The effect of mineral and organic nutrient input on yields and nitrogen balances in western Kenya

Running head: Nitrogen balances in smallholder maize systems

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Abstract:

Soil fertility declines constrain crop productivity on smallholder farms in sub-Saharan Africa. Government and non-government organizations promote the use of mineral fertilizer and improved seed varieties to redress nutrient depletion and increase crop yields. Similarly, rotational cropping with nitrogen (N)-fixing legume cover crops or trees is promoted to improve soil fertility and crop yields. We examined maize grain yields and partial N balances on 24 smallholder maize farms in western Kenya, where interventions have increased access to agricultural inputs and rotational legume technologies. On these farms, mineral fertilizer inputs ranged from 0 to 161 kg N ha^{-1} (mean = 48 kg N ha^{-1}), and maize grain yields ranged from 1-7 tons ha^{-1} (mean = 3.4 t ha^{-1}). Partial N balances ranged from large losses (-112 kg N ha^{-1}) to large gains (93 kg N ha^{-1}) with a mean of -3 kg N ha^{-1}. Maize grain yields increased significantly with N inputs (from fertilizer and legumes) in 2012 but not in 2013 when rainfall was lower. Nitrogen inputs of 40 kg N ha^{-1} were required to produce 3 tons of maize ha^{-1}. N balances varied both among farms and between years, highlighting the importance of tracking inputs and outputs on multiple farms over multiple years before drawing conclusions about nutrient management, soil fertility outcomes and food security. The addition of N from legume rotations was a strong predictor of grain yields and positive N balances in lower-yielding farms in both years. This suggested that legume rotations may be particularly important for buffering yields from climate variability and maintaining N balances in low rainfall years.

Keywords: Nitrogen balance; sub-Saharan Africa; maize yields; smallholder agriculture; legume rotations; improved fallow

1. Introduction

Continuous, low-input agriculture in sub-Saharan Africa (SSA) has removed nutrients from the soil without replenishing nutrient stocks (Moebius-Clune et al., 2011). As such, while most other regions in the tropics have seen increases in food production over the past fifty years, per capita yields in SSA have remained the same or even declined (Hazell and Wood, 2008). The "African Green Revolution" (AGR; Annan 2004) is an effort to increase use of nutrients, high-yielding seed varieties and extension services to increase low crop yields in SSA (Denning et al., 2009; Sanchez et al., 2009). Numerous national government agencies, non-government and international organizations support programs that provide these inputs at subsidized rates or through rural credit. Recent studies show that local cereal yields may double or even triple where adoption rates of both improved seeds and fertilizers are high (Denning et al., 2009; Nziguheba et al., 2010; Sanchez et al., 2007; Sanchez, 2015; Snapp et al., 2010).

The inclusion of legume cover rotations (often called "improved fallows") on farms has been promoted as a strategy for soil fertility improvement in SSA for many years (Buresh and Tian, 1998; Kiptot et al., 2007; Scherr, 1995; Sileshi et al., 2008). Fast-growing tree, shrub, and herbaceous legumes are grown for six months to two years after which they are cut and the fields planted in a cereal crop. By fixing atmospheric N_2, these legumes increase N inputs to a farm field. Their N contribution may partially replace or complement mineral fertilizer application while simultaneously increasing soil carbon (C) stocks (Sanchez, 2002). However, the amount of N_2 fixed by rotational legumes can vary from 24 to 142 kg N ha^{-1} depending on the species present and their plant density (Giller, 2001). Such technologies are often rapidly tested by farmers when introduced but widespread, continued adoption remains limited (Gathumbi et al., 2002b; Kiptot et al., 2007). Negative nutrient balances remain common at the farm and even country-level in SSA (Cobo et al., 2010; de Graaff et al., 2011; Nandwa and Bekunda, 1998; Van den Bosch et al., 1998).

Intensification of agriculture with higher fertilizer rates typically leads to imbalances between inputs and outputs (Heathwaite et al., 1993; Liu et al., 2010; Oenema et al., 2003; Vitousek et al., 2009). Resulting nutrient surpluses can cause declines in soil biodiversity (Wood et al., 2015a) and nutrient loading of terrestrial, aquatic, and atmospheric systems (Forester et al. 2007, Carpenter et al., 1998; Vitousek et al., 2009). These consequences occur widely in parts of the US, China, and Europe and have the potential to occur in locations such as SSA where nutrient inputs to farms may begin to increase substantially.

Because nutrient balances summarize the nutrient inputs and outputs of a farming system (Oenema et al., 2003), they are useful tools for farmers, extension agents, and policy makers when assessing the sustainability of the system. Nevertheless, these assessments must be considered in terms of the overall soil fertility status, the length of time that nutrient depletion has occurred, as well as other factors.

The aim of this study was to investigate the effects of farm management practices (e.g., fertilizer and legume rotations) on grain yields and nitrogen balances in smallholder maize farms in East Africa. We wanted to (i) test if higher N inputs lead to higher maize grain yields and less negative N balances, (ii) quantify the amount of N contributed through rotational legumes and determine their effect on yields and N balances, and (iii) determine the importance of soil chemical and physical properties on maize yields and N balances. We hypothesized that farms with the highest fertilizer application rates would have the highest grain yields and more positive N balances (more surplus N) across all farms regardless of site-specific soil properties. We expected farms receiving no or little fertilizer to have the lowest grain yields and negative N balances (N deficits). Finally, we hypothesized that farms cultivating rotational legumes would have intermediate maize grain yields and N balances. We expected maize grain yields to be positively correlated to N input and soil N concentrations and we expected that soils with legume rotations would have highest soil C content across all farms.

To test these hypotheses, we surveyed farmers participating in the Sauri Millennium Village Project, where agroforestry and rotational legume technology and trainings have been promoted since the early 1990s and where fertilizer subsidy programs were promoted from 2005 to 2008.

2. Methods

2.1. Study Sites

This study was conducted on 24 maize farms in the Sauri village cluster of the Millennium Village Project (MVP) in Yala Division, Siaya District, Nyanza Province, Kenya (Fig 1**)**. The area has a mean annual temperature of 24°C and an average monthly range from 14 to 34°C. Rainfall is bimodal with a mean annual precipitation of 1800 mm divided into a long rainy season from April to June and a short rainy season from September to December (Nziguheba et al., 2010; Palm et al., 2010). The soils are Kandiudalfic Eutrodox (Ferralsols), and are well-drained sandy clay loams. Although the soils are derived from fertile volcanic parent materials, several decades of cultivation have rendered them highly depleted in soil organic matter, N and plant available phosphorus (P; Awiti et al., 2008; Bossio et al., 2005; Kimetu et al., 2008).

The farming system is maize-based, with other crops such as beans, sweet potatoes, bananas/plantains, cassava, kale, tomatoes, and onions (Dixon et al., 2001). Land area is limited and farmers cultivate an average of 0.5 ha, with landholdings ranging from 0.1 to 1.6 ha with about 70% of the people living on less than $1 per day (Chen and Ravallion, 2007). Average maize yields have remained at 1 ton per ha for the last decade (FAO, 2013) in comparison 3 tons ha^{-1} in India, 5 in China and an average of 10 tons ha^{-1} in the US and Europe (Sanchez, 2015).

A primary intervention of the MVP in Sauri is to increase maize yields through subsidized high-yielding maize varieties and mineral fertilizers (primarily diammonium phosphate [DAP] and urea). If mineral fertilizer is used, it is typically applied basally with about one-third of N added at planting as DAP and the remaining two-thirds applied 5-8 weeks later as urea when the maize has 4-5 “true leaves” (V4-V5 stage). Maize is planted with the onset of rains in late March-early April and it is harvested in late August after being allowed to dry in the fields.

Legume rotation systems have been promoted in Sauri for about 20 years and are also part of the MVP interventions. These types of short term maize-legume rotations are often called “improved fallows” if the legume is a tree or a shrub (Mafongoya et al., 2006). Here, we refer to them as “legume rotations” as the farmers variously used legume tree, shrubs, or herbaceous cover crops.

2.2. Farm surveys

To locate study farms, we visited 42 farmers’ fields in January of 2012. Initially, the farms were placed into three nutrient input categories: *high fertilizer*, *low fertilizer*, and *legume rotation* by visually assessing the amount of maize stover (stems and leaves) and presence of *Striga*, a parasitic weed species, and an indicator of low soil N (Franke et al., 2006). We identified sets of farms that were located within 200 m of one another and along the same contour or slope to control for soil type. Sets of farms included two or three of the different nutrient input categories.

Although the initial categorization of farms by management was useful for identifying farms with different practices, we found that a few farmers who added little fertilizer the first year, added considerably more the second year. This variability in inputs led us to eliminate the categorical approach, and all data were analyzed with N input for each year as a predictor variable instead of input category.

Farmers were interviewed several times in May and June 2012, once with a different researcher present, and once with no researchers present (only a translator) to determine historical maize yields, fertilizer and manure application (during the past ten years), additional crops or intercrops, farm age and management history. We found yield numbers were consistent among the multiple interview situations, but fertilizer reporting often differed. Farms where fertilizer data differed substantially or was inconsistent between interview sessions were excluded from the final set of study farms. Ultimately, we restricted our field monitoring to 24 farms within seven villages (Fig 1) that met our criteria for dependability yield and fertilizer reporting. We then selected one field per farm on which to monitor inputs, management, and yield (Table S1). In July of 2012, we revisited farms and performed similar recall tests on fertilizer application in the long rains of 2013. In August 2013, and we measured farm field area by taking several waypoints along the farm perimeter using GPS (Garmin GPSMap 64).

2.3. Soil sampling and analysis

In May of 2012 soil samples were collected from each of the study fields at 0-20 cm and 20-50 cm depths using a 7-cm diameter bucket auger. Samples were taken from eight random locations within the preselected field and composited at each depth (2 samples per farm). A sub-sample was retained for nutrient and texture analysis. Soil samples were sun-dried and sieved to 2 mm. Soil texture was determined using the hydrometer method (Gee and Bauder, 1986), organic C by

Walkley-Black wet oxidation (Nelson and Sommers, 1982), total N by the micro-Kjeldhal digestion method. Soil pH was determined by 1:2 soil to water slurry (Hanna combination pH/EC/TDS/temperature probe, HI 98129). Water holding capacity (WHC) was measured on soils that were fully saturated and allowed to drain for 2 hours at which time soils were then weighed, dried at 105°C for 48 hours (or until a constant weight was attained) and re-weighed.

In June 2012, we re-sampled soils for chemical properties using a 2-cm diameter soil probe; 20 samples were collected per field (0-20 cm) and composited. A subsample of sieved soil was sun-dried and used to determine extractable Ca, Mg, P, Al, B, Ba, Cu, Fe, Mn, Na, and Z (Mehlich III extraction; 5-g soil in 20 mL solution; 5 min shake; (Mehlich, 1984). The solution was analyzed on an inductively coupled plasma spectrometer (Varian Vista MPX Radial ICP-OES).

In October and November of 2012, we measured bulk density with a slide hammer using a stacked-ring method (Core Sampler Complete, AMS Idaho, USA). We used bulk density (g cm^{-3}) to calculate soil N stock (0-20 cm and 20-50 cm), which was used a potential control variable in the statistical analysis.

2.4. Estimating maize yields

In July 2012 and 2013, we established three 3-m x 3-m yield plots on each preselected maize field. Plot locations were randomized, but we avoided farm edges and unique features (such as a brick pits, large trees, shrubs, etc.). Farmers were asked not to remove any biomass from inside the plots until we returned (one month later; at the end of August 2012 and 2013) to harvest the plots. Maize plants within the plots were counted as were the total number of maize ears. All maize stover and ears were weighed in the field using a hanging balance. A sub-sample of stover was collected for moisture and nutrient determination. Maize ears were divided into three categories: small, medium, and large and one ear from each category selected at random, shelled, and core and grain retained (note that ear = grain + fibrous core). Grain, core, and stover sub-samples were weighed fresh, oven-dried to a constant mass (60°C for 48 hours), and re-weighed dry to determine moisture content. Dry maize grain and core yields were estimated based on the total mass of cobs per plot and scaled to a hectare. Maize grain data alone were used to in the analysis of maize yields in tons ha^{-1}. The dry weight equivalent stover was scaled from plot-level to a hectare (Appendix B). Maize tissue sub-samples (grains, cores, and stover) were ground (2 mm mesh) and analyzed for C by ashing in a muffle furnace at 500ºC and %N by Kjeldahl acid digestion and titrimetric determination. Nitrogen concentrations were used to calculate the amount of N leaving the field as harvest (in grains, cores, and stover), and all these data were used to calculate the amount of N leaving the field in the maize harvest, providing an excellent comparison of outputs among farms in the study.

2.5. Estimating N added through manure additions

The amount of N added through manure can be highly variable from farm-to farm (Palm et al., 2001), therefore in April of 2013 (the beginning of planting season) we collected manure samples from all farms applying manure, and estimated moisture content. Manure subsamples were analyzed for C by dry ashing in a muffle furnace at 500ºC and N by Kjeldahl acid digestion and titrimetric determination.

2.6. Estimating N added and recycled through legume rotations

To estimate the amount of N fixed and recycled in legumes, we returned in the short rainy season (September 2013) to farms that used legume rotations. We observed plots and asked farmers to report the species planted, original planting density, thinning practices, wood harvesting and legume management. *Tephrosia candida* (shrub)*, Mucuna pruriens* (herbaceous cover crop) and

Crolataria grahamiana (shrub), were the primary species found in legume rotations on the study farms. We used farmer reported and observed plant density combined with literature data (Gathumbi et al., 2002b; 2002a; Ojiem et al., 2007) on the amount of N stored per plant to calculate the total amount of N added through N fixation and recycling. Because farmers tend to remove woody stems but incorporate fresh leaves, thus we subtracted the amount of N stored in woody biomass from this value to estimate the net N contribution from the legume species to the farm fields (Appendix C; Table S2).

2.7. Calculating N balances

This study used a partial nutrient balance metric, which was simply the difference between nutrient inputs and harvest and reside outputs.

Inputs. We calculated N balances (Eq. 1) for the long rains of 2012 and 2013 from farmer-reported data on the quantity of mineral N addition (DAP, urea, NPK, calcium ammonium nitrate [CAN], and manure) plus the estimated amount of N fixed and recycled. Of the inputs applied, DAP is 18% N, urea is 45% N, NPK is 20% N, and CAN is 26% N on a mass-basis. N inputs through manure addition and legume rotations were calculated at the individual farm-level as described above.

Eq 1:

$$Input\left(\frac{kg\ N}{ha}\right) =$$

$$(DAP \times 0.18) + (urea \times 0.45) + (NPK \times 0.20) + (CAN \times 0.26) + \left(manure \times \frac{dry}{wet} \times \frac{gN}{g\ dry\ manure}\right) + (N\ fixed - N\ recycled)$$

Outputs. We used harvest data from 2012 and 2013 to calculate the amount of N leaving the field as harvest (as grain, core, and stover; Eq. 2). We assumed that stover was removed entirely from the field, a common practice in this region (Mapfumo and Giller, 2001; Zingore et al., 2007). We used the following equation to calculate the farm field outputs:

Eq 2:

$$Outputs\left(\frac{kg\ N}{ha}\right)\quad\left(\frac{kg\ dry\ grain}{ha}\cdot\frac{g\ N}{dry\ grain}\right)\quad\left(\frac{kg\ dry\ cores}{ha}\cdot\frac{g\ N}{dry\ core}\right)\quad\left(\frac{kg\ dry\ stover}{ha}\cdot\frac{g\ N}{dry\ stover}\right)$$

2.8. Data analysis

We used a generalized linear model to examine if soil properties (WHC, pH, % clay, bulk density) and soil nutrients (% C and % N) differed among the seven villages and between the two depths (0-20 cm and 20-50 cm). We used linear mixed effects modeling (LMM) to analyze the mean effect of farm management strategy on yields and nutrient balances. Separate models were fit for years 2012 and 2013. Farm set ($n = 9$) was fit as a random effect to address spatial clustering in the location of farms. Response variables were found to conform to normality assumptions using the Shapiro-Wilk test. We selected an initial, full model that included the following predictor variables: N addition (fertilizer + manure), soil N stock, percent clay, and a binary variable for whether a farm used legume rotation practices. A final, most parsimonious model was selected to minimize Akaike Information Criterion (AIC) using automated model selection with the *MuMIn* package (Bartoń, 2013). The final, reported model retained N addition and legume rotation as predictor variables. LMMs were implemented using the *lme4* package (Bates et al., 2013). We report P-values for each parameter and adjusted r^2 as a measure of overall model fit. We report adjusted r^2 values that represent the amount of variance explained by the fixed effects only and by the fixed effects and the random effects. The r^2 values are calculated by adapting a previous approach for calculating non-adjusted r^2 values for LMEs (Nakagawa and Schielzeth, 2012). Because the denominator degrees of freedom are not considered valid for the *lme4* package (Baayen et al., 2008), we estimated P-values following the

Satterthwaite approach to estimating denominator degrees of freedom using the *lmerTest* package (Kuznetsova et al., 2013).

We used a quantile regression approach to determine the effect of management on higher-vs-lower yielding farms and N budget (Cade and Noon, 2003). Quantile regression estimates relationships between predictor and response variables for separate quantiles of the response variable distribution. We defined quantile thresholds at 33, 66, and 99 percent. Separate models were fit for 2012 and 2013. Independent variables were included based on model selection used for the mean response regression defined above. Parameter values and associated confidence intervals are estimated using the Barrodale-Roberts iterative algorithm (Buchinsky, 1998) and implemented using the *quantreg* package (Koenker, 2013). For a measure of model goodness of fit we report log likelihood values. For all statistical tests, we considered coefficients with $P < 0.05$ significant and coefficients with $P < 0.10$ marginally significant (Hurlbert and Lombardi, 2009).

3. Results

Soil properties (WHC, pH, percent clay, total organic soil C or total soil N) were similar among the villages. Soil bulk density (top and subsoil) was significantly different among the villages, but was not related to soil texture (Table 1 and 2). We found no significant statistical relationship between N fertilizer and soil properties or macro and micronutrient concentrations (Table S3). Overall, the 2013 growing season was very dry, with about 500 mm of rain between April and June compared with around 960 mm of rain in the same period in 2012 (Table 3). June is a critical growth period for maize in the region, and Kenya’s Yala district received about 30 mm of rain in June of 2013 compared with nearly 300 mm in 2012 (Table 3).

3.1. Yields

Mean maize yields were similar between years (mean 3.4 tons ha^{-1}, median 3.1 tons ha^{-1}) but ranged widely among farms from 0.7 to 7.1 tons ha^{-1}. Within-farm maize yields varied by 1.1 tons on average between the two years, with differences in annual yield ranging from 0.04 to 3 tons ha^{-1} within a single farm. In 2012, maize yields increased significantly with N addition ($p < 0.001$; Table 4). Further, yields were also elevated on farms where legumes had been cultivated during the previous short rains (legume rotations; Fig 2A; $p < 0.05$; Table 4). The effect of N addition on yields, represented by a standardized regression coefficient, was 85% greater than the effect of legume rotation (Table 4). In 2013, variation in maize yields was not significantly explained by either N addition or legume rotation (Table 4).

In 2012, the positive effect of N addition on yields was significant for farms in all yield quantiles (Fig S1 B, Table 4). By contrast, the positive effect of legume rotations on yield was only significant for the lower-yielding farms (0 and 33% quantiles; Fig S1 C, Table 4). The effect of mineral N addition was 43% greater than the effect of legume rotation for the lowest quantile farms and 17% greater for the 33% quantile farms. In 2013, we only observed a significant effect of N addition and legume rotation on the lowest-threshold farms, with the legume rotation effect being 57% stronger than the mineral N addition effect (Table 4; Fig S1 F).

3.2. Balances

Mean N inputs from mineral fertilizer were 45 kg ha^{-1} in 2012 and 50 kg ha^{-1} in 2013 and mean N inputs from manure were 8 kg ha^{-1} in both years. We estimated that an average of 60 kg N ha^{-1} were added by legume rotation (fixed and recycled) in 2012 and 68 kg N ha^{-1} in 2013 (equivalent to about 1.1 Mg C ha^{-1} in biomass each year). Although most farms received similar N inputs in the two years, a few farms received substantially different quantities of fertilizer between the two years (up to 58 kg N ha^{-1} difference; Fig 3). Not surprisingly the amount of N added by legume rotations differed within most farms between years because of differences in species and planting density. Further, on farms with legume rotations, about half the added N came from the legume residues with the other half coming from mineral fertilizer or manure.

In 2012, 13 farms had negative N balances (Fig 3A) and 15 farms had negative N balances in 2013 (Fig 3B). Balances ranged from -85 to 91 kg N ha^{-1} in 2012 (mean = 4) and from -112 to 113 kg N ha^{-1} in 2013 (mean = -11). In 2012, balances for all farm fields with legume rotations were positive, and only two were marginally negative in 2013. Surpluses and deficits were both, on average, greater in 2013 than in 2012 (Fig 3). Within-farm balances varied by 29 kg of N ha^{-1} between the two study years with 0.9 kg of N as the smallest and 109 kg N as the largest difference in N balances observed in a single farm (Fig 3).

In 2012, the effect of N addition on N budgets was 15% greater than the effect of legume rotations, and in 2013 the effect was 30% greater (Table 5). In 2012 and 2013, the positive effect of N addition on N balances was largest and most significant for farms with more positive N balances (Table 5; Fig S2 B and E). The positive effect of legume rotations was consistent across all quantiles (Table 5; Fig S2 C and F).

4. Discussion

Although soil physical and chemical properties were largely similar, we found large between- and within-farm variation in maize yields and N balances between the two study years. Most studies of nutrient balances examine only one growing season and build hypotheses around the effect of management practices on nutrient surpluses or deficits based on that single snapshot. Our results demonstrate a great deal of variation in inputs and outputs within farms from year to year, and that a snapshot approach may not adequately capture the inter-annual variability in N dynamics in smallholder farming systems. Further, differences in N balances between years were driven primarily by the variation in maize yields instead of variation in nutrient inputs (which remained the same in most farms between the two years, Fig 3). The decoupling of maize yields and nutrient inputs in the second year of the study lends support to this finding, which we attribute to moisture limitation during the growing season in 2013.

4.1. Yields

Average maize yields (3.4 tons ha^{-1}) were lower than those recorded several years earlier (5.1 tons ha^{-1}; Nziguheba et al., 2010), but still close to AGRA's 3 tons ha^{-1} target for SSA. In 2012, when there was sufficient rainfall during the maize growing season, N additions were a strong predictor of yields on all farms. However, in 2013, when rainfall during the growing season was significantly lower, maize yields were not correlated with N addition. Maize is typically planted between the end of March and the beginning of April in this region. Thus, the first reproductive stage (R1) falls in the first 2-3 weeks in June (a very dry month in 2013; Table 3), and a critical time for silking, which may explain the lack of correlation between yields and N inputs in 2013 (Folberth et al., 2013). In maize, moisture stress during pollination stages can cause delayed silking (R1), reduce the amount of viable pollen, and lead to yield reductions as high as 50% (*i.e.*, a 3-8% reduction for each day of stress; Shaw, 1988; Rhoads and Bennett, 1990). The decoupling of maize yields and N addition in 2013 indicated that during a dry year, moisture availability may be a more important factor determining yield than N addition. Planting date is also especially important during dry years. To maximize yields, maize is planted immediately following the onset of rains as delay of planting can lead to yield reductions of as much as 34 kg ha^{-1} for each day delayed (Fakorede, 1985). As climate change alters the variability of rainfall patterns in this region (Stige et al., 2006), it will be even more important to collect multiple years of data when evaluating yields and constructing N balances.

The study soils are Ferralsols, which may suffer from quick soil fertility declines after vegetation is removed (Sileshi et al., 2010) because soils acidify, increasing both free aluminum concentrations and P fixation (Stocking, 2003). Although soils in our study were not critically acidic, we did find that yields were higher in low-yielding farms with legume rotations, suggesting that their inclusion may provide a strategy to buffer yields against variation in rainfall while raising productivity of low fertility soils. Our research fits into a large body of work that highlights the benefits of the legume rotations. Biomass from legume rotations may improve water-use efficiency (Sileshi et al., 2011; Torquebiau and Kwesiga, 1996), increase soil C sequestration (Montagnini and Nair, 2004; Takimoto et al., 2008), enhance microbial activity (Wood et al., 2015b), and decrease soil temperatures (Swift and Woomer, 1993) all of which provide more stable growing conditions for maize and slow or reverse soil fertility decline (Sileshi et al., 2010).

An interesting policy implication of this research is that where there are low returns to investment in mineral fertilizers, such interventions may not always be profitable, especially on highly degraded soils (Duflo et al., 2008; Marenya and Barrett, 2009a; 2009b). Inclusion of legume rotations with fertilizer may increase returns on investments as well as improve soil fertility. Such policies would not necessarily replace fertilizer intervention programs in Africa, but they should match available technologies with local conditions in order to enhance farm productivity and food security.

4.2. Balances

We found a large range of N balances among smallholder farms that shared the same climate, soils, and infrastructure. There is evidence for high spatial variation in soil fertility and management within and among smallholder farms (Zingore et al., 2007), and our research shows that this translates into spatial heterogeneity in N balances. Further, we show that the balance between nutrient inputs and outputs can vary substantially from year to year within a single farm. As nutrient balances are often used to assess food security and soil fertility outcomes across SSA, it is important to examine multiple years of data before drawing conclusions about the consequences of land management practices.

Inter-annual variation in N balances was largely driven by differences in maize yields rather than variation in N inputs. Efforts to buffer yields against variations in rainfall will likely play a key role in supporting both high yields and positive nutrient balances. Fields with legume rotations maintained yields greater than 2.5 tons ha^{-1} across both years, and tended to have positive N balances even in the drier year. Legume fallows may therefore provide similar benefits to longer-term agroforestry fallows by buffering yields and supporting positive N balances in rain-fed systems (Albrecht and Kandji, 2003; Verchot et al., 2007). Further, we restricted our analysis to N balances from the long rainy season, and farmers who didn't plant legumes in the short rainy season cultivated maize, legumes (soya, groundnut), or vegetables (sweet potato). In general, fertilizer applications in the short rains are very low (in our study more than half the farms didn't apply any fertilizer or manure), and thus N added through legume rotation practices would only become more important for maize yields and N balances if we included data from the short rains which would likely result in larger negative balances.

Although most farms received similar N inputs in the two years, a few farms received substantially different quantities of fertilizer between the two years (up to 58 kg N ha^{-1} difference; Fig 3). Smallholder farmers in SSA often operate at the economic margin, and agricultural investments are often a lower priority than school fees, medical treatments, etc. In addition to climatic variability, shifts in crop disease pressure and markets may also push nutrient balances into “the red”. Planting legumes during the short rains may thus provide a financial buffer for farmers in cases where household priorities shift investments away from the farm. Regardless of their many benefits, barriers exist to widespread adoption of legume technologies. Farm area is limited across most of western Kenya, and if the primary growing season is dry, a second maize crop often replaces the legume rotation during the short rains to make up for low yields. Clearly the adaptive capacity of smallholder farmers in SSA is limited by reliance on variable climate and markets. Legume fallows and other agroforestry practices, coupled with fertilizer inputs, may allow farmers to simultaneously feed their families and replenish their soils. We have a limited understanding of the role that legume rotations and agroforestry may play in helping smallholder farmers adapt to shifts in climate and markets (Verchot et al., 2007), and future research in this area is critical.

In general, farmers in this study were applying slightly less mineral N (45-50 kg N ha^{-1}) than was recorded in the same region several years earlier (80 kg N ha^{-1}; Nziguheba et al., 2010). Nevertheless, farmers were able to attain 3 tons of maize ha^{-1} if they applied at least 40 kg N ha^{-1}, similar to the minimum application rate recorded in Zimbabwe of 60 kg N ha^{-1} (Zingore et al., 2007). Farms with positive N balances produced on average 35 kg of grain per kg N applied, which is substantially more efficient than the average N efficiency of smallholder farms in SSA of 12-16 kg of maize per kg N applied (Nziguheba et al., 2010). Farmers who applied more N than was exported in harvests tended to have N surpluses as high or higher than those reported in farms in the Midwestern US (Vitousek et al., 2009). Although farms are far smaller in SSA than Iowa and fertilizer applications are less, fertilizer application rates are increasing across SSA and this has the potential to increase N inputs to African lands (if 75 kg N ha^{-1} yr^{-1} is achieved) by 6 Tg N yr^{-1} (Hazell and Wood, 2008; Monfreda et al., 2008). This could have potential consequences for N releases to the atmosphere and surface waters and future research should investigate the potential pathways for and environmental consequences of N losses should fertilizer N application in SSA continue to increase.

5. Conclusions

There were large spatial and temporal differences in grain yields and N balances within and among smallholder farmers. Differences in N balances were driven primarily by variation in maize yields between the two study years. This suggests that a snapshot approach to evaluating N balances in smallholder systems may lead to erroneous conclusions regarding food security or soil fertility outcomes. While yields tracked N inputs in 2012, they were decoupled from N inputs during 2013 when conditions were drier. Legume rotations, coupled with N fertilizer applications, may help maintain yields and positive N balances on the marginal lands and during drier years. Future research should investigate their potential role in improving the adaptive capacity of smallholder farmers to climate and market risks.

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Literature Cited

Albrecht, A., Kandji, S.T., 2003. Carbon sequestration in tropical agroforestry systems. Agr Ecosyst Environ 99, 15–27. doi:10.1016/S0167-8809(03)00138-5

Anderson, E.L., 1988. Tillage and N fertilization effects on maize root growth and root: shoot ratio. Plant Soil 108, 245–251. doi:10.1007/bf02375655

Awiti, A.O., Walsh, M.G., Kinyamario, J., 2008. Dynamics of topsoil carbon and nitrogen along a tropical forest–cropland chronosequence: Evidence from stable isotope analysis and spectroscopy. Agr Ecosyst Environ 127, 265–272. doi:10.1016/j.agee.2008.04.012

Baayen, R.H., Davidson, D.J., Bates, D.M., 2008. Mixed-effects modeling with crossed random effects for subjects and items. J Mem Lang 59, 390–412. doi:10.1016/j.jml.2007.12.005

Bossio, D.A., Girvan, M.S., Verchot, L., Bullimore, J., Borelli, T., Albrecht, A., Scow, K.M., Ball, A.S., Pretty, J.N., Osborn, A.M., 2005. Soil Microbial Community Response to Land Use Change in an Agricultural Landscape of Western Kenya. Microb Ecol 49, 50–62. doi:10.1007/s00248-003-0209-6

Buchinsky, M., 1998. Recent Advances in Quantile Regression Models: A Practical Guideline for Empirical Research. J Hum Res 33, 88–126. doi:10.2307/146316

Buresh, R.J., Tian, G., 1998. Soil improvement by trees in sub-Saharan Africa. Agroforest Syst 38, 51–76. doi:10.1007/978-94-015-9008-2_2

Cade, B.S., Noon, B.R., 2003. A Gentle Introduction to Quantile Regression for Ecologists. Front Ecol Environ 1, 412–420. doi:10.2307/3868138

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8, 559–568. doi:10.1890/1051-0761(1998)008[0559:nposww]2.0.co;2

Chen, S., Ravallion, M., 2007. Absolute poverty measures for the developing world, 1981-2004. P Natl Acad Sci 104, 16757–16762.

Cobo, J.G., Dercon, G., Cadisch, G., 2010. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. Agr Ecosyst Environ 136, 1–15. doi:10.1016/j.agee.2009.11.006

de Graaff, J., Kessler, A., Nibbering, J.W., 2011. Agriculture and food security in selected countries in Sub-Saharan Africa: diversity in trends and opportunities. Food Sec. 3, 195–213. doi:10.1007/s12571-011-0125-4

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., Nkhoma, P., Zamba, C., Banda, C., Magombo, C., Keating, M., Wangila, J., Sachs, J., 2009. Input Subsidies to Improve Smallholder Maize Productivity in Malawi: Toward an African Green Revolution. Plos Biol 7, e23. doi:10.1371/journal.pbio.1000023

Dixon, J.A., Gibbon, D.P., Gulliver, A., 2001. Farming Systems and Poverty. Food & Agriculture Org.

Duflo, E., Kremer, M., Robinson, J., 2008. How High Are Rates of Return to Fertilizer? Evidence from Field Experiments in Kenya. American Economic Review 98, 482–488. doi:10.1257/aer.98.2.482

Fakorede, M.A.B., 1985. Response of Maize to Planting Dates in a Tropical Rainforest Location. Ex. Agric. 21, 19–30. doi:10.1017/S0014479700012217

Folberth, C., Yang, H., Gaiser, T., Abbaspour, K.C., Schulin, R., 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. Agr

Syst 119, 22–34. doi:10.1016/j.agsy.2013.04.002

Gathumbi, S.M., Cadisch, G., Giller, K.E., 2002a. 15N natural abundance as a tool for assessing N2-fixation of herbaceous, shrub and tree legumes in improved fallows. Soil Biol Biochem 34, 1059–1071. doi:10.1016/s0038-0717(02)00038-x

Gathumbi, S.M., Ndufa, J.K., Giller, K.E., Cadisch, G., 2002b. Do Species Mixtures Increase Above- and Belowground Resource Capture in Woody and Herbaceous Tropical Legumes? Agron J 94, 518–526. doi:10.2134/agronj2002.5180

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In “Methods of soil analysis. Part 1. Physical and mineralogical methods.”(Ed. A Klute) pp. 383–411. Soil Science Society of America: Madison.

Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems. CABI, Wallingford, UK.

Hazell, P., Wood, S., 2008. Drivers of change in global agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 495–515. doi:10.1098/rstb.2007.2166

Heathwaite, A.L., Bust, T.P., Trudgill, S.T., 1993. Overview-the nitrate issue. Nitrate: processes.

Hurlbert, S.H., Lombardi, C.M., 2009. Final Collapse of the Neyman-Pearson Decision Theoretic Framework and Rise of the neoFisherian. Ann Zool Fenn 46, 311–349. doi:10.5735/086.046.0501

Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W., Pell, A.N., 2008. Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality Along a Degradation Gradient. Ecosystems 11, 726–739. doi:10.1007/s10021-008-9154-z

Kiptot, E., Hebinck, P., Franzel, S., Richards, P., 2007. Adopters, testers or pseudo-adopters? Dynamics of the use of improved tree fallows by farmers in western Kenya. Agr Syst 94, 509–519. doi:10.1016/j.agsy.2007.01.002

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. P Natl Acad Sci 107, 8035–8040. doi:10.1073/pnas.0913658107

Mafongoya, P.L., Bationo, A., Kihara, J., Waswa, B.S., 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutr Cycl Agroecosyst 76, 137–151. doi:10.1007/s10705-006-9049-3

Mapfumo, P., Giller, K.E., 2001. Soil Fertility Management Strategies and Practices by Smallholder Farmers in Semi-arid Areas of Zimbabwe. ICRISAT/FAO, India.

Marenya, P.P., Barrett, C.B., 2009a. State-conditional Fertilizer Yield Response on Western Kenyan Farms. American Journal of Agricultural Economics 91, 991–1006. doi:10.1111/j.1467-8276.2009.01313.x

Marenya, P.P., Barrett, C.B., 2009b. Soil quality and fertilizer use rates among smallholder farmers in western Kenya. Agricultural Economics 40, 561–572. doi:10.1111/j.1574-0862.2009.00398.x

Mehlich, A., 1984. Determination of cation- and anion- exchange properties of soils. Communications in Soil Science and Plant Analysis 15, 1409–1416.

Moebius-Clune, B.N., van Es, H.M., Idowu, O.J., Schindelbeck, R.R., Kimetu, J.M., Ngoze, S., Lehmann, J., Kinyangi, J.M., 2011. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. Agr Ecosyst Environ 141, 86–99. doi:10.1016/j.agee.2011.02.018

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000.

Global Biogeochemical Cycles 22. doi:10.1029/2007GB002947

Montagnini, F., Nair, P.K.R., 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforest Syst 61-62, 281–295. doi:10.1023/b:agfo.0000029005.92691.79

Nakagawa, S., Schielzeth, H., 2012. A general and simple method for obtaining R 2 from generalized linear mixed-effects models. Methods in Ecology and Evolution 4, 133–142. doi:10.1111/j.2041-210x.2012.00261.x

Nandwa, S.M., Bekunda, M.A., 1998. Research on nutrient flows and balances in East and Southern Africa: state-of-the-art. Agr Ecosyst Environ 71, 5–18. doi:10.1016/s0167-8809(98)00128-5

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter, in: Page, A.L. (Ed.), Methods of Soil Analysis, Part 2, Second Edition. Madison, WI, pp. 539–579.

Nziguheba, G., Palm, C.A., Berhe, T., Denning, G., Dicko, A., Diouf, O., Diru, W., Flor, R., Frimpong, F., Harawa, R., Kaya, B., Manumbu, E., McArthur, J., Mutuo, P., Ndiaye, M., Niang, A., Nkhoma, P., Nyadzi, G., Sachs, J., Sullivan, C., Teklu, G., Tobe, L., Sanchez, P.A., 2010. The African Green Revolution, in: Advances in Agronomy. Elsevier, pp. 75–115. doi:10.1016/B978-0-12-385040-9.00003-7

Oenema, O., H, K., de Vries W, 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur J Agron 20, 3–16. doi:10.1016/S1161-0301(03)00067-4

Ojiem, J.O., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. Plant Soil 292, 119–135. doi:10.1007/s11104-007-9207-7

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agr Ecosyst Environ 83, 27–42. doi:10.1016/s0167-8809(00)00267-x

Palm, C.A., Smukler, S.M., Sullivan, C.C., Mutuo, P.K., Nyadzi, G.I., Walsh, M.G., 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. Proceedings of the … 107, 19661–19666. doi:10.1073/pnas.0912248107/-/DCSupplemental

Sanchez, P., Palm, C., Sachs, J., Denning, G., Flor, R., Harawa, R., Jama, B., Kiflemariam, T., Konecky, B., Kozar, R., Lelerai, E., Malik, A., Modi, V., Mutuo, P., Niang, A., Okoth, H., Place, F., Sachs, S.E., Said, A., Siriri, D., Teklehaimanot, A., Wang, K., Wangila, J., Zamba, C., 2007. The African Millennium Villages. P Natl Acad Sci 104, 16775–16780. doi:10.1073/pnas.0700423104

Sanchez, P.A., 2015. En route to plentiful food production in Africa. Nature Plants 1, 1–2. doi:10.1038/nplants201414

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295, 2019–2020.

Sanchez, P.A., Denning, G.L., Nziguheba, G., 2009. The African Green Revolution moves forward. Food Sec. 1, 37–44. doi:10.1007/s12571-009-0011-5

Scherr, S.J., 1995. Economic factors in farmer adoption of agroforestry: Patterns observed in Western Kenya. World Dev 23, 787–804. doi:10.1016/0305-750x(95)00005-w

Sileshi, G., Akinnifesi, F.K., Ajayi, O.C., Place, F., 2008. Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307, 1–19. doi:10.1007/s11104-008-9547-y

Sileshi, G., Akinnifesi, F.K., Debusho, L.K., Beedy, T., Ajayi, O.C., Mong'omba, S., 2010.

Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Research 116, 1–13. doi:10.1016/j.fcr.2009.11.014

Sileshi, G.W., Akinnifesi, F.K., Ajayi, O.C., Muys, B., 2011. Integration of legume trees in maize-based cropping systems improves rain use efficiency and yield stability under rain-fed agriculture. Agr Water Manage 98, 1364–1372. doi:10.1016/j.agwat.2011.04.002

Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. P Natl Acad Sci 107, 20840–20845. doi:10.1073/pnas.1007199107

Stige, L.C., Stave, J., Chan, K.S., Ciannelli, L., Pettorelli, N., Glantz, M., Herren, H.R., Stenseth, N.C., 2006. The effect of climate variation on agro-pastoral production in Africa. P Natl Acad Sci 103, 3049–3053. doi:10.1073/pnas.0600057103

Stocking, M.A., 2003. Tropical Soils and Food Security: The Next 50 Years. Science 302, 1356–1359. doi:10.1126/science.1088579

Swift, M.J., Woomer, P., 1993. Organic matter and the sustainability of agricultural systems: definition and measurement, in: K, M., R, M. (Eds.), Soil Organic Matter Dynamics and the Sustainability of Tropical Agriculture. Chichester, pp. 3–18.

Takimoto, A., Nair, V.D., Nair, P.K.R., 2008. Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. Agroforest Syst 76, 11–25. doi:10.1007/s10457-008-9179-5

Torquebiau, E.F., Kwesiga, F., 1996. Root development in a Sesbania sesban fallow-maize system in Eastern Zambia. Agroforest Syst 34, 193–211. doi:10.1007/bf00148162

Van den Bosch, H., Gitari, J.N., Ogaro, V.N., Maobe, S., Vlaming, J., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III. Monitoring nutrient flows and balances in three districts in Kenya. Agr Ecosyst Environ 71, 63–80. doi:10.1016/s0167-8809(98)00132-7

Verchot, L.V., Van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K.V., Palm, C., 2007. Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strat Glob Change 12, 901–918. doi:10.1007/s11027-007-9105-6

Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L.E., Holland, E., Johnes, P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A.R., Zhang, F.S., 2009. Nutrient Imbalances in Agricultural Development. Science 324, 1519–1520. doi:10.1126/science.1170261

Wood, S.A., Almaraz, M., Bradford, M.A., McGuire, K.L., Naeem, S., Palm, C.A., Tully, K.L., Zhou, J., 2015a. Agricultural intensification and the functional capacity of soil microbes on smallholder African farms. Frontiers in Microbiology 6, 1–10.

Wood, S.A., Bradford, M.A., Gilbert, J.A., McGuire, K.L., Palm, C.A., Tully, K., Zhou, J., Naeem, S., 2015b. Efforts to increase crop yield among smallholder farmers in Western Kenya are synergistic with greater functional capacity of soil microbial communities. J Appl Ecol 52, 744–752.

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. Agr Ecosyst Environ 119, 112–126. doi:10.1016/j.agee.2006.06.019

Tables

Table 1: Characteristics of topsoil (0-20 cm) in different sub-locations of the Sauri cluster.

Sublocation	Village	No. Farms	pH	Water Holding Capacity (%)	Sand (%)	Clay (%)	C (%)	N (%)	Bulk Density (g/cm^3)***
Anyiko	Tatro	2	5.71	42.93	12.62	31.00	1.89	0.17	1.25 ac[1]
Sauri	Madiri	3	5.28	37.43	12.47	28.57	1.94	0.18	1.17 ac
Marenyo	Ng'utmbaka	2	5.08	37.87	13.90	29.80	1.73	0.12	1.29 a
Nyamninia	Muhanda	2	5.66	41.47	9.73	34.55	2.05	0.16	1.06 ac
Nyawara	Nyamayoya B	3	5.23	31.44	6.00	36.53	1.92	0.15	0.98 b
Sauri	Sauri B	7	5.58	26.24	15.67	29.94	1.87	0.16	1.16 ac
Nyawara	Uyonga B	3	5.19	22.17	8.80	35.82	1.81	0.15	1.10 bc

Means presented by village.

[1] Within a column, values with different letters are significantly different ($P < 0.05$). Where *** indicates $P < 0.0001$.

Table 2: Characteristics of subsoil (20-50 cm) in different sub-locations of the Sauri cluster.

Sublocation	Village	No. Farms	pH	WHC (%)	Sand (%)	Clay (%)	C (%)	N (%)	Bulk Density (g/cm^3)**
Anyiko	Tatro	2	5.72	36.52	12.20	30.20	1.82	0.17	1.32 abc[1]
Sauri	Madiri	3	5.18	31.40	6.06	34.07	1.73	0.16	1.35 a
Marenyo	Ng'utmbaka	2	5.13	32.47	12.06	30.60	1.27	0.09	1.36 ac
Nyamninia	Muhanda	2	5.92	---	5.38	40.70	1.70	0.16	1.13 b
Nyawara	Nyamayoya B	3	5.34	36.67	12.00	30.13	1.66	0.13	1.17 bc
Sauri	Sauri B	7	5.46	33.29	16.44	29.76	1.51	0.12	1.31 a
Nyawara	Uyonga B	3	5.21	35.99	6.87	40.96	1.56	0.12	1.21 abc

Means presented by village.

[1] Within a column, values with different letters are significantly different ($P < 0.05$). Where ** indicates $P < 0.001$.

Table 3: Rainfall (in mm) over the primary maize growing season in Yala, Kenya in 2012 and 2013.

Month	**2012**	**2013**
April	466	318
May	200	177
June	293	29
July	40	60
August	162	177
September	262	180
Growing Season Total	1424	940

634

Table 4: Regression results of grain yield response to N addition and legume rotations for 2012 and 2013.

	Mean		**Quantile**							
	2012	*2013*	*2012*				*2013*			
			0	0.33	0.66	0.99	0	0.33	0.66	0.99
N addition	2.22****	0.85	1.71***	1.66**	1.72*	4.27**	0.81**	0.82	1.81	2.29
Legume rotation	1.20**	0.38	1.20*	1.42*	1.50	-0.58	1.27****	0.80	-0.73	-1.26
Intercept	3.34****	3.31****	1.93****	2.43****	3.30****	5.81****	1.83****	2.23****	3.97****	6.18****
Goodness of fit										
FE Adj. R2	0.40	0.05								
RE Adj. R2	0.78	0.29								
Log Likelihood			-31.74	-36.38	-41.09	-46.22	-35.22	-41.74	-47.75	-48.59

Models are fit for overall mean response and for individual quantiles to examine the influence of management on higher-vs.-lower yielding farms. Coefficients are of standardized variables and thus represent the relative effect of each variable within a model. Adjusted R^2 is reported for fixed effects alone and fixed effects + random effects in linear mixed models. Log likelihood is reported as a measure of model goodness of fit for quantile regression. * $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$, **** $P < 0.001$

Table 5: Regression results of the relationship of nitrogen (N) balances with N additions and legume rotation for 2012 and 2013.

	Mean		**Quantile**							
	2012	*2013*	*2012*				*2013*			
			0	0.33	0.66	0.99	0	0.33	0.66	0.99
N addition	49.76****	73.93****	4.76	46.85**	63.26****	61.61****	28.84	62.92**	78.40****	78.67****
Legume rotation	43.09****	56.97****	52.16**	23.43	44.62***	54.32****	70.52**	63.25**	45.65**	62.01****
Intercept	25.42**	27.05**	-10.88	15.41*	32.28****	47.48****	-23.16***	14.50	42.63****	54.13****
Goodness of fit										
FE Adj. R2	0.70	0.77								
RE Adj. R2	0.76	0.78								
Log Likelihood			-109.83	-108.92	-102.36	-99.10	-117.59	-116.01	-110.48	-104.14

Models are fit for overall mean response and for individual quantiles to examine the influence of management on higher-vs.-lower N balance farms. Coefficients are of standardized variables and thus represent the relative effect of each variable within a model. Standard error is reported in parentheses. Adjusted R^2 is reported for fixed effects alone and fixed effects + random effects in linear mixed models. Log likelihood is reported as a measure of model goodness of fit for quantile regression. * $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$, **** $P < 0.001$

Figure Captions

Fig 1. Site map of village and farm sets within the study area.

Fig 2. Mean farm yields as a function of N addition. N addition is measured as the amount of N added as mineral fertilizer and manure. Separate regression lines are visualized for farms that use legume rotation practices and those that do not. Mean yields significantly increase with N addition and legume rotation for 2012, but not for 2013. Results from multiple regression of yields against N addition and legume rotation and presented in Table 4.

Fig 3. Farm balance calculations by farm for two seasons (A) 2012 and (B) 2013 all units are in kg N ha^{-1} season^{-1}.

Fig 4. Mean N balance as a function of N addition. N balance is calculated as the surplus or deficit of N per field after one season of cultivation (long rains only). N addition is measured as the amount of N added as mineral fertilizer and manure. Separate regression lines are visualized for farms that use legume rotation techniques and those that do not. N surplus (positive N balance) is significantly greater with both N addition and legume rotation for both 2012 and 2013. Results from multiple regression of yields against N addition and legume rotation and presented in Table 5. Dashed lines represent a neutral (zero) balance where N inputs and outputs are equal.

Appendix A: Coefficients from quantile regressions.

Fig S1. Coefficients from quantile regression of yield against N addition and legume rotation for 2012 (A – C) and 2013 (D – F). Regression models were fit separately for four quantiles of yield: 0.0, 0.33, 0.66, 0.99 (x-axis). The coefficients for N addition and legume rotation are represented by points, while the gray envelope represents standard error of coefficient estimates. Increasing coefficient values with quantile (e.g. B) suggests that the given variable has a stronger effect on yields on higher yielding farms. Decreasing coefficient values (C) suggest that the given variable has a relatively higher impact on yields on lower yielding farms.

Fig S2. Coefficients from quantile regression of N balance against N addition and legume rotation for 2012 (A – C) and 2013 (D – F). Regression models were fit separately for four quantiles of yield: 0.0, 0.33, 0.66, 0.99 (x-axis). The coefficients for N addition and legume rotation are represented by points, while the gray envelope represents standard error of coefficient estimates. Increasing coefficient values with quantile (e.g. B, E) suggests that the given variable has a stronger effect on N balance on higher yielding farms. Decreasing coefficient values (C, F) suggest that the given variable has a relatively higher impact on N balance on lower yielding farms.

Appendix B: Calculating biomass removal using field data

To calculate dry grain, core, and stover removal we calculated the ratio of the total ear (grain + core) that was either grain or core, then all components were dried at 65 ºC for 48 hours and re-weighed to determine the dry to wet ratio for the two components. These ratios were multiplied by the number of ears per plot and data were scaled to tons ha^{-1}. For stover removal, we used the ratio of wet to dry stover subsamples to calculate the quantity of dry stover per plot and scaled to tons ha^{-1}. Because whole plants were uprooted in the field, we subtracted the proportion of mass attributable to roots (22% of the total plant mass; (Anderson, 1988). We averaged grain, core, and stover removal across the three plots and reported these yields in terms of maize grain, core, and stover (all of which are removed from the field upon harvest).

$$Dry\ grain\ \left(\frac{tons}{ha}\right) \quad \left(\frac{mass\ fresh\ grain}{mass\ fresh\ ear}\right) = \left(\frac{mass\ dry\ grain}{mass\ fresh\ grain}\right) \ast \left(\frac{kg\ ears}{plot}\right) \ast \left(\frac{1\ plot}{9\ m^2}\right) \ast \left(\frac{10{,}000\ m^2}{1\ ha}\right) \ast \left(\frac{1\ ton}{1000\ kg}\right) \qquad \text{Eq B1}$$

$$Dry\ core\ \left(\frac{tons}{ha}\right) \quad \left(\frac{mass\ fresh\ ear}{mass\ fresh\ core}\right) = \left(\frac{mass\ dry\ core}{mass\ fresh\ core}\right) \ast \left(\frac{kg\ ears}{plot}\right) = \left(\frac{1\ plot}{9\ m^2}\right) \ast \left(\frac{10{,}000\ m^2}{1\ ha}\right) = \left(\frac{1\ ton}{1000\ kg}\right) \qquad \text{Eq. B2}$$

$$Dry\ stover\ \left(\frac{tons}{ha}\right) \quad \left|\left(\frac{mass\ fresh\ stover}{plot}\right) = \left(\frac{mass\ dry\ stover}{mass\ fresh\ stover}\right) \ast \left(\frac{1\ plot}{9\ m^2}\right) \ast \left(\frac{10{,}000\ m^2}{1\ ha}\right) \ast \left(\frac{1\ ton}{1000\ kg}\right)\right| = 0.78 \qquad \text{Eq. B3}$$

Appendix C: Calculating N fixation and recycling from legume rotations

To calculate the amount of N contributed by N_2-fixation of legume rotation species, we combined field, interview, and literature data. Farms were visited in the short rains of 2013, and farmers were interviewed on-site regarding the density and management of legume rotations. We calculated plant density per species (some farmers had mixed rations) per hectare. We used literature data on the amount of N per plant (Gathumbi et al., 2002b; 2002a; Ojiem et al., 2007) to calculate quantity of N stored in aboveground biomass per hectare ($Nlegume_{total}$). As the farmers tended to harvest the woody biomass for fuel, we removed the amount of N stored in woody biomass (Nwood) from the total. Data on percent of the plant that is wood was garnered from the same studies. The remaining N ($Nlegume_{net}$) is considered to be a combination of N fixed (about 74%) and N recycled (about 26%).

$$Nlegume_{net} = Nlegume_{total} - Nwood \qquad \text{Eq C1}$$

where, $Nwood = \frac{plants}{ha} \ast \frac{g\ N\ in\ wood}{plant} \div 1000$ Eq C2

and $Nlegume_{total} = \frac{kg\ N}{plant}$ Eq C3

Table S1: Farm field-level data. All units in kg N ha^{-1} unless otherwise noted.

Farm ID	Sub Location	Village	Area (ha)	Year	Min N	Man N	N fix	N recyc	Yield (ton/ha)	Core (ton/ha)	Stover (ton/ha)	Yield	Core	Stover	Balance stoverON	Balance stoverOFF
1	Sauri	Madiri	0.66	2012	72	14	0	0	3	1	3	35	6	18	45	27
2	Sauri	Madiri	0.46	2012	59	5	0	0	2	0	3	30	2	20	32	12
3	Sauri	Madiri	1.33	2012	19	2	52	36	3	1	3	35	4	19	70	51
4	Sauri	Sauri B	2.12	2012	27	29	0	0	4	1	5	45	6	33	5	-28
5	Sauri	Sauri B	0.51	2012	9	0	0	0	1	0	1	8	1	4	0	-4
6	Sauri	Sauri B	1.58	2012	30	9	52	36	5	1	4	58	6	18	64	46
7	Nyawara	Nyam B	0.65	2012	41	0	0	0	2	1	3	31	4	17	6	-11
41	Nyawara	NyamB	0.12	2012	11	0	0	0	1	0	1	11	1	4	-1	-5
9	Nyawara	Nyam B	1.10	2012	81	0	44	16	4	1	4	41	5	24	95	71
10	Nyawara	Uyonga B	2.59	2012	42	19	0	0	3	1	3	42	5	17	14	-3
36	Nyawara	Uyonga B	0.12	2012	0	0	0	0	1	0	1	15	1	8	-17	-24
12	Nyawara	Uyonga B	0.70	2012	78	0	31	10	6	2	5	75	9	31	35	3
19	Sauri	Sauri B	3.68	2012	85	5	0	0	6	2	6	79	10	33	0	-33
20	Sauri	Sauri B	0.35	2012	0	0	0	0	2	0	3	19	2	19	-22	-41
21	Sauri	Sauri B	1.04	2012	96	9	52	36	6	1	3	79	6	23	108	85
30	Sauri	Sauri B	0.79	2012	69	17	31	10	5	1	7	65	9	51	53	2
32	Nyamn	Muhanda	1.10	2012	148	13	0	0	4	1	3	45	5	20	111	91
40	Nyamn	Muhanda	0.19	2012	16	7	0	0	1	0	1	18	1	6	3	-4
35	Nyawara	Uyonga B	0.26	2012	86	13	0	0	3	1	3	35	4	27	60	33
37	Nyawara	Uyonga B	1.31	2012	0	0	0	0	1	0	1	16	2	10	-17	-27
38	Anyiko	Tatro	1.66	2012	54	28	0	0	4	1	3	52	5	14	24	11
39	Anyiko	Tatro	0.95	2012	0	2	0	0	2	0	2	20	2	11	-20	-30
22	Marenyo	Ng'utmb	1.94	2012	52	15	0	0	7	1	8	83	9	60	-25	-85
23	Marenyo	Ng'utmb	1.27	2012	18	3	0	0	4	1	4	42	5	18	-27	-46
1	Sauri	Madiri	0.66	2013	72	34	0	0	3	1	6	37	6	27	63	35
2	Sauri	Madiri	0.46	2013	38	5	0	0	2	1	3	25	3	16	15	-1
3	Sauri	Madiri	1.33	2013	21	3	60	28	3	1	4	31	4	20	77	57
4	Sauri	Sauri B	2.12	2013	27	29	0	0	4	1	5	66	5	26	-16	-42

5	Sauri	Sauri B	0.51	2013	11	0	0	0	3	0	4	36	3	25	-27	-53
6	Sauri	Sauri B	1.58	2013	60	37	74	27	5	1	4	56	6	23	136	113
7	Nyawara	Nyam B	0.65	2013	96	0	0	0	2	1	6	23	4	32	69	37
41	Nyawara	Nyam B	0.12	2013	19	0	0	0	2	0	3	21	2	13	-4	-17
9	Nyawara	Nyam B	1.10	2013	107	0	44	16	4	1	11	52	4	119	111	-9
10	Nyawara	Uyonga B	2.59	2013	42	19	0	0	6	2	11	93	10	70	-42	-112
36	Nyawara	Uyonga B	0.12	2013	0	0	0	0	1	0	1	12	1	10	-14	-24
12	Nyawara	Uyonga B	0.70	2013	90	0	25	7	4	1	8	70	6	51	47	-5
19	Sauri	Sauri B	3.68	2013	85	7	0	0	5	1	14	65	7	76	20	-57
20	Sauri	Sauri B	0.35	2013	0	0	0	0	5	1	5	56	6	30	-62	-91
21	Sauri	Sauri B	1.04	2013	96	5	24	17	3	1	6	40	4	33	98	65
30	Sauri	Sauri B	0.79	2013	69	17	88	23	6	1	9	84	9	69	105	36
32	Nyamn	Muhanda	1.10	2013	148	13	0	0	3	1	5	36	4	28	121	93
40	Nyamn	Muhanda	0.19	2013	7	7	0	0	1	0	2	21	2	12	-9	-21
35	Nyawara	Uyonga B	0.26	2013	86	13	0	0	2	1	7	30	5	49	65	16
37	Nyawara	Uyonga B	1.31	2013	0	0	0	0	2	1	3	30	4	22	-34	-56
38	Anyiko	Tatro	1.66	2013	40	0	0	0	2	0	4	24	2	16	14	-2
39	Anyiko	Tatro	0.95	2013	0	0	0	0	3	0	6	41	2	22	-44	-65
22	Marenyo	Ng'utmb	1.94	2013	72	9	0	0	7	1	8	93	7	58	-19	-77
23	Marenyo	Ng'utmb	1.27	2013	18	1	0	0	4	1	8	54	4	38	-40	-78

Table S2: Net N contributions of legume rotations to the overall farm N economy (See Eq C1-C3).

Village (Farm)	Species	Density (plants/ha)	Plant N (g/plant)	Wood N (g/plant)	Biomass N (kg/ha)	N wood (kg/ha)	N added by legumes (kg/ha)
Madiri (3) Sauri B (6, 21)	T. candida	13333	8.4	1.9	112.5	25.3	87.2
Sauri B (30)	Mucuna	16667	2.5	---	41.7	0.0	41.7
Uyonga B (9)	T. candida	6667	4.6	1.1	30.7	7.1	23.6
Uyonga B (9)	C. grahamiana	6667	7.2	1.7	48.0	11.6	36.4

[1] Plant densities were calculated based on plant spacing in active legume rotations and via farmer interviews. Farm IDs are listed in parentheses, and can be cross-referenced with Farms in Table S1.

[a] Calculated from reported data in Gathumbi et al., 2002a; 2002b

[b] Calculated from data reported in Ojiem et al., 2007

Table S3: Macro and micronutrient concentrations (ppm) in soils collected from 0-10cm in different sub-locations of the Sauri cluster.

Sublocation	**Village**	Ca	K	Mg	P	Al	B	Ba	Cu	Fe	Mn	Na	Z
Anyiko	Tatro	1181.0	188.0	192.5	15.5	273.0	0.5	120.0	2.5	12.0	232.0	46.0	9.5
Sauri	Madiri	836.0	166.3	142.0	13.7	291.7	0.4	84.7	4.7	12.7	272.7	58.7	9.0
Marenyo	Ng'utmbaka	*no data*											
Nyamninia	Muhanda	1277.0	147.5	157.0	23.5	303.5	0.5	129.0	3.5	8.0	192.5	44.0	8.5
Nyawara	Nyamayoya B	944.7	88.3	121.7	14.7	245.3	0.4	100.7	11.3	11.7	188.3	48.0	9.0
Sauri	Sauri B	841.1	118.1	116.4	13.1	290.9	0.4	93.0	7.1	14.1	261.3	58.3	9.6
Nyawara	Uyonga B	814.4	134.6	124.8	15.4	271.0	0.4	94.6	5.0	12.4	199.0	50.4	8.0

Means presented by village. Arsenic, cadmium, chromium, molybdenum, nickel, and lead were all below <0.1 ppm.

Fig. 1

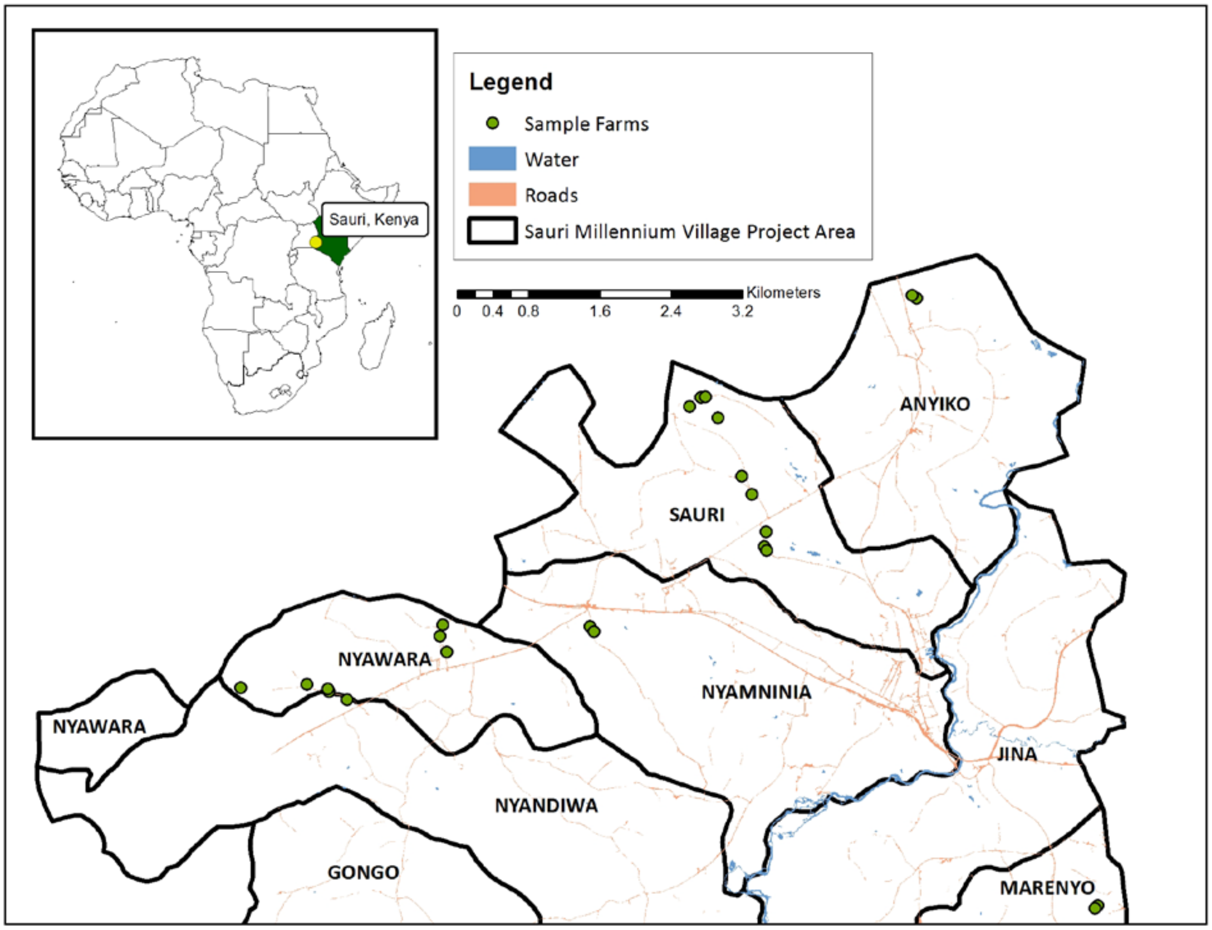
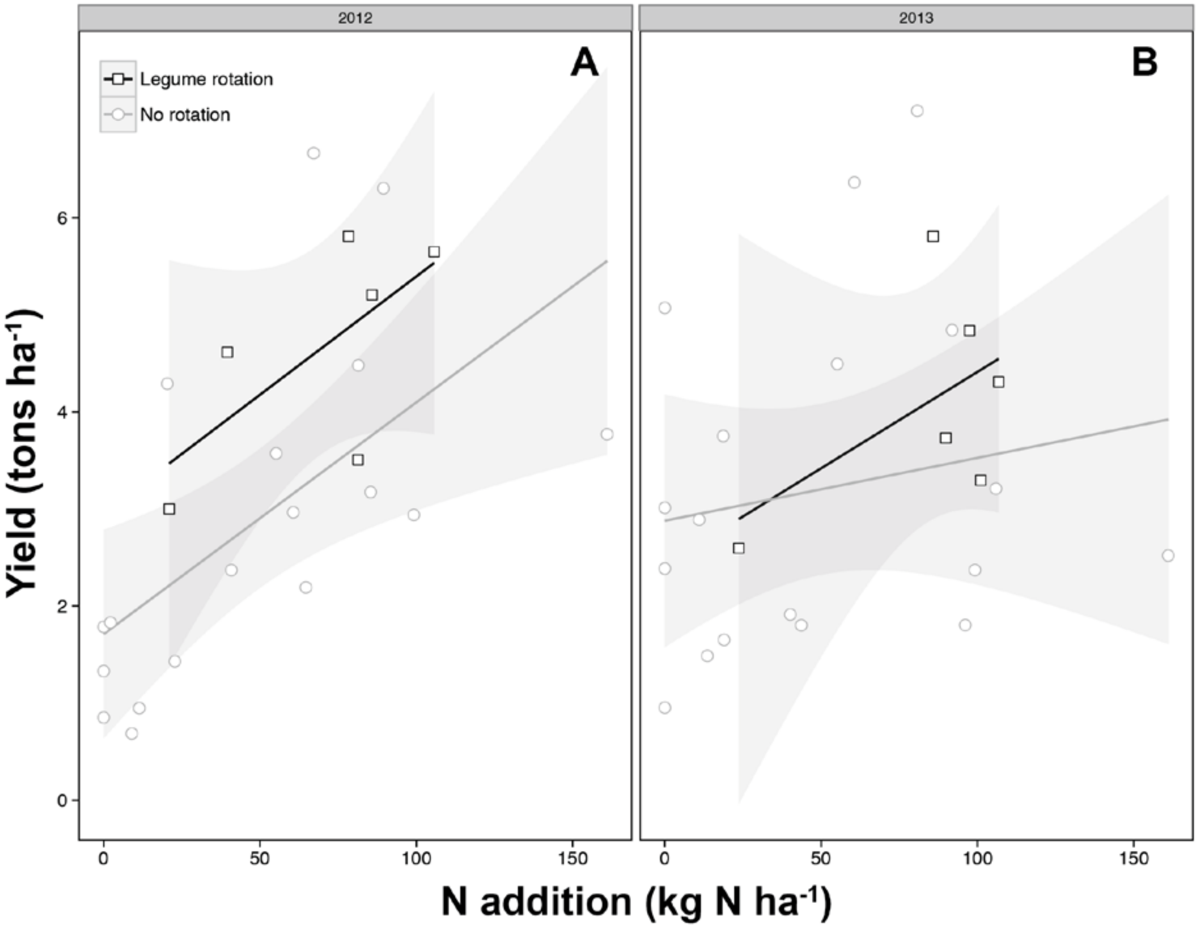

Sauri, Kenya
Legend
Sample Farms
Water
Roads
Sauri Millennium Village Project Area
Kilometers
0
0.4
0.8
1.6
2.4
3.2
ANYIKO
SAURI
NYAWARA
NYAMNINIA
NYAWARA
JINA
NYANDIWA
GONGO
MARENYO

Fig 2



2012
2013
A
B
Legume rotation
No rotation
Yield (tons ha^{-1})
N addition (kg N ha^{-1})
0
2
4
6
0
50
100
150
0
50
100
150

Fig 3

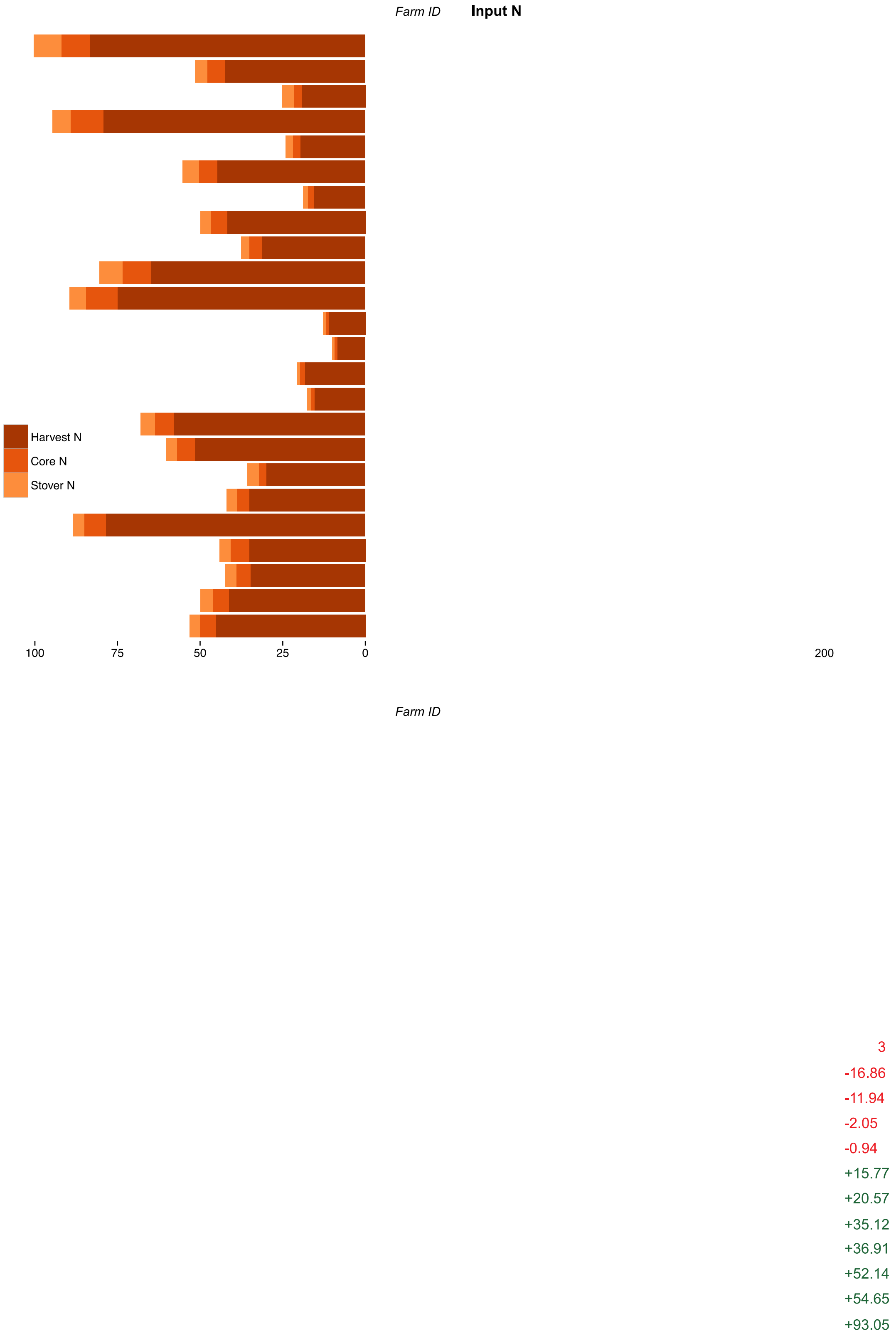
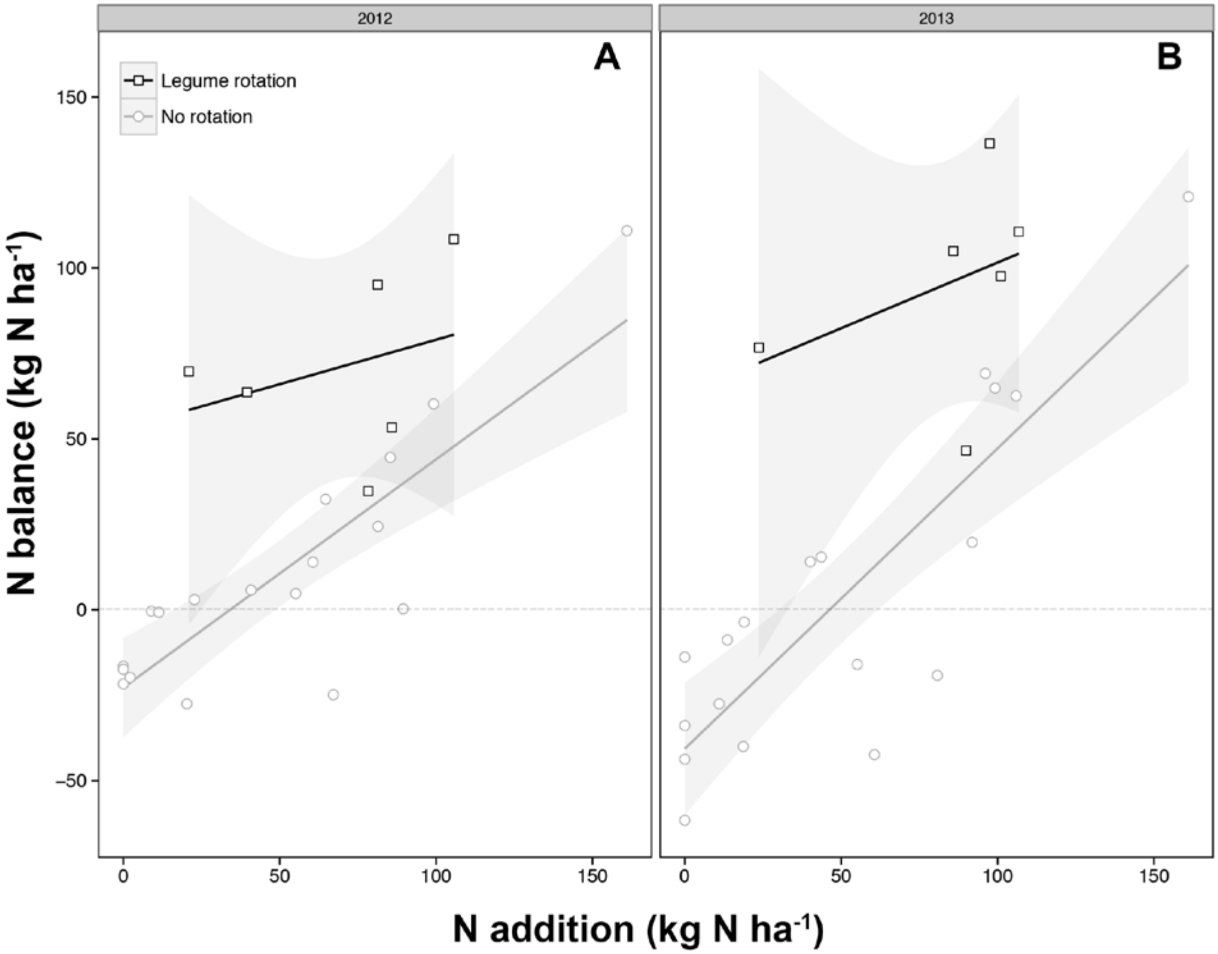
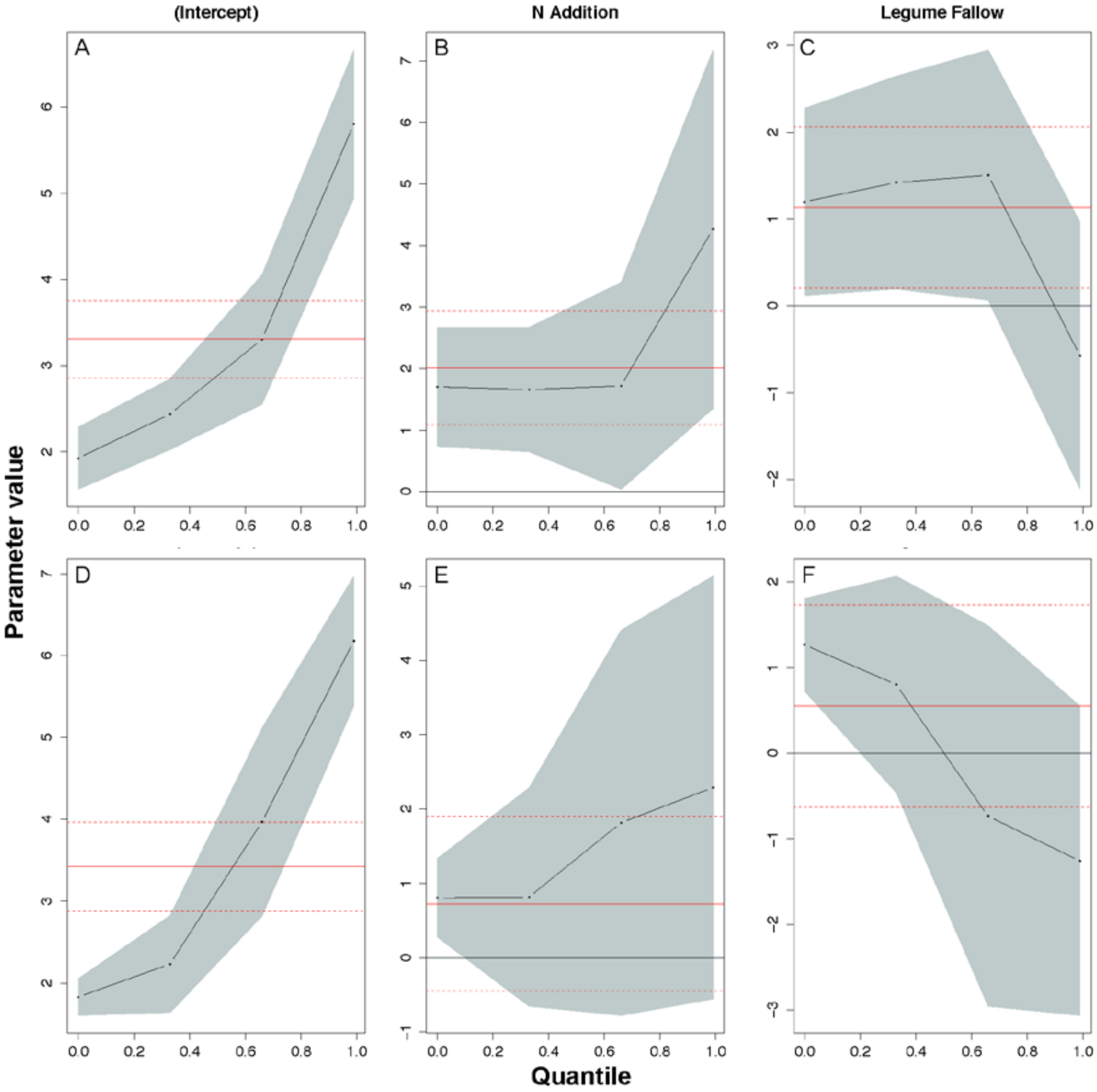

Farm ID
Input N
Harvest N
Core N
Stover N
100
75
50
25
0
200
Farm ID
3
-16.86
-11.94
-2.05
-0.94
+15.77
+20.57
+35.12
+36.91
+52.14
+54.65
+93.05

Fig 4



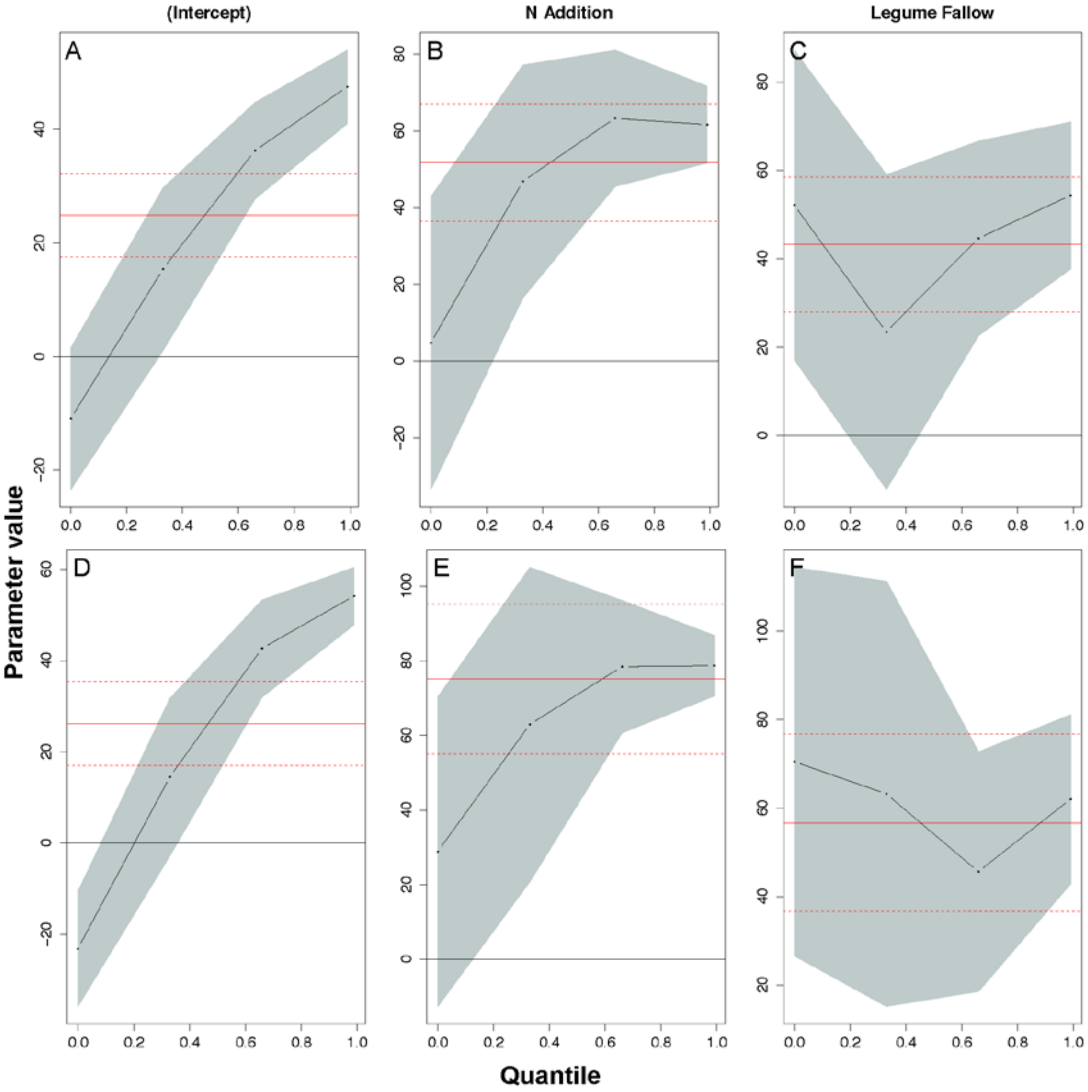
2012
2013
A
B
Legume rotation
No rotation
150
100
50
0
−50
N balance (kg N ha^{-1})
0
50
100
150
N addition (kg N ha^{-1})

Fig S1.



(Intercept)
N Addition
Legume Fallow
A
B
C
D
E
F
Parameter value
Quantile
0.0
0.2
0.4
0.6
0.8
1.0

Fig S2.


(Intercept)
N Addition
Legume Fallow
A
B
C
D
E
F
Parameter value
Quantile
-20
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0