Inorganic Fertilizer vs. Cattle Manure as Nitrogen Sources for Maize (*Zea Mays* L.) in Kakamega, Kenya

Melissa C. Herman*, Dr. Rattan Lal
Department of Environment and Natural Resources

Despite worldwide efforts, food security has not improved in Sub-Saharan Africa (SSA) since 2000 when the United Nations published its Millennium Development Goals. Inconsistent and inefficient soil management by farmers is a major contributing factor. Maize (Zea Mays L.) is a staple foods Kenya, but neither fertilizer nor manure are economically available to farmers in sufficient quantities. The objective of this study was to compare an inorganic fertilizer with an equivalent dry-weight rate of N from cattle manure for maize production in Western Kenya using six maize plots at four farm sites.

Results from this study conducted in 2007 showed that inorganic fertilizer produced grain yields 68% higher than that from manure. However, yields were low. Analysis of maize leaves at initial silking stage showed that many nutrients were below the critical levels. Further estimates showed that up to twice the amount of N applied to the field is exiting the field via maize grain and stover, thereby creating a negative nutrient budget. For these reasons, it can be concluded that the recommended N rate of 50 kg/ha is not enough to either sustain crop yields or restore the degraded soil systems.

Introduction

In 2000, the United Nations launched its Millennium Development Goals, creating a strategic plan for addressing problems such as health, education, equality, and environmental sustainability in countries classified as developing (United Nations, 2008). In the 2008 report, it was stated that little progress, if any, had been made in reducing the level of poverty in Sub-Saharan Africa (SSA). Additionally, the world population is expected to rise to 8.9 billion by 2050, most of which will occur in developing regions (United Nations Economic and Socials Affairs, 2004). Therefore considerable efforts will need to be made to ensure the level of poverty and food insecurity does not worsen in upcoming decades.

Kenya's population is predicted to increase from 30.5 million in 2000 to 45.8 million by the year 2100 (United Nations Economic and Social Affairs, 2004). Because population growth tends to increase demographic pressures for land resources, increases in food production need to come from increases in crop yields rather than through extensification of land resources (Lal, 2008). However, Kenya's increase in agricultural output is more a result of extensification rather than intensification. Land under cultivation for cereal crops has been steadily increasing in Kenya since about 1960 through 2006 (Fig. 1), but cereal yields have not changed in the 20 years ending in 2007 (World Bank, 2007). In Kenya, maize (*Zea mays* L.) is the staple food crop, encompassing approximately 1.6 million hectares (mha). In Western Kenya, maize is also grown as a cash crop, even

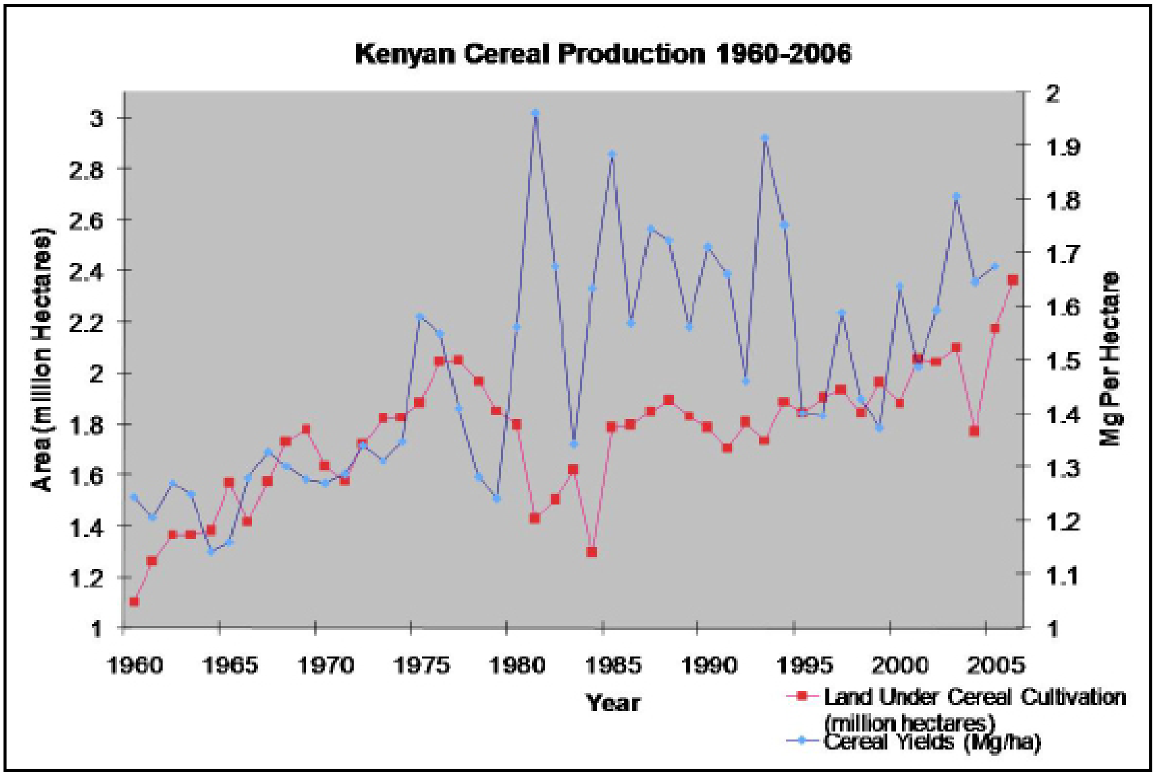

Fig 1 Kenya Cereal Production 1960-2006 (created from World Bank, 2007).

when production is not high enough to meet consumption needs, because the region's economy relies so heavily on agriculture (Salasya et al., 1998). In the Kakamega District of Western Kenya where the project was located, the area is only able to produce about 50% of its consumption needs during a normal year (Mwale and Wambua, 2008).

Soil productivity is stagnant or in decline, potentially leading to decreased food security and increased poverty. There are many causes for this dilemma, but poor soil and nutrient management are major contributors. In a study conducted by Kimetu et al. (2008) on humic Nitisols of Central Kenya, inorganic fertilizer was applied to maize fields of varying levels of soil degradation, due to the number of years of continuous cultivation since deforestation. Results showed that both grain yield and total biomass production decreased by 66% during the first 35 years of cultivation and remained low despite inorganic fertilizer applications. The soils of SSA have the capacity and ability to be productive, if managed correctly, as declines in soil quality are more often related to "how" than "what" crops are grown (Lal, 2009a).

A major limiting factor for nutrient management for Kenyan farmers is access to fertilizers, specifically sources of nitrogen (N) for maize production, as fertilizer use is not consistent (Table 1). In a study conducted by Salasya et al. (1998), 133 farmers in Western Kenya were surveyed, and only 34.6% reported to have used fertilizer; 68% of the surveyed farmers reportedly used manure, citing fertilizer prices as a deciding factor. Soil fertility will suffer whenever nutrient removal exceeds the soil systems nutrient inputs (Lal, 2009b). In response to increasing levels of both soil degradation and food insecurity, it is critical to secure both organic and inorganic nutrient sources for crop production and maximize their efficiency.

It is widely documented that manure has positive long-term effects on maize yield by improving the soil structure in addition to supplying crops with nutrients. Mucheru-Muna et al. (2007) conducted a seven-season study in Kenya, and reported that plots receiving a manure treatment had increased pH, SOC concentration, and exchangeable Ca^{2+} and K^{+}. In another study conducted by Kihanda et al. (2006), crop yields increased and then stabilized when manure was applied for seven consecutive years.

In a strict comparison between inorganic and organic nutrient sources, the available literature indicates mixed results. Studies by Kihanda et al. (2006) reported that, over a seven-year period, Kenyan maize yields were similar in plots treated with goat manure to those receiving inorganic fertilizer. However, Mallory and Griffin (2007) observed that inorganic N applications became available quicker than N applications from manure. Nziguheba et al. (2005) studied the effects of various organic treatments on biochemical properties, nutrient cycling, soil fertility, and crop yield. Results showed that the organic treatments improved several soil parameters, but there were only a few cases where the organic treatments had a greater effect than the inorganic treatments. This trend was primarily observed at higher

1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
33	63	51	53	54.2	69.9	80	62.7	118.5	74.6	38.9

Table 1 Kenya's yearly N fertilizer consumption from 1995-2005, thousand metric tons (United Nations Statistical Division, 2008).

rates of N mineralization and was dependent on the specific application rate of the inorganic fertilizer.

Kimetu et al. (2004) showed that maize biomass yields were higher from organic N sources than from urea during a season with inadequate rainfall. Grain yields were poor with all sources, but it was estimated that the organic N sources acted as mulch, thus increasing water retention in the soil and resulting in higher biomass yields in comparison to inorganic N sources.

Kapkiyai et al. (1999) studied maize yields and soil quality under different management strategies using combinations of inorganic fertilizer, cattle manure, and maize stover retention during an 18-year experiment. They showed that all management strategies decreased soil organic matter (SOM) over time, with the greatest loss from inorganic fertilization and stover removal; when manure was added and maize stover retained, the rate of SOM depletion was less. Little significant differences were observed between treatments regarding total SOC in the soil, but particulate organic matter (POM) was greatly influenced by management and was a strong indicator of soil fertility, particularly N mineralization. A regression of SOC and crop yields indicated that every t C per hectare conserved through management resulted in an average maize yield increase of 243 kg per hectare per year. This relationship was the strongest with manure applications.

A study by Kimetu et al. (2008) showed that application of inorganic fertilizer together with 12 Mg of C per ha of wood charcoal, with a low N content and a high C:N ratio, produced maize yields that were about 2 Mg/ha higher than that from the inorganic application when the soil was highly degraded. This yield increase could not be explained by increasing nutrient availability, but possibly through improving soil pH, CEC, or soil moisture retention. A different study by Kimetu et al. (2004) concluded that the effects of using an organic source of N greatly depend on the quality of the organic source and its rate of decomposition. The study further reported that organic C might help increase N mineralization from organic sources, thus expanding the N pool and increasing the amount of N available for crop production.

The objective of this project is to examine fertilizer and manure sources of N in an attempt to increase resource efficiency and improve food security. Specifically, a N rate from an inorganic fertilizer was compared to an equivalent dry-weight rate of N from cattle manure using six maize plots at four farm sites. All nutrient applications were made according to the management recommendations from the Kenya Agricultural Research Institute's (KARI) Regional Research Center in Kakamega.

Materials

Study Area

The study area is located in the Kakamega District of Western Kenya. The district's elevation lies between 1,250 and 2,000 m above sea level (m.a.s.l.) and covers an area of 1,395 km^2 (Mwale and Wambua, 2008). Temperatures average between 18-20.5ºC throughout most of the year, and mean rainfall averages 1200-2100 mm per year. The district experiences two yearly rainy seasons: the long rains, typically lasting from March until June, and the short rains from August through October. Kakamega is long-rain dependent, as the short rains are inadequate for maize production. The district's soil is dominated by Humic Nitisols (sub group Dystro-mollic Nitisol), classified as deep, red friable soils (Kenya Soil Survey, 2004). A Humic Nitisol is equivalent to a typic Palehumult by the USDA soil classification system (Kihanda et al., 1996). These soils are clayey and possess an argillic B-horizon (ISEM, 2007). Due to their highly weathered characteristics, these soils are slightly acidic and finely textured. The soils are non-saline, very deep, and possess a high capacity for water retention; but inherent fertility is low.

The experiment was carried out at four farms within the district. They will be labeled as *Farm A, B, C*, and *D*. Farm A was previously cultivated with napier, or elephant, grass (*Pennisetum purpureum*) during the last cropping season, and inorganic fertilizer had been applied, but at an unknown rate, by the farmer. Farm B was cultivated with maize during the previous long rain season and sweet potatoes during the previous short rain season. No fertilizer had been applied. Farm C was cultivated with maize during the previous season, and no fertilizer had been applied. Farm D had only been under cultivation for five years, in comparison to the other three farms which have had long-term cultivation. During the last cropping season, maize was grown during the long rain season and vegetables were grown during the short rain season, and inorganic fertilizer had been used.

N Sources

The inorganic fertlizer plots were treated with diammonium phosphate (DAP), nutrient content of 18-46-0, at the time of planting and calcium ammonium nitrate (CAN), nutrient content of 26-0-0, as a side-dress six weeks after emergence. Both fertilizers were applied at a rate of 120 kg/ha, allowing the plots to receive N at a rate of 5.28 g/m^2 (~53 kg/ha). The organic fertilizer plots were treated with cattle manure, which had been purchased to maintain consistency. The manure was analyzed for its nutrient content on a dry-weight basis at the Kenya Plant Health Inspector Services (KEPHIS) in Kitale, Kenya, located just north of the Kakamega District. The manure was applied at a rate of 8 Mg/ha, allowing the plots to receive N at an average rate of 7.64 g/m^2 (~76 kg/ha).

Methods

Before planting, five soil samples, each at two depths (0-15 cm and 15-30 cm), were collected from each farm site. These samples were combined to form one 0-15 cm sample and one 15-30 cm sample for each farm. Samples were dried and then analyzed at KEPHIS. One manure sample was also taken from each of the two manure sources and analyzed at KEPHIS.

The maize was planted at each farm site in April 2008 using a completely randomized design. An additional plot was located adjacent to the experimental plots and Farm C where no nutrient source was added, serving as a control plot for the experiment. Maize variety KSTP 94 was planted uniformly in all plots with a spacing of 30 by 75 cm.

DAP was applied at a rate of 120 kg/ha to plots with the inorganic treatment. Fertilizer was applied manually to the seed hole and incorporated before the seed was added. Cattle manure was applied to the plots receiving the organic fertilizer treatment at a wet rate of 8 Mg/ha. The manure was applied using a hole-placement method, in which the manure is added to the soil with the seed.

Stand counts were determined for each plot by counting the total number of plants that have emerged from the middle two rows of each plot. Six weeks after emergence CAN was applied at a rate of 120 kg/ha to all the plots receiving the inorganic fertilizer treatment. The CAN fertilizer was applied manually in a rill about 10 cm deep and 10 cm away from the maize rows. Plots were weeded and maintained as needed by the farmer in ownership of the land.

When the maize entered the silking stage in its development, plant height was measured for 10 plants from the inner two rows of each plot by using a meter stick to measure the distance from the ground at the base of the plant to the collar of the ear leaf. The average plant height for each plot was calculated for statistical analysis. A leaf color chart (a general indicator of the N content within the plant) was also used to measure the color of the ear leaf for 10 separate plants from the inner two rows of each plot to the nearest half unit. The average color measurement for each plot was calculated for statistical analysis. Ten ear leaves were sampled from the inner two rows of each plot. The leaves were dried and ground, without their collars, in an electric grinder, creating one homogenous sample from each plot. Samples were analyzed in the soil chemical lab at The Ohio State University, Columbus. Five soil samples were collected from each plot, each at two depths (0-15 cm and 15-30 cm). Samples were combined to form one 0-15 cm sample and one 15-30 cm sample for each plot. Samples were air dried and analyzed in the soil physics lab and the soil chemistry lab at OSU.

All the maize was harvested during the last week of August in 2008. Yield data was only taken from two of the four farms, as the other two sites had already been partially or wholly harvested by the farmer. Ears were harvested from the middle section of the middle two rows of each plot, and the maize was shelled and weighed in the field. A moisture meter was used to determine the average moisture content from each plot, and the yields were converted to a 14% moisture content. Stand counts were determined again for each plot by counting the total number of plants, with or without an ear, from the middle two rows of each plot. Because the area harvested was not completely uniform for each plot, the number of plants harvested were counted and divided by the final stand count for the middle two rows to determine the harvested area in order to calculate yield. Three soil samples were collected from each plot, each at two depths: 0-15 cm and 15-30 cm. Again, samples were combined to form one 0-15 cm sample and one 15-30 cm sample for each plot. Samples were air-dried in the shade, and then analyzed at the soil chemistry lab at OSU. Fresh plant biomass was determined by bundling and weighing the plants harvested from each plot without the husks or ears. Soil bulk density was measured in each plot by creating a smooth surface area in the field sampling to a depth of 5 cm with a .75 inch diameter soil probe. Soils cores were dried in an oven at 105º C for two days, and bulk density was calculated by the gravimetric method.

Laboratory Analysis

Soil samples from the R1 stage and harvest stage were analyzed together in the soil chemistry and soil physics laboratories at OSU in Columbus, OH. Soil samples were prepared for analysis by crushing the samples using a mortar and pestle. Soil pH was measured in a 1:1 soil:deionized water suspension using a combination pH electrode (Thomas, 2001). Total N and total C were measured in the soil samples by the dry combustion following acid pretreatment (Nelson and Sommers, 2001). Total CEC in the soil was measured using an unbuffered ($BaCl_2$) salt extraction method (Sumner and Miller, 2001). Plant available nutrients in the soil were measured using the Mehlich 3 extraction with subsequent analysis by ICP-AES (Mehlich, 1984). Sub-samples from each 0-15 cm soil sample were combined to form one sample per treatment per farm site per sampling time to determine the percentage of water stable aggregates by wet sieving.

Ear leaf tissue samples were prepared by running the samples through a grinder. Total N and total C were measured in the tissue samples by the dry combustion following acid pretreatment (Nelson and Sommers, 2001). Tissue samples were analyzed for nutrient content by adding 1 mL hydrochloric acid and 5 mL nitric acid to each 0.5 g tissue sample and leaving the samples underneath a laboratory hood overnight. Samples were then heated on a hot plate where the temperature remained over 100ºC for 30 minutes. Deionized water was then added to each sample until the volume equaled 25 mL at room temperature. The samples were then filtered and the solutions were analyzed using an ICP-AES.

Statistical Analysis

JMP 7 statistical software was used to conduct an analysis of variance and combined analysis of variance will be conducted using ANOVA to compare treatment means within each site and between all four sites.

Results and Discussion

Organic vs. Inorganic Sources of Nutrients

The inorganic fertilizer produced an average grain yield of 3.95 Mg/ha in comparison with that of 2.35 Mg/ha produced from the organic cattle manure (different at 0.05%). These yields indicate a difference of 68% in favor of the inorganic fertilizer. This trend in crop yield is also supported by the analyses. There were no differences in soil nutrient concentrations to a depth of 15 cm during either of the sampling times. However, treatment differences were observed in the maize ear leaf nutrient contents. The inorganic fertilizer treatment resulted in higher levels of N, P, Ca, Mg, S, and Zn within the maize ear leaf than those in the treatment receiving organic manure (significant to 0.05%) (Table 2).

The total N content in the leaves was 50% higher from the inorganic fertilizer than from the manure. Phosphorus, a limiting soil nutrient in Western Kenya, was 28.9% higher in the ear leaf from the inorganic fertilizer than that from the manure treatment. Although soil nutrients levels were not significantly different among treatments, plant nutrient levels were (Table 2).

Trends in the nutrient concentration in maize leaves show that the necessary nutrients for plant growth, and ultimately reflected in grain yields, are more readily available to the plants from an inorganic than organic source (Mallory and Griffin, 2007). However, had the study been extended over several growing seasons, there would potentially be an insignificant difference between inorganic fertilizer and manure (Nziguheba et al., 2005), as was shown during a seven-year study by Kihanda et al. (2006). Manure may have also performed better than the inorganic fertilizer if rainfall had not been adequate (Kimetu et al., 2004). The rainfall received during the growing season was adequate.

Although it was not a component of this study, much of the available literature shows that the best solution is to combine inorganic and organic N sources. Mtambanengwe et al. (2006) observed that N availability from low quality organic materials can be improved with the application of an inorganic N fertilizer. Kapkiyai et al. (1999) reported that yields as well as SOC concentrations were the highest when both fertilizer and manure were applied along with retaining the maize stover on the field.

No soil quality advantages were observed as a result of the manure treatment. The lack of difference in soil quality may be because of the short duration of a single-season study. Organic sources often do not show soil quality advantages over inorganic fertilizers during a short-term time frame (Nziguheba et al., 2005). It is also possible that the application rate of manure was not high enough to compensate the degradation of the soil by cultivation.

Crop Yields

Although both farms and treatments produced higher yields than Kenya's national average, experimentally measured yields in this study were low. The threshold level of nutrient concentration in ear leaves at silking and tasseling stages is 29-30 g/kg N, below which deficiency symptoms are apparent and adversely impact crop growth (Jones et al., 1995). Application of manure resulted in an average N content within the maize ear leaf at silking of 15.2 g/kg,

Trt.	N		P		K		Ca		Mg		S		Fe		Zn	
	g/kg												mg/kg			
F	22.8	a	2.2	a	18.4	a	5.2	a	1.7	a	1.5	a	336.0	a	19.0	a
M	15.2	b	1.7	b	19.6	a	3.8	b	1.3	b	1.3	b	389.7	a	16.8	b
CL	30.0		2.5		19.0		4.0		2.5		—		15.0		17.2	

CL = Critical Level for ear leaf at tassel (data taken from Jones et al., 1995).

Table 2 Treatment effect on ear leaf nutrients at R1, α = 0.05.

SCIENCE & TECHNOLOGY

Location	Treatment	Yield (Mg/ha, 0% Moisture)	Grain or Stover	N Removed	P Removed	K Removed
				----------	kg/ha	----------
Farm C	Fertilizer	3.17	Grain	52.1	10.1	10.9
			Stover	31.2	3.2	47.7
			Total	**83.2**	**13.2**	**58.6**
Farm C	Manure	2.25	Grain	37.0	7.1	7.7
			Stover	22.1	2.3	33.9
			Total	**59.1**	**9.4**	**41.6**
Farm D	Fertilizer	3.75	Grain	61.6	11.9	12.9
			Stover	36.9	3.8	56.4
			Total	**98.5**	**15.6**	**69.3**
Farm D	Manure	1.88	Grain	30.9	6.0	6.5
			Stover	18.5	1.9	28.3
			Total	**49.4**	**7.8**	**34.8**

**Nutrient Removal Rates taken from NRCS (2008); Stover and grain yields were assumed equal*

Table 3 Nutrient Removal from Maize Grain and Stover.

compared with 22.8 g/kg from inorganic fertilizer. Nutrient removal rates estimated from maize grain and stover yields (NRCS, 2008) were used to calculate the quantity of nutrients harvested through maize production (Table 3). These estimates may be slightly high, as nutrient concentrations found during this experiment were below the critical levels. Nonetheless, the data shows that more N is leaving the field every year than is being applied. The nutrient deficit can be reduced if crop residue is left on the field, but some will still be lost to volatilization, leaching, and immobilization. For these reasons, the current N recommendation rate in Western Kenya of 50 kg N per hectare is too low to obtain a high yield.

Similarly, the critical P level in the maize ear leaf at tassel is 2.5 g/kg (Jones et al., 1995). Ear leaf concentrations of P were also below the critical level (Table 2). The fertilizer treatment produced P levels of 2.22 g/kg compared with that in manure of 1.73 g/kg. Therefore, maize crop also suffered from P deficiency. In contrast to leaf concentrations of N and P, K levels were near the critical limit for both treatments. Concerning Ca, only the fertilizer treatment produced an average concentration above the critical value. Concentrations of Mg were below the critical level for both treatments, and Zn concentrations were sufficient for the fertilizer treatment and near the critical limit for the manure treatment (Table 2).

Concentrations of Fe were at toxic levels for both treatments, with no statistical difference between treatments. Jones et al. (1995) sites literature regarding the upper limit of the sufficiency range for Fe in the maize ear leaf at tassel as 120 and 250 mg/kg. The author explains that these may be only general estimates for the upper limit, as less research has been done to identify them. Regardless, iron concentrations for this experiment averaged 336 mg/kg from the fertilizer treatment and 390 mg/kg from the manure treatment—far beyond the toxic limit.

Soil acidity, high Fe levels in the soil, and toxic Fe concentrations in the plants probably significantly hindered grain yields. At 15 cm depth at harvest, average pH levels ranged from 5.4 at Farm C to 4.8 at Farm A (Table 4). At both sampling times and depths, there were no significant differences among soil P levels, which is known to be deficient in Western Kenya. This deficiency is primarily a result of low soil pH levels, resulting in toxic Fe concentrations within the soil that bind to P, preventing it from becoming plant available. A regression analysis showed a negative correlation between soil pH and soil Fe levels, with a R2 value of .56. Regression equations also showed a negative correlation between soil Fe and soil P levels, and positive correlations were calculated between both soil pH and soil P levels with grain yields. However, the R2 values for these equations were only .09, .04, and .11 respectfully, due to the small sample numbers.

It is probable that soil degradation had a significant effect on nutrient availability in the soil and consequently final grain yields. Although there were no statistically significant differences between treatments concerning nutrient levels within the soil, there were many location effects at both sampling depths. Farm D has only been under cultivation for the past five years, whereas the other three sites have been under long-term cultivation (Fig. 2). The high degree of soil quality at this site is obvious by the lowest soil bulk density (data not shown), and the highest mean weight diameter (MWD), as calculated from its percentage water stable aggregates (WSA) (Table 6). The highest amounts of total N, total C, Ca, and Mg were all observed at Farm D (Table 5). Among the fertilizer treatments, the MWD from Farm D at harvest was 244% higher than that at Farm A and C and 625% greater than the MWD at Farm B. Among the manure treatments at harvest, the MWD at Farm D was 299% high than that at Farm A, and 273% higher than that at Farm C. This indicates a strong correlation between soil quality and grain yields.

The differences between treatments were much greater at Farm D than at Farm C, which has been under long-term cultivation (Fig. 3). The data in Figure 3 indicate a correlation between soil quality and the effectiveness of the inorganic

Location	R1		H	
Farm A	4.8	b	4.8	c
Farm B	5.7	a	—	—
Farm C	5.6	a	5.4	a
Farm D	—	—	5.0	b

Table 4 Soil pH at 15 cm at R1 and Harvest samplings.

fertilizer. This conclusion was also reached by Kimetu et al. (2008) whose study showed that maize yields would remain low on fields that have been cultivated for more than 35 years despite full inorganic fertilizer applications. Showing a direct relationship between the degree of degradation, or time of cultivation, and the amount of response from the added OM, the study extended to show that adding organic amendments to the soil in addition to the inorganic fertilizer application could reverse this yield decline.

Poor maize stands may have also contributed to low yields. The seeding rate used in this experiment was 44.4 thousand seeds per ha. Final plant stands, as calculated at harvest, ranged from 29.5 thousand plants per ha to 45.7 thousand plants per ha (data not shown). There was as high as a 33.6% decrease in plant populations in comparison to its seeding rate.

Conclusion

Under the parameters of this study, inorganic fertilizer produced maize yields 68% greater than did cattle manure, even though N rates were equal. Tissue analysis of the maize ear leaves showed significantly higher levels of N, P, Ca, Mg, S, and Zn from the inorganic than organic treatment. These higher nutrient levels corresponded to higher yields. However, yields were still low, and most of the nutrients in the plant tissue were below the critical nutrient levels. Further, it was estimated that up to twice the amount of N was leaving the field via the grain and plant biomass than was applied in the form of fertilizer and manure. For these reasons, it can be concluded that the recommended rate of 50 kg N per ha is not enough. This is especially true if the soil is to be replenished of the nutrients lost from long-term cultivation and soil degradation.

There is also a potential correlation between the level of soil degradation and the extent to which fertilizer out-performed the organic manure. At the farm site where the soil was considerably less degraded, the significance between treatments was much greater than at the site with degraded soil. This shows the importance of soil quality and SOM as they affect soil fertility. The soil may not be able to take full advantage of fertilizer rates if the soil is degraded. In order for the soils to provide the necessary

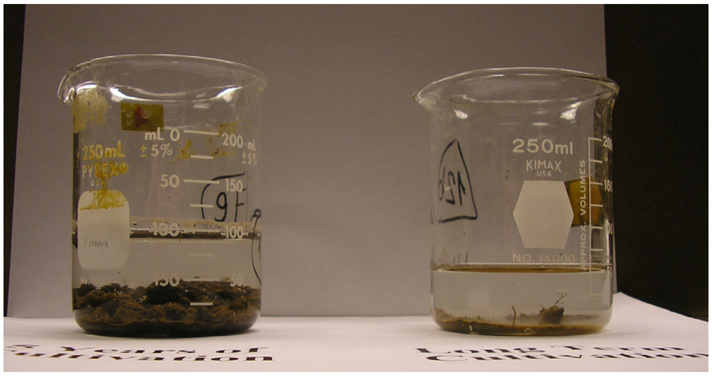

Fig 2 4.75 mm samples from WSA analysis. Left: Farm D (5 years of cultivation). Right: Farm A (long-term cultivation)

nutrients for plant production, management should focus on building up the OM content of the soils to increase soil quality. Applying manure and other sources of OM is the most common method for this.

Because farmers do not usually have the economic means to apply high rates of fertilizer to all of their fields, farmers should consider the economic costs and benefits from concentrating their nutrient resources on one specific

Location	Total N (g/kg)		Total C (g/kg)		Ca (mg/kg)		Mg (mg/kg)	
Farm A	0.58	b	9.60	b	329.87	b	29.06	b
Farm C	0.45	c	6.87	c	691.64	a	79.94	a
Farm D	1.34	a	20.72	a	879.12	a	106.77	a

Table 5 Soil nutrients in top 15 cm at Harvest.

	Fertilizer Treatment		Manure Treatment	
Location	WSA (%)	MWD (mm)	WSA (%)	MWD (mm)
Farm A	75.5	1.20	72.2	0.91
Farm B	65.4	0.57	—	—
Farm C	72.8	1.20	70.5	1.15
Farm D	87.8	**4.13**	83.6	**3.63**

Table 6 Percentage of water stable aggregates and mean weight diameter at Harvest.

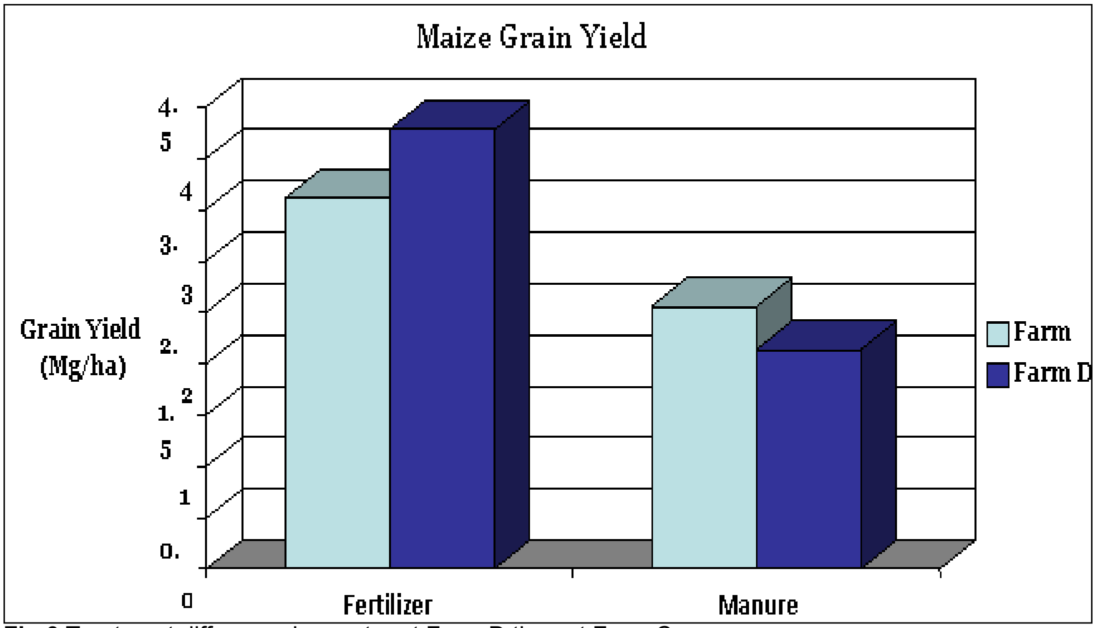

Fig 3 Treatment difference is greater at Farm D than at Farm C.

yield effect from both total N rate and different sources of N. This study also showed that the greatest treatment difference was observed at Farm D, which had the lowest degree of soil degradation. Future studies should explore this relationship further to determine if and where thresholds exist that would alter recommendations concerning the rate and source of N.

site for maize production, and possibly grow a crop that is less nutrient demanding on remaining land. Unless nutrient resources are concentrated, the soil will continue to degrade and available nutrients in the soil will continue to be depleted.

Future research should include developing nutrient response curves, especially for N, for maize production in the tropics. This experiment showed that the current recommended rate of 50 kg N per ha is not enough to reach the critical level required for maize to produce high yields. Other studies have focused on comparing different combinations of N additives, but these studies fail to maintain the same total N input within the experimental framework. Consequently, the effects of different N sources are masked by the amount of N each treatment is receiving. The end results typically show that the highest yields are attained when the most N is applied. Future studies must be designed to compare the

Acknowledgements

I thank my academic advisor, Dr. Rattan Lal, for his continual supervision and support throughout this study. I specially thank Christine Omboko (KARI-Kakamega) for coordinating this experiment with the Kenyan farmers and for assisting with fieldwork; Shane Whitacre (SENR) for his supervision and assistance in the soil chemistry lab; and Ji Young Jung (SENR) for her supervision and assistance with the statistical analysis.

I also thank the following people and organizations for funding support: OSU Office of International Affairs, OSU Libraries, OSU Undergraduate Student Government, Golden Key International Honor Society, Dr. R. Mullen (SENR-OARDC), and Dr. R. Lal (SENR).

References

[1] International Society for Ecological Modeling (ISEM). (2007). *FAO - Soil Unit Classification Scheme: Nitisols*. Retrieved December 31, 2007 from co.wiz.unikassel.de/ecobas/help_docs/nitisols.html.

[2] Jones, J.B. Jr., Eck, H.V., & Voss, R. (1995). Plant Analysis as an Aid in Fertilizing Corn and Grain Sorghum. p. 521-547. In Westerman, R.L. (Ed.), *Soil Testing and Plant Analysis* (3rd ed.) (pp. 521-547). Madison, Wisconsin: SSSA.

[3] Kapkiyai et al., (1999). Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term and organic input management. *Soil Biology and Biochemistry*, 31, 1773-1782.

[4] Kenya Soil Survey. (2004). *Gateway to Land and Water Information*. Food and Agriculture Organization of the United Nations. Retrieved December 31, 2007 from fao.org/ag/agl/swlwpnr/reports/y_sf/z_ke/ke.htm.

[5] Kihanda, F.M., Warren, G.P., & Micheni, A.N. (2006). Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. *Nutrient Cycling in Agroecosystems*, 76, 341-354.

[6] Kihanda et al., (1996). Fertilizer nitrogen recovery efficiency in the sub-humid highlands of Central Kenya. In Edmeades et al. (ed). *Developing Drought- and Low N- Tolerant Maize* (pp. 91-95), El Batán, Mexico. March 25-29, 1996. CIMMYT.

[7] Kimetu et al., (2004). Nitrogen fertilizer equivalencies of organics of differing

quality and optimum combination with inorganic nitrogen sources in Central Kenya. *Nutrient Cycling in Agroecosystems*, 68, 127-135.

[8] Kimetu et al., (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, 11, 726-739.

[9] Lal, R. (2009a). Laws of sustainable soil management. *Agronomy for Sustainable Development*, 29, 7-9.

[10] Lal, R. (2009b). Soils and food sufficiency. A review. *Agronomy for Sustainable Development*, 29, 113-133.

[11] Lal, R. (2008). Soils and sustainable agriculture. A review. *Agronomy for Sustainable Development*, 28, 57-64.

[12] Mallory, E.B., & Griffin, T.S. (2007). Impacts of soil amendment history on nitrogen availability from manure and fertilizer. *Soil Science Society of America Journal*, 71, 964-973.

[13] Mehlich, A. (1984). Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, 15, 1409-1416.

[14] Mtambanengwe, F., Mapfumo, P., & Vanlauwe, B. (2006). Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. *Nutrient Cycling in Agroecosystems*, 76, 271-284.

[15] Mucheru-Muna et al., (2007). Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agroforestry Systems*, 69, 189-197.

[16] Mwale, M., & Wambua, H. (2008). *Kakamega District Food Security Rapid Assessment Report February 2008* (Kenya Ministry of Agriculture). Retrieved April 10, 2008 from aridland.go.ke/shortrains08district_reports/kakamega.pdf.

[17] NRCS. 2008. *Plant Nutrient Content Database*. Retrieved May 22, 2009 from nrcs.usda.gov/technical/ecs/nutrient/tbb1.html.

[18] Nelson, D.W., & Sommers, L.E. (2001). Total Carbon, Organic Carbon, and Organic Matter. In Sparks, D.L. (Eds.), *Methods of Soil Analysis, Part 3—Chemical Methods* (pp. 961-1010). Madison, Wisconsin: SSSA.

[19] Nziguheba, G., Merckx, R., & Palm, C.A. (2005). Carbon and nitrogen dynamics in a phosphorus-deficient soil amended with organic residues and fertilizers in western Kenya. *Biology and Fertility of Soils*, 41, 240-248.

[20] Salasya et al., (1998). *An assessment of the adoption of seed and fertilizer packages and the role of credit in smallholder maize production in Kakamega and Vihiga Districts, Kenya.* Mexico: International Maize and Wheat Improvement Center (CIMMYT).

[21] Sumner, M.E., & Miller, W.P. (2001). Cation Exchange Capacity and Exchange Coefficients. In Sparks, D.L. (Ed.), *Methods of Soil Analysis, Part 3—Chemical Methods* (pp. 1201-1229). Madison, Wisconsin: SSSA.

[22] The World Bank Group. (2007). *WDI Online*. Retrieved December 31, 2007 and April 6, 2009 from ddp-ext.worldbank.org.proxy.lib.ohiostate.edu/ext/DDPQQ/member.do?method=getMembers&userid=1&queryId=6.

[23] Thomas, G.W. (2001). Soil pH and Soil Acidity. In Sparks, D.L. (Ed.), *Methods of Soil Analysis, Part 3—Chemical Methods* (pp.475-490). Madison, Wisconsin: SSSA.

[24] United Nations. (2008). *Millennium Development Goals: Progress Report*. Retrieved April 3, 2009 from undp.org/publications/MDG_Report_2008_En.pdf.

[25] United Nations Economic and Social Affairs. (2004). *World Population to 2300*. Retrieved April 6, 2009 from un.org/esa/population/publications/longrange2/WorldPop2300final.pdf.

[26] United Nations Statistics Division. *Data Extract—Download Selection*. Retrieved April 11, 2008 from unstats.un.org/unsd/cdb/cdb_advanced_data_extract_fm.asp?HYrID=1995&HYrID=1996&HYrID=1997&HYrID=1998&HYrID=1999&HYrID=2000&HYrID=2001&HYrID=2002&HYrID=2003&HYrID=2004&HYrID=2005&HSrID=3520%2C3530&HCrID=404&continue=Continue+%3E%3E.