz, A., Grauel, B. and Veldkamp, E. (2000). Intensive field measurements of nitrouss oxide emissions from a tropical agricultural soil. *Global Biogeochemical Cycles* 14, 85-95.

Crutzen, P.J. and Ehhalt, D.H. (1977). Efects of nitrogen fertilizers and combustion on the stratospheric ozone layer. *Ambiology* 6, 112-117.

Dacqui, L.P., Dodero, A., Santi, C., Pezzarossa, B., Pini, R., Petacco, F., Scatena, M., Risaliti, R. and Mazzoncini, M. (2002). The soil ecosystem and its interaction with C fluxes on the Isle of Pianosa. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Volume 1, Symposium 10, paper 2095.

Davidson, E.A. (1991). Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In*:* Rogers, J. E. and Whitman, W. B. (eds). Microbial production and consumption of greenhouse gases: Methane, Nitrogen oxides and Halomethanes. *American Society of Microbiology*, Washington, D.C, 219-236.

Davidson, E. A. and Kingerlee, W. (1997). A global inventory of nitric oxide emissions from soils. *Nutrient Cycling in Agroecosystems* 48, 37-50.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V. and Veldkamp, E. (2000). Testing a conceptual model of soil emissions of nitrous and nitric oxide. *Bioscience*, 50, 667-680.

de Catanzaro, J. B. and Beauchamp, E. G. (1985). The effect of some carbon substrates on denitrification rates and carbon utilization in soil. *Biology and Fertility of Soils* 1, 183-187.

Denmead, O.T. (1991). Sources and Sinks of greenhouse gases in the soil-plant environment. In: Henderson-Sellers A. and Pitman A.J. (eds). Vegetation and Climate interactions in semi-arid regions. *Vegetation* 91, 73-86. Kluwer Academic Publishers, Belgium.

Doran, J. W. (1980a). Microbial changes associated with residue management and reduced tillage. *Soil Science Society of America Journal* 44, 518-524.

Dorich, R.A, and Nelson, D.W. (1984). Evaluation of manual cadmium reduction methods for determination of nitrate in potassium chloride extracts of soils. *Soil Science Society of America Journal* 48, 72-75.

Duxbury, J. M. (1994). Significance of agricultural sources of greenhouse gases. *Fertilizer Research* 38, 151-163, 1994. ©1994 Kluwer Academic Publishers, Netherlands.

Eric, A. D. (1991). Soil water content and the ratio of nitrous oxide to nitric oxide emitted from soils. *Environment Abstracts*, Volume 24, numbers 1–12, 94 – 17538.

Faniran, A. and Areola, O. (1978). Essentials of soil study with special reference to tropical areas. Heinenmann Education Ltd. Nairobi.

Feller, C. (2002). Relevance of organic matter forms associated to particle size fractions for studying efficiency of carbon sequestration: Examples for Tropical agroecosytems. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Vol.1 Symposium 5, paper 1736.

Firestone, M.K., Firestone, R. B. and Tiedje, J. M. (1980). Nitrous oxide from soil denitrification: Factors controlling its biological production. *Science* 208,749-751.

Fox, R. H., Myers, R. J. K. and Vallis, I. (1990). The nitrogen mineralization rate of legume residues in soils as influenced by their polyphenol, lignin and nitrogen contents. *Plant and Soil* 129, 251-259.

Frankenberger, W.T. and Abdelmagid, H. M. (1985). Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soils. *Plant and Soil* 87, 257-271.

Fuzhu, Z. (1993). Measurement of nitrous oxide emission dynamics from Soil. *Environment Abstracts*, Volume 24, Numbers 1 –12, 94 – 04441.

Gathumbi, S.M., Cadish, G. and Giller, K.E. (2002a). ^{15}N natural abundance as a tool for assessing N_2- fixation of herbaceous, shrub and tree legumes in improved fallows. *Soil Biology and Biochemistry* 34, 1059-1071.

Giller, K. E. and Cadisch, G. (1995). Future benefits from biological nitrogen fixation in agriculture: An ecological approach. *Plant and Soil* 174, 255-277.

Goreau, T.J. and de mello, W.Z. (1988). Tropical deforestation: Some effects on atmospheric chemistry. *Ambiology* 17, 275-281.

Gray, T.R.S. and Williams, S. T. (1971). Soil Microorganisms. T and A Constable Ltd.,Edinburgh, Britain.

Gulbert, H. (2002). Kinetics of soil organic matter particle size and consequences for the cation exchange capacity of Alfisols. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Symbosium 47, Paper 22.

Handayanto, E., Cadish, G. and Giller, K. E. (1994). Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. *Plant and soil* 160, 237-248.
Haslam, E. (1989). Plant polyphenols: Vegetable tannins revisited. Cambridge University Press, Cambridge, United Kingdom.
Hernault, C. and Germon, J.C. (2002). NOE, a model for forecasting N_2O emissions by nitrification and denitrification in soils. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Volume 1, Symposium 7, paper 2271.
Hoekstra, D. (1988). Summary of the zonal agroforestry potential and research across land use systems in the highlands of Eastern and Central Africa. *AFRENA Report* 5, *International Centre For Research In Agroforestry* Nairobi, Kenya.
Hoekstra, D. and Corbett, J.D. (1995). Sustainable Agriculture growth for the highlands of East and Central Africa: Prospects to 2020. *International Food Policy Research Institute*, Washington DC.
Intergovernmental Panel on Climate Change. (2001). In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Oai, X., Maskell, K. and Johnson, C.A. (eds). Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom.
Kachaka, S., Vanlauwe, B. and Merckx, R. (1993). Decomposition and nitrogen mineralization of prunings of different quality. In: Mulongoy, K. and Merckx, R. (eds). Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. 199-203. John Wily and Sons, Chichester, United Kingdom.
Kang, B.T., Wilson, G. F. and Lawson, T.L. (1984). Alley cropping, a stable alternative to shifting cultivation. *International Institute of Tropical Agriculture*, Nigeria.
Keeney, D. R. (1982). Nitrogen management for maximum efficiency and minimum polution. In: Stevenson F. J. (ed.), Nitrogen in Agricultural Soils, *American Society of Agronomy*, 605-649, Madison W1.
Keller, M., Mitre, M. E. and Stallard, R. F. (1990). Consumption of atmospheric methane in soils of Central Panama: Effects of agricultural development. *Global Biogeochemical Cycles* 4, 21-27.
Keller, M., Kaplan, W. A. and Wofsy, S .C. (1986). Emissions of N_2O, CH_4 and CO_2 from tropical forest soils. *Journal of Geophysical Research* 91, 11791-11802.
Kinzig, A.P and Sokolow, R.H. (1994). Human impact nitrogen cycles. *Physics Today* 47, 24-31.
Ko, M.K.W., Sze, N.D. and Weinstein, D.K. (1991). Use of satellite data to constrain the model-calculated atmospheric lifetime for N_2O: Implications for other trace gases. *Journal of Geophysical Research* 96, 7547-7552.
Kroeze, C., Mosier, A. and Bouwman, A. F. (1999). Closing the global N_2O budget: A retrospective analysis 1500-1994. *Global Biogeochemical Cycles* 13, 1-8.
Kwesiga, F. R. and Coe, R. (1994). The effect of short rotation *Sesbania Sesban* planted fallows on Maize yields. *Forest Ecology and Management* 64, 199-208.
Lal, R. (2002). Offsetting global CO_2 emissions by soil carbon sequestration. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science*

Conference 'Soil Science: Confronting New Realities in the 21st Century'. International Soil Science Society, Bangkok, Thailand, Volume 4, Symposium 45, paper 1209.

Li, C., Frolking, S.E., Harris, R. C. and Terry, R.E. (1994). Modelling Nitrous Oxide Emissions From Agriculture: A Florida Case Study. In: *Chemosphere*, Volume 28, Number 7, 1401-1415. Elsevier Science Limited. Great Britain.

Lijinsky, W. (1977). How nitrorsamines cause cancer. *New Scientist* 27, 216-217.

Linn, D. M. and Doran, J .W. (1984). Aerobic and anaerobic microbial populations in no-till and plowed soils. *Soil Science society of America Journal* 48, 794-799.

Lupwayi, N. Z., Rice, W. A. and Clayto, G. W. (1999). Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation. *Canadian Journal of Soil Science* 79, 273-280.

Mafongoya, P.L, Giller, G.E. and Palm, C.A. (1998). Decomposition and nitrogen release patterns of tree prunings and litter. *Agroforestry Systems* 38, 77-97.

Mellilo, J.M., Steudler, P,A., Aber, J. D. an Bowden, R. D.(1989). Atmospheric deposition and nutrient cyling. In: Andrae, M.O. and Shimel, D.S. (eds). Exchange of trace gases between terrestrial ecosystems and the atmosphere. John wiley and sons Ltd., Chichester, 63-280.

Mills, H. A. and Jones, J. B. Jr. (1996). Plant Analysis Handbook II: A practical sampling, preparation, analysis, and interpretation guide. Micro Macro Publishing, Inc. Athens, Georgia USA.

Millar, N. (2002). The effect of improved fallow residue quality on nitrous oxide emissions from tropical soils, PhD thesis, university of London.

Millar, N. and Baggs, E. M. (2004). Chemical composition, or quality, of agroforestry residues influences N_2O emissions after their addition to soil. *Soil Biology and Biochemistry* 36 (2004), 935-943.

Millar, N., Ndufa, J. K., Cadisch, G. and Baggs, E. M. (2003a). Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. *Global Biogeochemical Cycles* (submitted).

Molongoy, K. and Merck, R. (1997) (eds). Soil Organic Matter dynamics and sustainability of Tropical agriculture. John Willey and Sons Ltd., New York.

Mosier, A.R. (1998). Soil Processes and climate change. *Biology and Fertility of Soils* 27, 221-229.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O. and Minami, K. (1998). Assessing and mitigating N_2O emissions from agricultural soils. *Climatic Change* 40, 7-38. Kluwer Academic Publishers, Netherlands.

Nandasena, K.A. (2002). Nitrogen status and it's supplying capacity of tropical soils of Sri Lanka. The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Volume 1, Symposium 5, Paper 1101.

Nair, R.P.K. and Nair, V.D. (2002). Carbon sequestration in agroforestry systems. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference 'Soil Science: Confronting New Realities in the 21st Century'*. International Soil Science Society, Bangkok, Thailand, Volume 1, Symposium 10, Paper 989.

Neill, C., Piccolo, M. C., Steudler, P. A., Mellilo, J. R., Feigl, B. J. and Cerri, C.C. (1995). Nitrogen dynamics in soils of forests and active pastures in the Western Brazilian Amazon basin. *Soil Biology and Biochemistry*, Volume 27, Number 9, 1167-1175, Copyright of 1995 Elsevier Science Ltd, Great Britain.

Nyambati, R.O. (2000). Soil P fractions as influenced by Phosphorous and N sources on two sites in Western Kenya. Msc Thesis, Moi University Eldoret, Kenya.

Palm, C.A. (1995). Contribution of agroforetry trees to nutrient requirements of intercropped plants. *Agroforestry Systems* 30, 105-124.

Palm, C. A. and Sanchez, P. A. (1991). Nitrogen release from the leaves of some tropical legumes as affected by their liginin and polyphenolic contents. *Soil Biology and Biochemistry* 23, 83-88.

Palm, C. A., Alagre, J. C., Arevalo, L., Mutuo, P., Mosier, A. and Coe, R. (2002). Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. *Global Biogeochemical Cycles* 16, 1073-1085.

Palm, C. A., Gachengo, C. N., Delve, R.J., Cadisch, G. and Giller, K. E. (2000). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic residue database. *Agriculture, Ecosystems and Environment* 1692, 1-16.

Palm, C.A. and Rowland, A.P. (1997). A minimum dataset for characterisation of plant quality for decomposition. In: Cadish, G. and Giller K.E. (1997) (eds). *Driven by Nature,* 379-392 Wallingford, CAB International.

Paul, J.W. and Beauchamp, E.G. (1989). Denitrification and fermentation in plant residue-amended soil. *Biology and Fertility of soils* 7, 303-309.

Pearce, F. (1989). Methane: the hidden greenhouse gas. *New Scientist*, 6 May 1989,19-23.

Pearrman, G.I. and Fraser, P.J. (1988). Sources of increased methane. *Nature* 332,482-490.

Postgate, J.R. (1982). The fundamentals of nitrogen fixation. Cambridge University Press, New York.

Rasmussen, R.A, Krasnec, J. and Pierotti, D. (1976a). N_2O analysis in the atmosphere via electron capture- gas chromatography. *Geophysical research letter* 3, 615 –618.

Robinson, J.B.D. (1957). The critical relationship between soil moisture content in the region of wilting point and mineralization of natural soil nitrogen. *Journal of Agricultural Science* (Cambridge) 49, 100-105.

Rommelse, R. (2000). Economic assessment of biomass transfer and improved fallow trials in Western Kenya. Natural Resource Problems, Priorities and Policies programme. *Working Paper 2001-3, International Centre for Research In Agroforestry*, Nairobi, Kenya.

Sanchez, P. A. (1999). Improved-fallows come of age in the tropics. *Agroforestry Systems* 47, 3-12.

Sanhez, P.A. Shepherd, K., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.N., Mokwunye, A.U., Kwesiga, F,R., Nderitu, C.G. and Woomer, P.L. (1997). Soil Replishment in Africa: An investiment in Natural Resource Capital. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds). Replenishing Soil Fertility in Africa: *Soil Science Society of America, Special Publication number* 51, ICRAF Madison, Wisconsin USA.

Scott, D.E., Elliot, L.F., Papendick, R.I. and Campbell, G.S. (1986). Low temperature or low water effects on microbial decomposition of wheat residues. *Soil Biology and Biochemistry* 18, 577-582.

Shen, S.M., Hart, P.B.S., Powlson, D. S. and Jenkinson, D.S. (1989). The nitrogen cycle in the broad balk wheat experiment: ^{15}N-labelled fertilizer residues in the soil and in the soil microbial biomass. *Soil Biology and Biochemistry* 21, 529-533.

Six, J., Feller, C., Dene, F. K., Ogle, S. M., Sa, J.C.D. and Albrecht, A. (2002). Soil organic matter, biota and aggregation in temperate and tropical soils – Effects of no-tillage. *Agronomie* 22, 755-775.

Smith, K.A., Clayton, H., McTaggart, I.P., Thomson, P.E., Arah, J.M. and Scott, A. (1995). The measurement of nitrous oxide emissions from soil by using chambers. *Philosophical Transactions of the Royal Society*, London, A 351 327-338.

Soil Survey Staff. (1999). Soil Taxonomy: A basic Classification for making and interpreting soil surveys, second edition. USDA, Washington DC.

Steudler, P. A., Bowden, R. D., Melillo, J. M. and Aber, J. D. (1989). Influence of nitrogen fertilisation on methane uptake in temperate forest soils. *Nature* 341, 314-316.

Stevenson, F.J. (1986). *Cycles of Soil Carbon, Nitrogen, Phosphorus, Sulfur and Micronutrients*. John wiley and sons Ltd., New York, USA.

Swain, T.1. (1979). Tannins and Lignins. In: Rosenthal, G.A. and Janzen, D.H. (eds). Herbivores: their interaction with secondary plant metabolites. Academic Press, New York, 657-682.

Swift, M.J., Heal, O.W., and Anderson, J.M. (1979). Decomposition in Terrestrial ecosystems. *Studies in Ecology*, Volume 5. Blackwell Scientific Publications, Oxford, United Kingdom.

Swinkels, R.A., Franzel, S., Shepherd, K.D., Ohlsson, E. and Ndufa, J.K. (1997). The economics of short rotation improved fallows: Evidence from areas of high population density in Western Kenya. *Agricultural Systems* 55, 99-121.

Tan, K.H. (1994). Environmental Soil Science. Marcel Dekker Inc., New York.

Tengnas, B. (1994). Agroforestry Extension Manual for Kenya. *International Centre for Research in Agroforestry*, Nairobi. English Press, Nairobi, Kenya.

Thomas, K. and Balwant, S. (2002). Carbon Storage and Australian Vertisols. In: International Union of Soil Science, The Soil and Fertilizer Society of Thailand, Ministry of Agriculture and Cooperatives of Thailand (eds*) 17th World Congress of Soil Science Conference* '*Soil Science: Confronting New Realities in the 21st Century*'. International Soil Science Society, Bangkok, Thailand, Volume l, Symposium 10, paper 1546.

Tiedje, J. M., Sexstone, A. J., Parkin, T. B., Revsbech, N. P. and Shelton, D. R. (1984). Anaerobic processes in soil. *Plant Soil* 76, 197-212.

Tisdale, S. L. and Nelson, W. L. (1975). Soil fertility and fertilizers, third edition. Macmillan publishing co. inc.

Topp, E. and Pattey, E. (1997). Soils as sources and sinks for atmospheric methane. *Canadian Journal of Soil Science*, 77, 167-178.

Verchot, L.V., Mosier, A., Baggs, E.M. amd Palm, C. (2004). Soil-atmosphere gas exchange in tropical agriculture: Contributions to climate change. In: Noordwijk, M.V., Cadish, G. and Ong, C.K. (eds). Below-ground interactions in tropical agroecosystems: Concepts and models with multiple plant components. CABI publishing, United Kingdom.

Verchot, L.V., Davidson, E.A., Cattanio, J. H. and Ackerman, I. L. (2000). Land-use change and biogeochemical controls on methane fluxes in soils of eastern Amazon. *Ecosystems* 3, 41-56.

Verchot, L.V., Davidson, E.A., Cattanio, J.H., Ackerman, I.L., Erickson, H.E. and Keller, M. (1999). Land use change and biochemical controls of nitrogen oxide emissions from soils in eastern Amazon. *Global Biogeochemical cycles*, 13, 31-46.

Webster, P. J. (1985). Great events, grant experiments: Man's study of the variable climate – Part II: Prospects of a warming earth. *Earth and Mineral Sciences*, Volume 55, 21-24.

Weitz, A.M., Linder, E., Frolking, S., Crill, P.M. and Keller, M. (2001). N_2O emissions from humid tropical agricultural soils: effects of soil moisture, texture and nitrogen availability. *Soil Biology and Biochemistry* 33, 1077-1093.
Wild, A. (1972). Nitrate leaching under bare fallow at a site in northern Nigeria. *Journal of Soil Science* 23, 315-324.
World Meteorological Organisation, (1987). The global climate system autumn 1984 – spring 1986. CSM R84/86. WMO, Geneva.