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Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana

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ABSTRACT

The CERES-sorghum module of the Decision Support System for Agro-Technological Transfer (DSSAT) model was calibrated for sorghum (*Sorghum bicolor* (L.) Moench) using data from sorghum grown with adequate water and nitrogen and evaluated with data from several N rates trials in Navrongo, Ghana with an overall modified internal efficiency of 0.63. The use of mineral N fertilizer was found to be profitable with economically optimal rates of 40 and 80 kg N ha^{-1} for more intensively managed homestead fields and less intensively managed bush fields respectively. Agronomic N use efficiency varied from 21 to 37 kg grain kg^{-1} N for the homestead fields and from 15 to 49 kg grain kg^{-1} N in the bush fields. Simulated grain yield for homestead fields at 40 kg N ha^{-1} application was equal to yield for bush fields at 80 kg N ha^{-1}. Water use efficiency generally increased with increased mineral N rate and was greater for the homestead fields compared with the bush fields. Grain yield per unit of cumulative evapo-transpiration (simulated) was consistently higher compared with yield per unit of cumulative precipitation for the season, probably because of runoff and deep percolation. In the simulation experiment, grain yield variability was less with mineral N application and under higher soil fertility (organic matter) condition. Application of mineral N reduced variability in yield from a CV of 37 to 11% in the bush farm and from 17 to 7% in the homestead fields. The use of mineral fertilizer and encouraging practices that retain organic matter to the soil provide a more sustainable system for ensuring crop production and hence food security.

1. Introduction

The decline in soil productivity in the tropics and particularly in dryland areas continues to be a major concern to scientists and policy makers due to its direct implications on food security. Cereals are very important source of food in Sub-saharan Africa. Their productivity is, however, low due to the poor resource base, low input use and returns and rapid population increases. Inherently poor soils and unfavourable climatic conditions are further reasons for the low productivity.

Grain production is primarily rainfed in Ghana with annual precipitation ranging from 750 to 1150 mm in the semi-arid region. Onset and distribution of rainfall are erratic with frequent occurrence of drought periods that constrain yield. Early season runoff is substantial because of lack of ground cover at the end of the dry season. More so, the soils in this region are highly weathered, sandy, low in fertility and the use of external inputs is marginal. More than 60% of the population is smallholder farmers. Resource management strategies by farmers in their attempt to increase soil fertility have resulted in soil fertility gradient, with fertility decreasing with increasing distance from the settlements (Kpongor, 2007). This brought about two distinct farm types namely the homestead fields and the bush fields, which differ significantly in soil fertility. The homestead fields are close to the settlements and the bush fields are outside of the settlements. The homestead fields are more fertile and have higher organic carbon compared to the bush fields (Table 1). The use of fallow periods to restore soil organic carbon and fertility are no longer effective due to reduction in the length of the fallow periods as a result of increasing population pressures (Braimoah and Vlek, 2004).

Abbreviations: BD, bulk density; SAT, volumetric water content at saturation; LL, lower limit; DUL, drained upper limit; CERES, Crop Evaluation through Resource and Environment; DSSAT, Decision Support System for Agro-Technological Transfer; E_1, modified coefficient of efficiency; CGIAR, Consultative Group on International Agricultural Research; FAO, Food and Agriculture Organisation; AE_N, agronomic efficiency of mineral N use; SYI, sustainable yield index.

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Table 1
Soil chemical attributes (means and standard deviations) of top soil (15 cm) from the homestead and the bush fields at Navrongo Ghana.

Soil attributes	Homestead fields		Bush fields	
	Mean	SD	Mean	SD
pH	6.39	0.77	5.45	0.33
SOC (mg g^{-1})	6.50	6.10	4.20	2.40
Total N (mg g^{-1})	0.90	0.40	0.50	0.20
CEC (cmol (+) kg^{-1})	7.15	4.54	2.84	1.05
$P_{Available}$ (mg g^{-1})	28.11	23.87	3.24	9.36

Soil fertility in the region is often associated with soil organic carbon because of the low use of mineral fertilizers. It also depends on biomass managements and inputs, mineralization, leaching and erosion (Nandwa, 2001). Continuous removal of crop residues from the fields for domestic use is a practice that further depletes soil nutrients as external inputs of nutrients are low.

Nitrogen is the most limiting nutrient in crop production in Sub-Sahara Africa. About half the total amount of fertilizer used is in the cultivation of cereals. Although the area of land cultivated for sorghum and millet is large, very little of this area is fertilized. When these crops are fertilized, the rates are very low (Gerner and Harris, 1993). It is estimated that only an average of 9 kg of mineral fertilizer is used in Sub-Saharan Africa as compared to a world average of 93 kg (FAO, 2004). Hence, levels of fertilizer input do not compensate for nutrient lost through crop harvest, thus, creating a negative nutrient balance (Stoorvogel and Smaling, 1990; Vlek, 1993).

The low adoption of fertilizers use in Africa (Sanchez, 2002) is mainly because they are expensive compared to other continents. Also, there is a low proportion of irrigated land in the sub-region, hence, lower fertilizer efficiency under erratic rainfall events. It is therefore necessary to access nutrient and water productivity under the specific conditions of smallholder farmers in order to make informed decisions. As the environment is also an important biophysical yield-limiting factor, especially in the semi-arid regions of West Africa, nutrient and water productivity were accessed under a wide range of weather conditions. To do this requires the use of weather data for several years.

Crop simulation models have proven to provide an excellent approach in capturing the interactive soil-weather-management effect on crop productivity, CERES-sorghum (Crop Evaluation through Resource and Environment, version 4.0) module of DSSAT, a crop simulation model was used in the study. It is based on CERES-maize, a process level based model (Jones et al., 2003). It provides a daily time step simulation of biomass (above and below ground) leaf development, grain yield and other yield components. Input data required by the model are weather (daily minimum and maximum temperature, rainfall and solar radiation) crop genetic information, soil characteristics and plant management information (planting, fertilization, etc.). Phenological development is a function of growing degree days or thermal time and photoperiod. Thermal time is computed using an algorithm by Jones and Kiniry (1986) which assumes development rate increases as a linear function of temperature between the base temperatures (8 °C) and an optimal temperature of 34 °C.

This study seeks to (i) evaluate mineral fertilizer and water productivity of sorghum in both the homestead and the bush fields, (ii) evaluate the impact of varied weather conditions on crop productivity in these two locations.

2. Materials and methods

2.1. Study area

The study was conducted in Navrongo, in the Upper East region of Ghana. The region is bordered by latitude 10°15″ and 11°10″N and 0°0″ and 1°0″W. It falls in the transition between Guinea and Sudan savanna ecological zones. The main soil types found in the area are Endoeutric-stagnic Plinthosol and Eutric Gleyic Regosol (FAO classification). This study was carried out on Eutric Gleyic Regosol. The area has a uni-modal rainfall pattern with the rains starting from May, peaking in August and ending in September/October. Mean annual rainfall (based on 15 years data) value is 731 mm with a coefficient of variation of 17%. Monthly mean values of some weather parameters during the growing season are show in Table 2.

2.2. Experiment for model calibration

Experimental data used for the calibration of the CERES-sorghum model were principally generated from two planting date trials in 2005. Field experiments were conducted during the 2005 cropping season. The cultivar used was ICSV III, a pure-line cultivar developed at ICRISAT Asia center, Patancheru, India. Sorghum was cultivated under optimum conditions (no water or N limiting growth conditions) for two different sowing dates within the growing season (June–September). First sowing was on the 5th of June and the second on the 26th of June. Sorghum was sown in rows at distances of 75 cm × 25 cm. Manure (N = 0.95%) was applied at 3 t ha^{-1}, mineral N applied at 120 kg ha^{-1} (recommended rate is 80 kg ha^{-1}) in the form of sulphate of ammonia and P applied at 60 kg ha^{-1} (P_2O_5) in the form of single super phosphate. Supplementary irrigation was carried out to limit water stress on plants. The plants were monitored and phenological data as well as management information were collected. These include sowing date, date of fertilizer application, date of flag leaf stage, date of flowering, date for grain filling and date of maturity. The phenological stages were noted when 50% of plant population attained that stage. Final total biomass and grain yield were also measured from a plot size of 9 m^2 by harvesting above-ground biomass and separating them into the various components according to the procedure described in Hoogenboom et al. (1999). Grain yield and total biomass were expressed in t ha^{-1}. Soil samples (both disturbed and

Table 2
Monthly total rainfall, monthly mean solar radiation, maximum and minimum temperature in 2005 at Navrongo, Ghana.

Months	Solar radiation (MJ m^{-2} d^{-1})	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)
January	17.6	34.5	20.4	0
February	18.9	39.7	25.7	4.5
March	20.2	41.1	27.5	0
April	19.9	40.2	28.2	20.7
May	21.0	37.0	26.1	13.7
June	18.8	32.1	24.1	176.6
July	17.2	31.1	23.0	179
August	17.4	30.8	22.8	205.5
September	20.7	31.5	23.1	98.3
October	21.0	35.0	22.4	28.7
November	21.7	38.1	20.9	0
December	21.9	38.9	20.5	0

Table 3
Soil properties used for modeling sorghum yield in both the bush farms and the homestead farms.

Soil parameters	Layer				
	1 150[a]	2 150[a]	3 200[a]	4 250[a]	5 250[a]
Bush farms					
BD (g cm^{-3})	1.56	1.58	1.56	1.58	1.56
SAT	0.352	0.321	0.320	0.372	0.246
LL (cm cm^{-1})	0.046	0.096	0.110	0.122	0.139
DUL (cm cm^{-1})	0.203	0.209	0.205	0.209	0.195
Organic C (g 100 g^{-1})	0.39	0.36	0.32	0.37	0.32
Homestead farms					
BD (g cm^{-3})	1.54	1.53	1.62	1.63	1.64
SAT (cm cm^{-1})	0.353	0.357	0.369	0.341	0.338
LL (cm cm^{-1})	0.054	0.094	0.106	0.161	0.130
DUL (cm cm^{-1})	0.231	0.219	0.212	0.219	0.197
Organic C (g 100 g^{-1})	0.58	0.56	0.45	0.37	0.32

BD: bulk density, SAT: volumetric water content at saturation, LL: wilting point, DUL: field capacity.

[a] Layer thickness (mm).

undisturbed) were taken at different horizons (0–15, 15–30, 30–50, 50–75, 75–100 cm). Soil organic carbon, pH, soil particle distribution, wilting point, field capacity, bulk density and saturation were all determined as described in Hoogenboom et al. (1999).

2.3. Experiment for model evaluation

To evaluate the performance of the model, an independent experiment was set up (2005) in a randomized complete block design. Four different levels of mineral N fertilizer (0, 40, 80 and 120 kg N ha^{-1}) in the form of sulphate of ammonia were applied in the homestead farms as well as the bush farms. P was applied at 60 kg P_2O_5 ha^{-1} to all fields in the form of single super phosphate. Single super phosphate was used because it contains 8.7% of sulphur which is enough for plant requirement and ensures the effects of N and not S from the sulphate of ammonia was measured. Organic manure was applied in the homestead, a day before sowing at a rate of 1 t ha^{-1} (the average amount used in the study area). Experiments were conducted on the 5th and 26th of June 2005 (first and second planting dates respectively). Each experimental plot was 36 m^2. Treatments were replicated seven times in the homestead fields and four times in the bush fields. In the bush field, experiment was repeated for a second sowing date. Sorghum was sown in rows at distances of 70 cm × 25 cm. Data were collected on final total biomass and grain yield as indicated above. Total above-ground biomass accumulation over the growing season for the treatment with 120 kg N ha^{-1} was taken on a 1 m ^{2} plot sizes bi-weekly in the homestead. Plant samples were oven dried (70 °C to a constant weight) and analysed for tissue N content. Soil samples were collected at different horizons and results of test are reported in Table 3.

2.4. Model calibration and evaluation

Weather and phenological data for each sowing date experiments were used to determine a set of genetic coefficients. The original radiation use efficiency of 3.2 g plant dry matter/MJ PAR for the sorghum used in the version 4.0 of DSSAT was adjusted to 3.8 as used in version 3.5 (Ritchie et al., 1998) since the model was under predicting yield. The extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above the critical threshold was set at 0.01 degree days (MacCarthy et al., 2009). This was done to eliminate the influence of photoperiod on plant growth and development as the cultivar used was insensitive to photoperiod (Murty et al., 1998). Based on the phenological data collected, thermal degree times (P1, P5 and PHINT) were calculated from daily temperature data collected for the study area as mentioned earlier above. Table 4 shows the 5 genetic coefficients and their values as used in the study.

The mean estimated parameters of the two sowing dates (under optimal growth conditions) were used to calibrate the CERES-sorghum model (Jones et al., 2003). The genetic coefficients were calibrated until there was an appreciable agreement between measured and observed values for phenology and yield data.

2.4.1. Soil and water dynamics

CERES (Godwin)-based soil carbon and nitrogen balance were used for the simulations. Soil fertility factor was used to indicate the differences in fertility (Table 1) between the two study sites. Soil samples were taken from profile pits from the experimental sites at different horizons and analysed for organic carbon, pH, NH_4, NO_3 (Hoogenboom et al., 1999) bulk density and particle size distribution. Soil water balance method used is the tipping bucket method (Ritchie water balance). Evapo-transpiration was simulated using Priestley–Taylor/Ritchie method. These are all well documented in Hoogenboom et al. (2003).

Soil water dynamics is described in the soil water balance submodel of Ritchie (1998). Soil water content varies between the lower limit (LL) and the saturated upper limit (SAT). Excess water above the drained upper limit (DUL) drains to the next lower layer. DUL and LL were determined in the laboratory using pressure plate method and SAT was determined by determining soil water contents of core soil samples that had been saturated with water. Bulk density was determined using the core sampling method. Some of parameters used in running the model are presented in Table 3.

2.4.2. Weather

Weather data used by the model in running simulations were daily rainfall amount, daily solar radiation, minimum and maximum daily temperature. A summary of weather parameters for the growing season is presented in Table 2. These were collected from a weather station located in the study area. Fifteen years historical weather data for the study area were used as input data for the LARS-WG (Semenov and Brooks, 1999) a stochastic weather gener-

Table 4
The genetic coefficients of used for modeling the CSVII sorghum variety in CERES-sorghum model at Navrongo, Ghana.

Codes	Definitions	Values
P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod (expressed in degree days).	470
P5	Thermal time from beginning of grain filling to physiological maturity (expressed in degree days).	620
G1	Scaler for relative leaf size	21.0
G2	Scaler for partitioning of assimilates to the panicle (head)	7.0
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	65.0
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P_2O, the rate of development is reduced.	12.60
P2R	The extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P_2O.	0.01

ator to simulate 30 years weather data for the study area. This was used to evaluate the impact of weather on crop, nutrient and water productivity.

2.5. Statistical analysis

Generalised linear procedure of ANOVA was used to analyse the effect of N fertilizer on grain yield. Significant differences were considered at $p = 0.05$. ANOVA was also used to determine significant differences between yields from the homestead and bush fields. Statistical methods were employed in evaluating the performance of the crop simulation model in comparison with field measured/observed data. Methods used included Tukey test of pair-wise comparison, coefficient of determination (R^2), root mean square error (RMSE) and the coefficient of model efficiency (E_1).

RMSE is defined as; $\mathrm{RMSE} = [n^{-1}\sum(\mathrm{Yield}_{\mathrm{simulated}} - \mathrm{Yield}_{\mathrm{Observed}})^2]^{0.5}$ where n is the number of replicates in each sowing date experiment.

The modified coefficient of efficiency (E_1) originally defined by Nash and Sutcliffe (1970) is defined as

$$E_1 = 1 - \frac{\sum_{i=1}^{n}\left|\mathrm{Observed}_i - \mathrm{Simulated}_i\right|}{\sum_{i=1}^{n}\left|\mathrm{Observed}_i - \mathrm{Mean}_{\mathrm{obs}}\right|}$$

E_1 values range from $-\infty$ to 1.0, with higher values indicating better agreement between model simulations and observations. An E_1 value of zero denotes model performance is as good as the mean observed value of treatments. $E_1 = 1$ denotes a perfect fit for simulated and observed values. When $E_1 < 0.0$, then the observed mean value is a better predictor than the model.

A benefit to cost ratio estimates the equivalent monetary value of the benefits and costs to one or more strategies in order to establish whether they are worth while. A benefit to cost of using fertilizers was calculated for each of the management systems based on field data using the formula below:

$$\mathrm{B/C} = \frac{[\mathrm{PS} \times \mathrm{YI}]}{\mathrm{CF}}$$

where B/C is benefit to cost ratio, PS is price of sorghum, YI is yield increase under fertilizer treatments over the control, and CF the cost of applied fertilizer. Agronomic N use efficiency $\mathrm{AE_N}$ was calculated as the amount (kg) of grain yield increase per kg of applied N fertilizer.

$$\mathrm{AE_N} = \frac{Y_\mathrm{N} - Y_0}{F_\mathrm{N}}$$

where F_N is amount of N fertilizer (kg ha^{-1}) applied, Y_N is grain yield at a particular rate of N and Y_0 is grain yield under no N application. Partial productivity factor refers to the ratio of grain yield to the total nutrient applied (Pandey et al., 2001).

2.6. Long-term simulation experiment

Impacts of weather conditions on mineral fertilizer use efficiency as well as the water productivity were analysed using long-term weather data. The long-term weather data were generated based on 15 years data collected from the study area. The most economic rates of mineral N fertilizer for each management system were used as well as farmers' usual practice of not applying fertilizer. Soil data presented in Table 3 were used as baseline information for model application and initial soil parameters were reset for each simulation year (soil parameters were assumed to be the same at the start of each season). Sowing was allowed when soil water within 15 cm depth was above 15 mm within the month of June (June 1st to June 30th). The sustainable yield index (SYI) suggested by Singh et al. (1990) was used to evaluate the sustainability of crop production in the two management systems (homestead and bush fields).

$$\mathrm{SYI} = (Y_\mathrm{a} - \sigma){Y_\mathrm{m}}^{-1}$$

where Y_a is the mean yield, σ the standard deviation, and Y_m is the maximum yield obtained under each set of management system.

Table 5
Observed yield of sorghum in response to mineral N application in the homestead and bush fields at Navrongo, Ghana.

N applied (kg ha^{-1})	Homestead 1st sowing date (t ha^{-1})	Bush field 1st sowing date (t ha^{-1})	Bush field 2nd sowing date (t ha^{-1})
0	1.43	0.63	0.81
40	2.78	2.42	2.88
80	3.89	3.36	3.56
120	4.40	3.77	3.57

3. Results and discussions

3.1. Grain yields

Grain yield measured ranged from 1.43 t ha^{-1} when no mineral N fertilizer was applied, to 4.4 t ha^{-1} at 120 kg N ha^{-1} application in the homestead fields. In the bush fields, yield ranged from 0.63 t ha^{-1} grain in the control to 3.77 t ha^{-1} grains at 120 kg N ha^{-1} application for the first sowing date (Table 5). Significant ($p = 0.05$) grain yield increases in sorghum cultivation were observed between the homestead and the bush fields for all levels of mineral N fertilizer application. The low yields in the control which is a normal practice of farmers explain their reluctance to cultivate the bush fields for sorghum. The yield gaps between the two sites were not compensated for by the application of as much as 120 kg N ha^{-1} an indication that mineral N is not the only yield-limiting factor. This means that mineral fertilizer alone cannot solve crop production problems on poor soils. Yield differences are more likely to be attributed to the differences in their soil fertility (organic carbon). Thus, for improved crop production on the bush farms, mineral fertilizer must be complemented with measures to increase soil organic carbon as it is highly associated with fertility.

Risk is one of the main reasons for low pace in adopting new technologies (Walker and Ryan, 1990), hence, a benefit to cost analysis was carried out. A benefit to cost analysis based on field data, indicated that application of 40 kg N ha^{-1} yielded the highest financial returns to farmers on the homestead whilst 80 kg N ha^{-1} yielded the highest returns to farmer on the bush field. Thus mineral fertilizer can be used in both the homestead and the bush fields with benefits accrued to farmers.

3.2. Model evaluation

Sorghum grain yield in response to applied mineral N fertilizer was reasonably predicted by the DSSAT–CSM with a RMSE of 0.44 t ha^{-1}. Pair-wise comparisons of observed and simulated values indicate no significant difference ($p = 0.05$). The RMSE values measured for total biomass were also low, 0.65 and 0.60 t ha^{-1} for the bush fields and homestead respectively and with an overall coefficient of the model being 0.63. These results are comparable to those of Mavromatis et al. (2001) in their study on developing genetic coefficients for CSM with data set from crop performance trials. Simulations on the homestead fields (higher fertility) were better than those on the bush fields. This supports suggestion that the model was developed for environments with fewer problems with soil fertility (Gijsman et al., 1996). Both total biomass and grain yields were generally well predicted (Figs. 1 and 2). Tissue N uptake

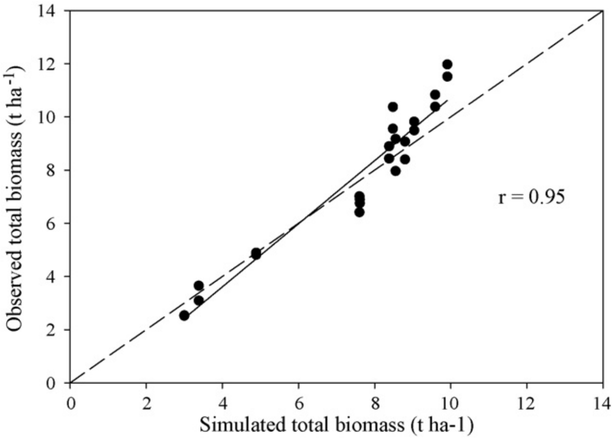

Fig. 1. Comparison of measured (mean) total biomass yield of sorghum and simulated total biomass values under different rates of mineral N applications on the homestead and bush fields at Navrongo, Ghana.

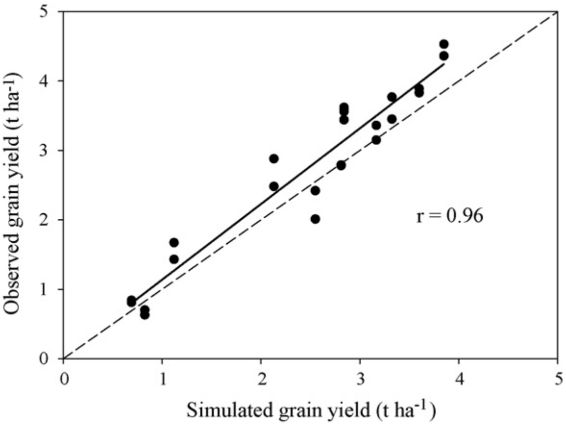

Fig. 2. Comparison of measured (mean) grain yield of sorghum and simulated grain yield values under different rates of mineral N applications on the homestead and bush fields at Navrongo, Ghana.

was also reasonably predicted (Fig. 3), an indication that nutrient uptake from soil is well simulated by the model.

3.3. *Nutrient and water use efficiencies of smallholder systems*

Since the model predicted grain yield reasonably well, AE_N, PF_N and water productivities based on observed data were similar to those based on simulations (Figs. 4 and 5). Agronomic N use efficiency in the homestead fields ranged from 25 kg grain kg^{-1} N at 120 kg N ha^{-1} to 34 kg grain kg^{-1} N at 40 kg N ha^{-1}. On the bush fields, the AE_N of sorghum ranged from 26 kg grain kg^{-1} N at 120 kg N ha^{-1} to 45 kg grains kg^{-1} N at 40 kg N ha^{-1}. Thus, AE_N was generally highest at low N application rates in both management systems, a trend which is comparable to that observed by Mushayi et al. (1999) and Zingore et al. (2007). The partial factor, an index of nutrient use efficiency calculated for each management system also indicated a similar trend of decreased nutrient use efficiencies with increasing application of mineral N fertilizer (Fig. 4). Though the homestead fields produced higher yields than the bush fields, the agronomic efficiencies were generally higher in the later due to the higher yields from the control in the homestead compared to lower values for the bush fields used in the calculations. Partial factor index differentiated between the homestead and the bush fields better in terms of fertilizer use efficiency of sorghum compared to agronomic nutrient use efficiency. The partial factor index provides a better basis for this comparison. It however, does not

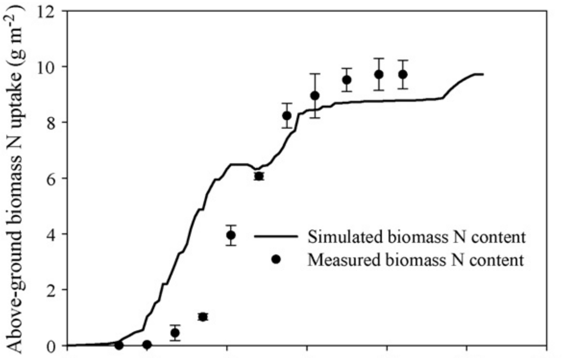

Fig. 3. Above-ground biomass N uptake (mean) over the growth cycle for the treatment with 120 kg N ha^{-1} applied in the homestead fields at Navrongo, Ghana.

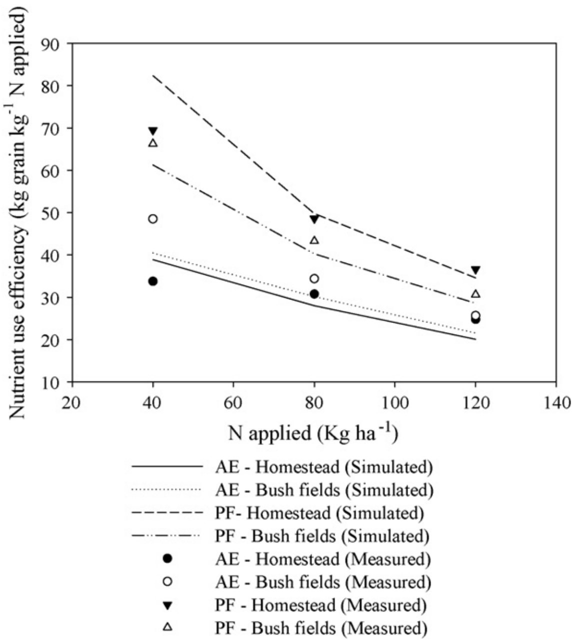

Fig. 4. The effect of the amount of mineral N applied on the efficiency attained in grain sorghum production in smallholder farming systems at Navrongo, Ghana.

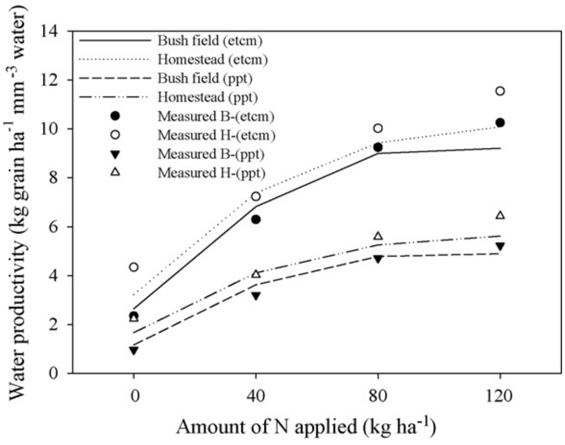

Fig. 5. The effect of amount of nitrogen fertilizer applied on the water productivity of sorghum on both the homestead and the bush fields in smallholder farming systems at Navrongo, Ghana.

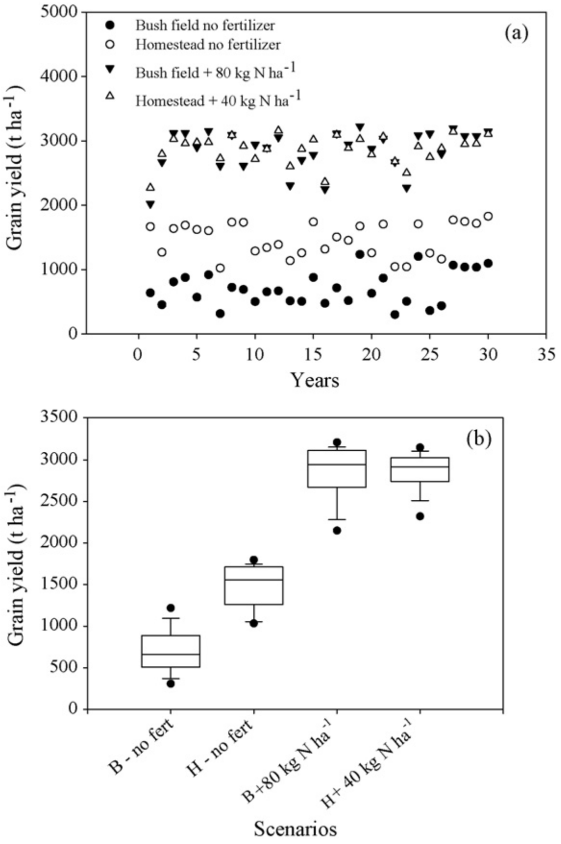

Fig. 6. The effect of 30 years of generated weather data for Navrongo on grain yield with 0 kg N ha^{-1} and economically optimal N rate in the homestead and bush fields at Navrongo, a semi-arid region of Ghana. Each box in the graph shows the distribution of grain yield over the simulation period. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the mean, and the upper boundary of the box indicates the 75th percentile. Whiskers above and below the box indicate the 95th and 5th percentiles. B: bush fields, H: homestead fields, fert: fertilizer.

account for inherent soil N content of the different management systems. Decreasing efficiency of N use with increasing mineral N fertilizer application observed in both systems is a situation typical of poorly managed and depleted sandy soils (Mushayi et al., 1999; Dobermann, 2005; Wopereis et al., 2006). There is therefore, the need to identify the most appropriate level of mineral fertilizer to be applied, given that it is a limited resource in the study area. The differences in nutrient use efficiencies shown in this study between the different management systems in light of the variable soil fertility conditions and responses to mineral N applications, provide a basis to discourage the current practice of “blanket” fertilizer recommendations.

Unlike the efficiency of nutrient use, water productivity increased generally (Fig. 5) with increasing application of N fertilizer and was higher in the homestead compared with the bush fields. As in AE_N and PF, productivity of water per calculations based on data from field observations and simulations was comparable (Fig. 5).

3.4. Scenarios simulation experiment

Sorghum grain yield at 40 kg N ha^{-1} in the homestead fields was similar to those at 80 kg N ha^{-1} in the bush fields over the simulation period (Fig. 6b). Higher grain yield in the homestead fields at half the amount of mineral fertilizer applied in the bush fields can be attributed to the differences in soil fertility. Yield simulations with 30 years weather data highlighted that the distribution of rainfall poses a risk to efficient use of mineral fertilizer on both management systems. This is evident in Fig. 7 where AE in both systems fluctuated with different rainfall regimes. The risks are higher on the bush fields soils compared with the homestead field which are relatively more fertile. Grain yield over the simulation period varied within each management system with or without mineral fertilizer application (Fig. 6a). Variability is however less in the homestead fields compared with bush fields when no fertilizer was applied. Differences in soil fertility resulted in 49% increase in grain production when no N fertilizer was applied. Hence, farmers can improve crop yields by adopting farming practices that help to improve organic matter of the soil. It also reduced the variability in water productivity from 31 to 13%. Also, applying mineral N fertilizer reduced the uncertainty (as expressed in CV) of low grain production from 13 to 7% in the homestead and from 31 to 10% in the bush fields. Seasonal variation in grain production in this study can be attributed mainly to rainfall pattern. This is buttressed by the results of the analysis of weather parameters that influence crop yield. Rainfall recorded the highest coefficient of variation of 244% as against 22 and 20% for average temperature and solar radiation respectively.

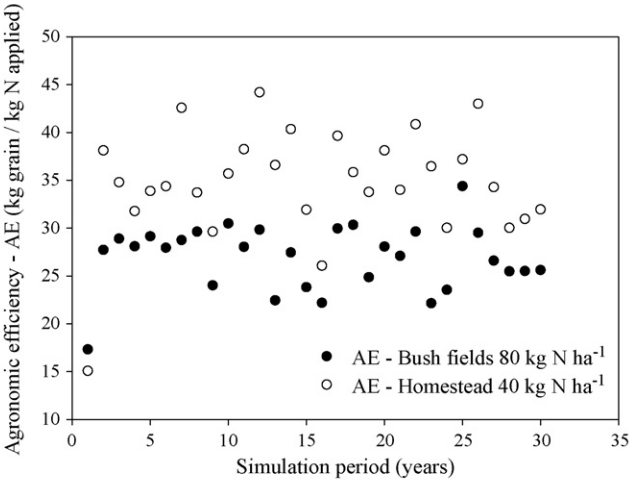

Fig. 7. The effects of 30 years weather data (generated) for Navrongo, Ghana on the agronomic efficiency of N use (AEN) in the homestead and bush fields.

Over the simulation period, productivity of water in the homestead fields at 40 kg N ha^{-1} was similar to those in the bush fields at 80 kg N ha^{-1}. Grain yield per unit cumulative evapo-transpiration (simulated) (Fig. 8b) was significantly higher than the productivity of water based on cumulative precipitation over the same growth period (Fig. 8a). These differences can probably be attributed to the amount of water lost through surface runoff and deep percolation, hence the need to implement measures (such as use of green manure) aimed at reducing surface runoff and deep percolation. The distribution of rainfall poses a risk to the efficient use of mineral fertilizer on both management systems, with the risks being higher in the bush fields as compared with the homestead fields.

3.5. Sustainability of grain production in the management systems

Sustainability indices of the various management scenarios as influenced mainly by changing weather pattern over 30 years are shown in Table 6. The highest SYI (0.84) was obtained in the homestead management system where 40 kg N ha^{-1} mineral fertilizer was applied. The least sustainable management practice (SYI = 0.36) was the bush field where no fertilizer was applied. Sustainable management practices, however, imply more than maintaining yields (Bhattacharyya et al., 2008; Lynam and Herdt,

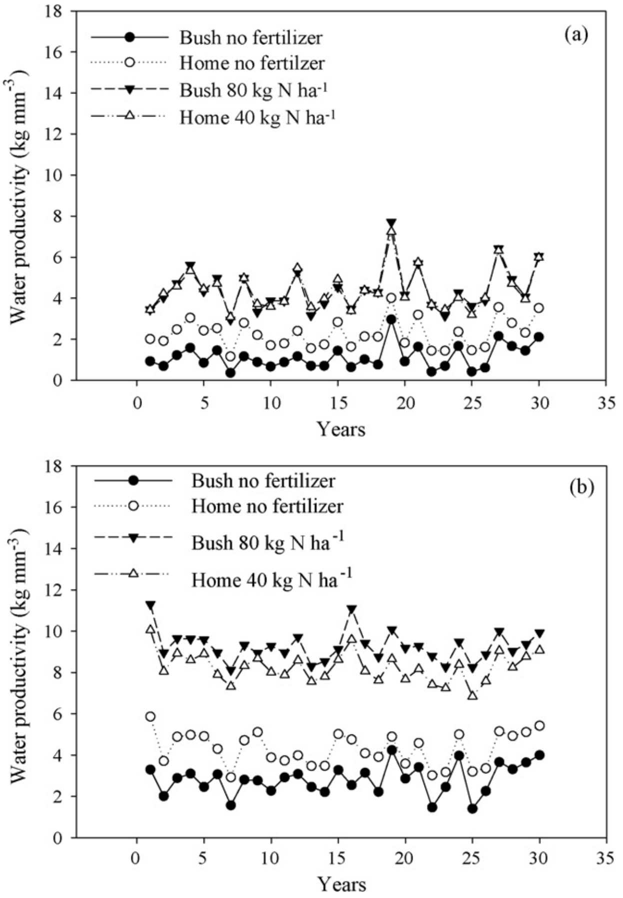

Fig. 8. Differences in water productivity of sorghum, using generated weather data under the different scenarios over the simulation period (30 years) in both homestead fields and bush fields. Water productivity is as a factor of (a) total precipitation since sowing and (b) as a factor of evapo-transpiration since sowing.

1989) hence AE, which provides information on the efficiency with which fertilizers are used, was also examined. From Fig. 7, it is clear that, applying 40 kg N ha^{-1} in the homestead fields was more agronomically efficient than applying 80 kg N ha^{-1} in the bush fields. This is indicated by the consistently higher AE values illustrated in the figure.

Differences in AE between the two systems can also be attributed to differences in soil fertility which positively influences the soil chemical and physical properties that are necessary for crop production. Though AE index is not recommended for comparing two different systems due to differences in their inherent soil properties (Dobermann, 2005), it however showed the differences in the efficiency of using mineral fertilizer in this study.

The highest cumulative rainfall amount over the simulation period was 978 mm with 433 mm being the least (Fig. 9). Grain yield under the least cumulative rainfall was however higher than that under the highest cumulative rainfall. The relation between total rainfall amount over the growing season and AE was also poor in both systems (r^2 = 7E−06 and r^2 = 9.8E−03 in the bush fields and homestead fields respectively). These imply that total amount of rainfall is not important in the study area, but its distribution over the growing season. The risk of lower sorghum yield due to erratic rainfall pattern was higher in the bush fields (CV = 37%) than the homestead fields (CV = 17), hence, to improve grain production in this region, practices that encourage the build up of organic matter (which is synonymous to soil fertility in the study region) are indispensable. Also, the risk of unstable yields over simulation period was reduced by the application of fertilizers in both systems (with fertilizer application, CV of 37% was reduced to 11% in the bush fields, and from 17 to 7% in the homestead fields).

Table 6
Summary statistics of grain yield projected over 30 year's period in Navrongo, Ghana.

Scenarios	Mean	SD	Max	Min	SYI
Bush farm, 0 kg ha^{-1}	0.71	0.264	1.2	0.3	0.36
Homestead, 0 kg ha^{-1}	1.48	0.256	1.8	1.0	0.67
Bush farm, 80 kg ha^{-1}	2.86	0.316	3.2	2.0	0.79
Homestead, 40 kg ha^{-1}	3.16	0.220	3.2	2.2	0.84

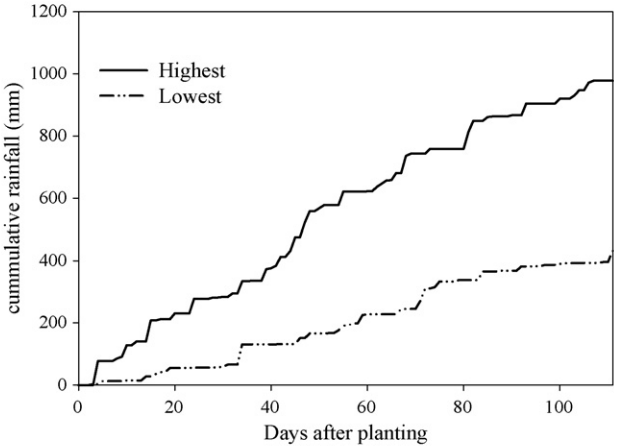

Fig. 9. Cumulative rainfall distribution (generated data) for the least and highest total rainfall amounts (over a 30 years period) during the respective growth periods.

4. Conclusions

The use of mineral fertilizer in sorghum cultivation is feasible in both management systems with higher returns from the homestead fields. Also, the risk of lower sorghum yield due to erratic rainfall distribution is higher in the bush fields with lower soil fertility (organic matter content). Smallholder farmers would be well off by investing in practices that improve soil fertility (organic matter) as to reduce risk associated with erratic rainfall distribution. It is also necessary to explore means of supplementing rainfall water to eliminate crop loss due to unfavourable distribution of rainfall during the growing season. CERES-sorghum currently, however, does not simulate P dynamics for sorghum, hence, limiting its use on P limiting soils. AE$_N$ was largely influenced by varied rainfall pattern as well as soil fertility (organic matter). The use of mineral fertilizer and encouraging practices that retain organic matter (such as retaining crop residues to soil) provide a sustainable system for ensuring crop production. Differences in nutrient use efficiencies between the different management systems in light of their varied soil fertility conditions and yield responses to mineral N fertilizer provide a basis to discourage the current practice of "blanket" fertilizer recommendations.

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