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Does long-term low-rate organic and inorganic nitrogen management guarantee maize yield under semi-arid conditions of eastern Kenya?

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Abstract

Drier parts of Embu County endure high atmospheric heat, prolonged dry spells, declining soil fertility and erratic rainfall. Integrated soil fertility management (ISFM) technologies have been developed, and tested, with standardized application procedures and rates aimed at optimizing overall yield productivity. Despite their significant impacts, high variability in local soils and climate contributes to large variations and inconsistence in research results among replications of the expensive and limited (time/site/scenarios) experimental treatments. This occasions poor comparability of results within-and-without different agro-ecological zones (AEZs) due to the complex non-linear soil-climate-crop relations. Crop-growth simulation models suitably complement experimental research, to support decision making regarding soil fertility and water management. This study evaluated the performance of the Agricultural Production Systems Simulator (APSIM) model, parameterized and calibrated based on a rain-fed randomized complete block trial (2010-to-2013) at a research station in Machang'a, Embu County; and the long-term N management in maize production. The trials combined three and two level amendments each as follows; inorganic fertilizers (30 kg N ha^{-1}, 60 kg N ha^{-1} and 90 kg N ha^{-1}), goat manure, *Lantana camara*, *Tithonia diversifolia* (each at 30 kg N ha^{-1} and 60 kg N ha^{-1}), *Mucuna pruriens* (N depended on residue harvested; in a mirror rotation with maize) and control (TSP 60 kg ha^{-1}); replicated three times. Half rate (30 kg N ha^{-1}) applications were complimented by half rate inorganic fertilizer application. Model validation was based on goodness-of-fit between observed and simulated parameters derived from residual-errors statistics; root mean square error (RMSE), square of the correlation coefficient (R^2), and model efficiency (EF). APSIM simulations adequately predicted observed maize crop-growth (Leaf Area Index; LAI, Grain yield, and biomass). Grain prediction across the treatments was good (R^2=0.87 and EF>0.9) but biomass was slightly under-predicted (R^2=67 and EF=0.87). Long-term (26 cropping seasons) simulations showed that moderate and low cost application of N (40 kg N ha^{-1} from combined manure and mineral fertilizer) improved both long-term average and the minimum guaranteed grain yield (2.5 Mg ha^{-1}) and thus recommended for smallholder farmers especially in dry areas. These findings should be considered in conditions where P is added proportionally to N (P/N in the range of 20 to 30%).

Key words: Agro-ecological zones, integrated soil fertility management

Résumé

Les parties sèches du comté d'Embu subissent une haute chaleur atmosphérique, des périodes de sécheresse prolongées, la baisse de la fertilité des sols et de l'irrégularité des précipitations. La gestion des technologies de la fertilité intégrée des sols (GIFS) a été développée, et testée, avec des procédures et des taux d'application normalisés visant à optimiser la productivité globale du rendement. Malgré leurs impacts significatifs, une grande variabilité dans les sols locaux et le climat contribuent à d'importantes variations et incohérence dans les résultats de recherche entre les répétitions des (temps / site / scénarios) coûteuses et limitées traitements expérimentaux. Ceci donne une mauvaise comparabilité des résultats au sein et en dehors de différentes zones agro-écologiques (ZAE) en raison de non-linéaire des relations complexes sol-climat-cultures. Les modèles de simulation de croissance des cultures convenables, complètent la recherche expérimentale, pour appuyer la prise de décisions concernant la fertilité des sols et la gestion de l'eau. Cette étude a évalué la performance du modèle des Systèmes de Simulateur de Production Agricole (APSIM), paramétrée et calibrée sur la base d'un procès pluviale de blocs aléatoires complets (2010 à 2013) à une station de recherche dans Machang'a, dans le comté d'Embu comté; et la gestion de N, à long terme, dans la production de maïs. Les essais combinés de trois et de deux modifications apportées au niveau de chaque comme suit : engrais minéraux (30 kg N ha^{-1}, 60 kg N ha^{-1} et 90 kg N ha^{-1}), le fumier de chèvre, *Lantana camara, Tithoniadiversifolia* (chacun à 30 kg N ha^{-1} et 60 kg N ha^{-1}), *Mucunapruriens* (N dépendait du résidu a récolté; dans une rotation à reflet avec le maïs) et de control (TSP^{-1}60 kg ha); répliquée trois fois. Les applications de taux de moitié (30 kg N ha^{-1}) ont été complétées par la moitié du taux de l'application d'engrais inorganique. La validation du modèle a été basée sur la bonté de l'ajustement entre les paramètres observés et simulés provenant de résiduels-erreurs statistiques; l'erreur quadratique moyenne (RMSE), le carré du coefficient de corrélation (R^2), et le modèle d'efficacité (EF). Les Simulations APSIM prédisaient correctement la récolte de maïs de croissance observée (indice foliaire du lieu, LAI, le rendement grainier et la biomasse). La prédiction de grains dans les traitements était bon (R^2 = 0,87 et EF> 0,9) mais la biomasse était légèrement sous-estimée (R^2 = 67 et EF = 0,87). À long terme (26 saisons de culture), les simulations avaient montré que l'application d'un coût modéré et faible de N (40 kg N ha^{-1} à partir de fumier combiné et engrais minéraux) ont amélioré à la fois la moyenne à long terme et le rendement en grains minimum garanti (2,5 Mg ha^{-1}) et donc recommandé pour les petits agriculteurs en particulier dans les zones arides. Ces résultats devraient être considérés dans des conditions où P est ajouté proportionnellement à N (N / P dans la gamme de 20 à 30%).

Mots clés: zones agro-écologiques, la gestion intégrée de la fertilité

Background

In Kenya, most smallholder farmers in the densely populated Central Highlands are resource deprived operating below their agricultural potential. Arid and semi-arid (ASALs) parts of Eastern endure high atmospheric heat, prolonged dry spells/droughts, low and declining soil fertility and erratic rainfall patterns with large and growing population segments. Integrated soil fertility management (ISFM) and soil-water conservation (SWC) technologies have been developed and tested with standardized application procedures and rates for the region (Bationo *et al.*1995, Micheni *et al.*2004, Mugwe *et al.*2006; Mucheru-Muna *et al.*2009 and Ngetich, 2012). Despite their significant impacts, field experiments are quite expensive, only allow for a few fertility management options to be tested, on a limited number of sites and years and thus cannot fully capture the complex and highly non-linear soil-climate-crop relations. Experimental trials also do not report consistent results from year-to-year, site-to-site as well as amendment-to-amendment. Besides, substantial literatures argue that investing in the recommended optimal N rates/sources pose high socio-economic risks to poor smallholder farmers often due to persistent crop failures (Shapiro and Sanders, 1998; and Abdoulaye and Sanders, 2005). Indeed maximizing yield productivity is undisputable, most smallholder farmers in these ASALs often aim at minimizing inter-seasonal yield variability, failure and production costs to guarantee some minimum yield to meet family food requirements (Shapiro and Sanders, 1998 and Christianson *et al.*1990). This is a palpable case of the drier parts of Eastern Kenya. To address such limitations, the predominant shorter-term experiments can be complemented with properly calibrated and validated mathematical dynamic crop models which simulate the most important biophysical processes (soil water and N dynamics and crop growth) and scenarios. APSIM application in the central Highlands of Kenya remains limited yet its utilization may aid in enhancing agricultural productivity in the region. For all these reasons and need for increased replication of experimental trials, This study therefore sought to calibrate and validate the APSIM model in line with maize production systems under selected soil fertility (N) amendments (Manure, *Lantana camara*, *Mucuna pruriens*, *Tithonia diversifolia*, and inorganic fertilizers). The model was subsequently used to simulate long-term maize response to N management in the otherwise heterogeneous maize production system of the drier parts of Embu County; Eastern Kenya. This was envisaged to guide on better adapted recommendations to smallholder in the region.

Literature review

Nutrient depletion, low soil fertility due to Nitrogen and Phosphorus deficiencies and low levels of soil water availability have predominantly contributed to per capita and yield production in the central highland of Kenya, (Mugwe et al, 2006). The region continues to be highly dependent on the agricultural sector for its livelihood. Small-scale farmers predominate in a climate of increasing population pressure, food insecurity, very low (and declining) levels of agricultural productivity, and rapid natural resource degradation (Mucheru-Muna et al., 2009). Ongoing studies and field-experiments in the region have incepted mechanisms that will ensure food self sufficiency, especially for maize, which is both a staple and main food security crop. Inception of ISFM strategies has been intended to optimize productivity through reduction of these limiting biophysical factors. Shisanya et al (2006) notes that, Soil fertility and water conservation strategies, aimed at maximizing rainwater utilization, have the potential of contributing to mitigate rainfall fluctuations, and thereby increase overall yield levels, stabilize yields over time due to increased water availability and improved nutrient uptake by crops, hence, more crop per drop of rain. Besides, modification of the soil surface through tillage and residue management leads to changes in the soil water balance and hence WUE through impact on evapotranspiration and crop yield (Shisanya 1996). The soil nutrient status has been shown to have a positive impact on water use efficiency (Hatfield et al., 2001). Combined with alternative cropping strategies, benefit maximization may be realized. Choice of the optimal alternative cropping strategies relies on biophysical factors of a given region that ought to be determined. These comprise of the key facets of ISFM strategies that require further ex-ante appraisal to determine their optimal benefits to small scale farmers in the study area.

Study description

The study was conducted in the drier parts of Eastern Kenya, in Mbeere South Sub-county, (of Embu County) in the larger Central highlands of Kenya (Figure 1). Mbeere South Sub-county lies in the lower midland (LM) 3, 4 and 5, Upper midland (UM) 1,2,3 and 4, and Inner lowland (IL) 5 (Jaetzold *et al.*2006) at an altitude of approximately 500 m to 1200 m above sea level (a.s.l). The region experiences annual mean temperature and rainfall range of 21.7 to 22.5^o C and 700 to 900 mm respectively. It has a population density of 82 persons per km^2 with an average farm size less than 5.0 ha per household. The rainfall is bimodal with long rains (LR) from mid March to June and short rains (SR) from late October to December hence two annual cropping seasons. The soils are predominantly Ferralsols and Acrisols (Jaetzold *et al.*2006).

The studied experimentation period ran from SR2009 to LR2012 at a trial site in Machang'a Secondary School. Each plot measured 6 m by 4.5 m in area and the test crop was maize (*Zea mays* L, DH04 variety). Three maize seeds per hill were planted with a spacing of 0.9 m by 0.6 m between the plant and within the rows. Two weeks after germination, thinning was done to ensure the recommended population density per site. The experimental setup followed a randomized complete block design with the treatments shown in Table 1. Treatment with *Mucuna pruriens* adopted a mirror-rotation design whereby after each harvest, sole *Mucuna pruriens* biomass harvested was incorporated into the soil (then maize planted) and the previous plots with maize were grown with *Mucuna pruriens* at half (N at 30kg ha^{-1}) and full (N at 60kg ha^{-1}) rates. Each of the half rate organic fertility treatments were complemented with half rate mineral fertilizer spot applied as NPK 23:23:0 and Triple Super Phosphate (TSP) leading to the recommended N rate of 60 kg ha^{-1} while supplying 30 kg P ha^{-1}. The balance (60 kg P ha^{-1}) of phosphorous was applied as TSP to give a total P of 90kg ha^{-1}. All other standard agronomic practices were followed for optimal productivity. The organic materials (*Tithonia diversifolia and Lantana camara*) were harvested from the nearby plots established for the study purpose. N content of all organic inputs were determined and the amounts equivalent for providing 30 or 60 kg N ha^{-1} were calculated. Quantities of *Mucuna pruriens* supplied depended on the biomass produced.

The APSIM 7.5 model was utilized during this study. The model is a modular modeling framework inbuilt with five modules: maize crop module (APSIM-Maize), soil water module (SoilWat), soil nitrogen module (Soiln), residue module (Residue), and the manure module (Manure) (Keating *et al.*2003). Model validation entailed examination and comparison of measured versus simulated parameter values based on all treatments and six growing seasons' data of the experiment. Simulated crop parameters were grain yield, total above ground biomass and Leaf Area Index (LAI) as influenced by nitrogen (sources and rates) and soil water, in selected treatments and growing seasons. Owing to the fact that selected model parameters had to be adjusted or programmed on the basis of the study experiments (two), evaluation of the model performance would be considered a true calibration. Both statistical and graphical techniques were utilized during model calibration and validation. Statistical analyses were based on goodness of fit between observed and simulated derived values from residual errors. The statistics used were root mean square error (RMSE) (Equation (*i*), the square of the correlation coefficient (R^2; whose range is; 0d"R^2d" 1) (Equation *ii*), and model efficiency (EF; which is d"1) (Equation *iii*).

Research application

The model on overall reproduced well trends in maize grain (R2>80) yield in response to N rates and adequately reproduced complete crop failure of LR2011 (R2=1) as experienced during the field experimentation (Table 1).

Table 1. Root Mean Square Error (RMSE), linear correlation coefficient (R^2) and modeling efficiency (EF) values of total above-ground biomass and grain yield as affected by combined application of manure, crop residue incorporations, and mineral fertilizers during growing seasons from SR2009 to LR2012.

	Above-ground biomass						Average
	SR2009	LR2010	SR2010	LR2011	SR2011	LR2012	
RMSE (mg ha^{-1})	4.572	2.537	0.261	0.011	3.616	2.581	2.262
R^2	0.01	0.80	0.88	1.00	0.60	0.88	0.70
EF	-2.47	0.77	0.86	0.99	0.57	0.83	0.26
Grain							
RMSE (kg ha^{-1})	0.149	0.586	0.011	0.000	0.261	0.127	0.189
R^2	0.77	0.84	0.87	1.00	0.79	0.95	0.73
EF	0.74	0.82	0.86	0.00	0.76	0.94	0.67

SR=Short Rain, LR=Long Rain, RMSE=Root Mean Square Error, Ms=Measured, Sml=simulated, R2=Linear Correlation Coefficient, and EF=Modeling Efficiency

It was established that application of low rates of N (0 to 40 kg ha^{-1} N) would lead to less inter-seasonal variations in grain yield compared to high rate N applications. While the recommended application of N (60 kg ha^{-1}) appeared to yield high grain, variations in yield were found to be markedly high with very low minimum guaranteed yield, despite its cost implications. Use of mulch at a rate of 5 and 6 Mg ha^{-1} under combined mineral and manure N at 40 kg ha^{-1} proved to increase harvestable grain yield to 3.5 Mg ha^{-1} which substantially can guarantee better harvest for small-holder famers (Fig. 1)

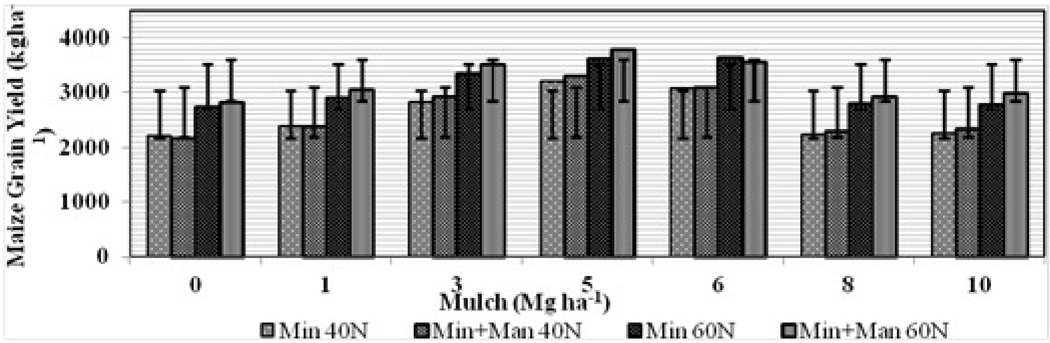

Figure 1. Long-term maize grain yield response to different rates (40 and 60 kg ha^{-1} N) and sources (sole mineral fertilizer or when combined with manure) of N and different mulch rates (0 to 10 mg ha^{-1}) in Machang'a. Error bars denote standard deviation of the means

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