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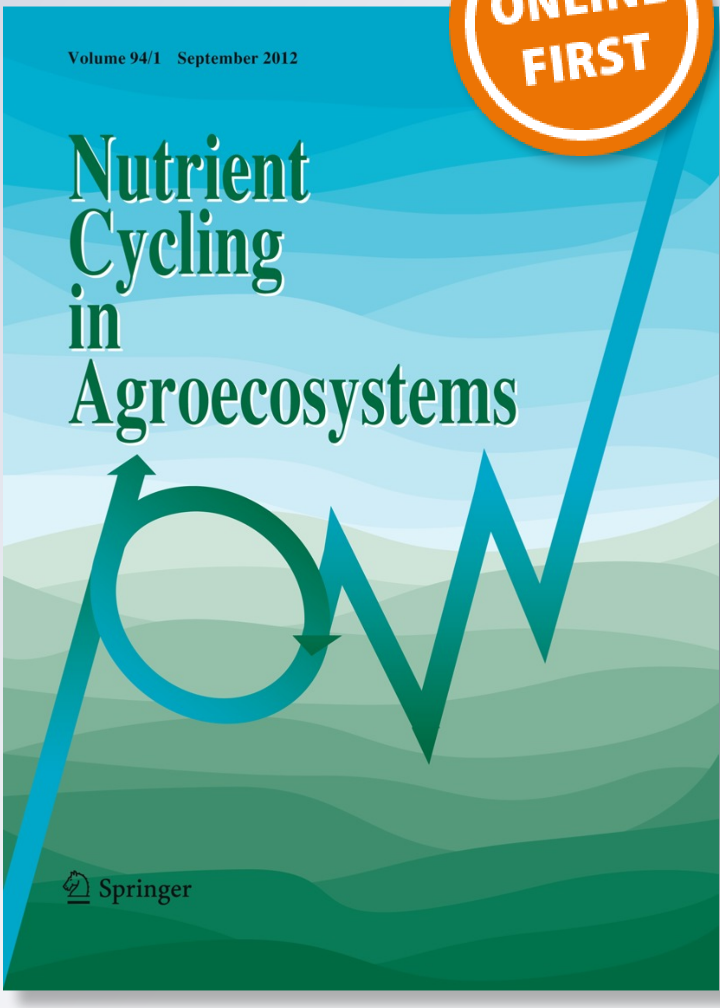

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ORIGINAL ARTICLE

Simulating impact of seasonal climatic variation on the response of maize (*Zea mays* L.) to inorganic fertilizer in sub-humid Ghana

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Abstract Under low input subsistence farming systems, increased pressure on land use and decreased fallow periods have led to a decline in soil productivity. The soils in sub-humid region of Ghana are generally poor and require mineral fertilizer to increase crop productivity. This paper presents the use of Agricultural Production Systems sIMulator (APSIM) to simulate the long term influence of nitrogen (N) and phosphorus (P) on maize (*Zea mays* L.) yield in Sub-humid Ghana. The APSIM model was evaluated at two sites in Ejura, on a rainfed experiment carried out on maize in 2008 major and minor seasons, under various nitrogen and phosphorus rates. The model was able to reproduce the response of maize to water, N and P, and hence simulated maize grain yields with a coefficient of correlation (R^2) of 0.90 and 0.88 for Obatanpa and Dorke cultivars, respectively. A 21-year long term simulation, with different rates of N and P mineral fertilizer application, revealed that moderate application of N (60 kg N ha^{-1}) and 30 kg P ha^{-1} improves both the long term average and the minimum yearly guaranteed yield. Variability in grain yield increased with increasing application of N fertilizer in both seasons. Treatments with P fertilizer application shows a similar trend for the major season and reverse trend for the minor season, thereby suggesting an interactive effect with rainfall amounts and distribution. Application of 30 kg P ha^{-1} significantly increased the response to N. The response to mineral fertilizer (N and P) applications varied between seasons, suggesting the need to have a range of fertilizer recommendations to be applied based on seasonal weather forecast.

Keywords Maize · Modelling · Nitrogen · Phosphorus · Simulation · Productivity

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Introduction

Maize is one of the most important cereal crops in Ghana, being one of the major staple foods for most communities as it contributes about 20 % of calories to their diet (Braimoh and Vlek 2006). The sub-humid region is one of the high food producing zones in the country. There is, however, a decreasing trend in the yield of maize over the years due to continuous

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cropping on the same piece of land with inadequate or no fertilizer use. Increased demand on land for other purposes has resulted in a decreased fallow period leading to a decline in soil fertility in the sub-humid region of Ghana. The farming systems are dominantly low-input and based around subsistence production. Due to the low input nature of the system, cereal production is hampered by low concentration of soil nitrogen (N) and phosphorus (P), and erratic and poorly distributed rainfall patterns (Bationo et al. 2003).

Most farmers are unable to purchase fertilizer to boost crop production due to the high cost of mineral fertilizers (Fosu et al. 2004). In Ghana most soils are deficient in phosphorus and nitrogen which are major constraints to food production. The total N in the top 15 cm of the study area ranged from 0.03 to 0.13 mg g^{-1} while the mean available P ranged from 8.28 to 12.7 mg kg^{-1} and these are woefully inadequate for crop productivity. Phosphorus deficiency reduces the response of crops to mineral N application (Smalberger et al. 2006, MacCarthy et al. 2009) through its negative influence on the photosynthetic activity of crops, resulting in poor growth and poor yield. The low concentrations of soil N and P are threats to food security in the country, unless measures are taken to improve on soil fertility. There is therefore, the need for external input of N and P and the need to determine optimal concentration to increase crop productivity. While these are crucial, it is important to consider variability in climatic condition when recommending best management of N and P fertilizers, as maize response to N is strongly dependent on climatic conditions mostly the amount and distribution of rainfall.

Systematic analysis of crop responses to N and P requires long term crop yield data sets. Experimental data are limited and expensive, as they require several years of experimental data gathering. The use of robust and well-tested crop growth models can be an effective way to analyse the complex relationship between management options and crop productivity. In recent years, crop simulation models have been increasingly used in sub Saharan Africa, thought the bulk of the studies have been concentrated in the semi arid and the sahelian regions. For example, Naab et al. (2004) used CROPGRO-Peanut to quantify yield gaps in peanut production in the Guinea Savannah region of Ghana. APSIM has also been used to aid decision making, regarding N fertilization in Pearl millet in the sahelian region (Akponikpe et al. 2010). There has been an assessment of the impact of contrasting nutrient and residue management practices on the yield of sorghum in semi-arid Ghana (MacCarthy et al. 2009). Delve et al. (2009) simulated P responses in annual crops on contrasting soil types using the APSIM-model for maize and beans in Kenya. MacCarthy et al. (2012), reported on evaluating DSSAT-CERES model to simulate the response of maize to N fertilization in the Sub-humid region of Ghana. Adiku 2007 also used DSSAT in their study "Can ENSO help in agricultural decision-making in Ghana?" Soler et al. (2008) also used the DSSAT model for optimal planting date determination for millet in the Sahel. DSSAT was again used to assess future upland rice production in the Volta Region of Ghana (Tabi et al. 2010).

The capability for simulating crop growth in response to soil P makes Agricultural Production Systems sIMulator particularly suitable for analyzing crop production in Africa and hence Ghana, where crop yield and N use efficiency of applied mineral fertilizers are greatly affected by low soil available P. This paper aims at (a) evaluating the performance of APSIM in simulating maize growth and yield in response to inorganic N and P fertilization in sub-humid Ghana, and (b) assessing the impact of seasonal variations in weather parameters on the response of maize yield to inorganic fertilizer application.

Materials and methods

Study area

The study was conducted in Ejura, in the Sekyedumase District of the Ashanti Region of Ghana. Ejura is located in the southern fringes of the Volta Basin in a slightly hilly terrain (150–250 m above sea level (m.a.s.l.)). It lies in the sub-humid agro ecological zone, with the Moist forest in the south and the Guinea savannah zone to the north. The region is bounded by latitude 7°22′N and longitude1°21′W. This zone is characterized by a bimodal rainfall (major and minor seasonal rainfall) with mean annual rainfall of about 1,400 mm. The soils in the study area are Haplic Lexisol and Plinthosol (FAO classification). These soil types have high sand content and are acidic and are generally low in nitrogen and organic carbon.

APSIM model description

The Agricultural Production Systems sIMulator is a modular modelling framework that can be used to simulate complex climate-soil-crop systems (Keating et al. 2003). The APSIM-Maize, SOILN2, SOILWAT2 (Probert et al. 1998), met, and SOILP (soil phosphorus) modules were linked within APSIM version 6.1 to simulate the yield response of maize to inorganic N and P application.

The APSIM-Maize module simulates crop phenology, biomass accumulation, leaf area index (LAI), grain yield, water, N and P uptake on a daily time-step. The Maize module has 11 crop stages and 10 phases (time between stages). Commencement of each stage is determined by accumulation of thermal time, except during the sowing to germination period, which is driven by soil moisture. The phase between emergence and floral initiation is composed of a cultivar-specific period of fixed thermal time, commonly called the basic vegetative or juvenile phase. Between the end of the juvenile phase and floral initiation the thermal development rate is sensitive to photoperiod if the cultivar is photoperiod sensitive (further details are available in APSIM documentation at http://www.apsim.info/Wiki/Maize.ashx).

The SOILN2 module accounts for the dynamics of both carbon (C) and N in each soil layer. There are three pools of soil organic matter (FOM, BIOM and HUM). The FOM is the fresh crop residue and roots added to the soil and when these decompose, it is partitioned into the BIOM and HUM pools. The BIOM is the more labile, soil microbial products and has a high turnover rate, whilst the HUM forms a more stable soil organic matter. The decomposition rate of soil organic matter depends on soil water content, soil temperature, and C:N ratio. The SOILP module in APSIM simulates the mineralization of organic P sources in each soil layer, which is linked to decomposition of carbon from HUM, BIOM and FOM pools. SoilP assumes constant C:P ratios in BIOM and HUM but tracks C:P ratios of FOM and surface residues as crops add residues of varying P concentration. In addition to mineralization, P dynamics in soil depend on addition of P by fertilizer and crop residues, dissolution of rock P, loss of availability with time, and removal of P by crop uptake (for detailed description of SOILP refer to Probert 1985).

The SOILWAT2 module is cascading soil water balance model which works on a daily base to simulate soil water balance. The SOILWAT2 in the model are specified by the drained upper limit (DUL), lower limit of plant extractable water (LL15) and saturated water content (SAT). The measurement of soil water content before sowing defined the initial soil water content of the soil. All soil water characteristics were measured from the study site.

Experiments for APSIM parameterization

The APSIM–maize model was parameterized by using data collected during major and minor growing seasons in 2008 at Ejura Agricultural College in experimental trials with plots size of 6 m × 5 m. The treatments were laid out in a randomized complete block design (RCBD), with 3 replicates and 2 maize varieties (Obatanpa: a medium maturity cultivar; and Dorke: an early maturity cultivar). Seeds were sown at a depth of about 5 cm. Plots were fertilized with 120 kg N ha^{-1} and 60 kg P ha^{-1}. The full rate of phosphorus and half the rate of N were applied 10 days after sowing in the form of triple super phosphate (P_2O_5) and ammonium sulphate, respectively. The other half of N was applied 45 days after sowing. Supplemental irrigation (about 10 mm) was provided when necessary, to prevent water stress. Crop spacing was 75 cm between rows and 40 cm within rows, with planting density of 6.7 m^{-2}. Weeding was done manually, with hoe to keep the fields free from weeds.

The soil was sampled before establishment of the experiment (0–100 cm at 15 cm interval). Samples were air dried and passed through a 2 mm sieve, and soil analysis was carried out to determine soil pH, available P (Bray 1), total N [micro Kjeldahl distillation and titration method (Bremner and Mulvaney 1982)] and soil organic carbon (Walkely Black). Soil characteristics required for APSIM, such as initial ammonium and nitrate contents, and initial soil water, were obtained from detailed soil analysis. Access tubes were installed in plots, where profile probe was used to monitor soil water dynamics (graph not shown). The determination of SAT, DUL, and LL15 were based on the method described by Dalgleish and Foale (1998). Three samples were averaged to give the values. Labile P was measured, using Hedleys method (Tiessen and Moir 1993). The soil samples were also analyzed for P-sorption, as described in Owusu-Benoah and Acquaye (1989) (Table 1; Haplic Lixisol (Expt. 2), using an average value of three samples. Field observations and recording were done when 50 % of plant population per plot attained flag leaf, flowering, silking and physiological maturity stages. Time series plant sampling, from 1 m^2 plots, was done at two week intervals and biomass N and P concentrations were determined from dried plant biomass till flowering and dough stage. Samples were oven dried at 70 °C till constant weight was attained, and sub samples analyzed. Measurements of LAI were made with a canopy analyzer (LAI-Sun scan), in the center of each plot (three measurements were averaged to give one LAI value per plot) at 2-week intervals.

At physiological maturity, grain yield was determined by harvesting plants from the central portion of each plot (3 × 4 m); grains were separated from cobs on the stover and dry weights of stover and grains were determined after drying the samples at 70 °C until constant weight. Samples of both grain and stover were analyzed for N, using the Kjeldahl digestion method (Anderson and Ingram 1996) and P concentration, using the wet digestion procedure.

Experiments for APSIM evaluation

To evaluate the APSIM model, 4 experiments were conducted in Ejura during the major and minor seasons of 2008 at two different sites. Experimental plots of 6 × 5 m^2 were laid out in a randomized complete block design. Four concentrations of N (0, 40, 80, and 120 kg ha^{-1}) in the form of ammonium sulphate and three concentrations of P (0, 30, 60 kg ha^{-1}) in the form of triple super phosphate were applied. Treatments were replicated three times in each experiment. In the major season, Obatanpa and Dorke maize cultivars were sown on April 21 and 24 in experiment 2 and 1, respectively. In the minor season sowing was done on August 8 and 9 in experiment 3 and 4, respectively. Experiment 1 and 3 were located in Ejura farms site and experiment 2 and 4 in the Agricultural College.

Experiments 1, 2 and 3 were established on Haplic Lixisol, whereas the soil type for experiment 4 was Plinthosol. Plant density was the same as in the experiments for model parameterization. Soil characteristics, required for the APSIM model, were obtained from all experimental sites as earlier described under experiments for model parameterisation (Table 1). Phenological development (date of 50 % flowering and maturity), total biomass and grain yield were recorded as described earlier for use in evaluating the performance of model. Final harvests for both grain and biomass yield were done from the central area of each plot (4 m × 3 m). Plant tissue N using the Kjeldahl digestion system (Anderson and Ingram 1996) and P contents of above-ground biomass were also determined.

Model parameterization

Soil water, soil N and soil P modules

Drained upper limit water content (DUL), soil water content at lower limit (LL15), and SAT water content were determined (Table 1; Haplic Lixisol (Expt. 2)) and used to parameterize the model. The bare soil runoff curve number was set to 50, to account for low runoff due to the flat nature of the topography and the characteristic nature of a sandy soil. Layer drainage rate coefficient (SWCON) of 0.35 and a second stage evaporation coefficient (CONA) value of 2.0 mm/$t^{1/2}$ were used with other soil characteristic measured, to adequately represent soil water dynamics as measured in the field. Additionally, the default maximum root depth growth rate from juvenile to flowering stages were adjusted from 33 to 35 mm day^{-1}. Parameterization of organic carbon and soil pH were done based on measured data from experiment for model parameterization (Table 1; Haplic Lixisol (Expt. 2)). Nitrogen and P concentrations of biomass at different growth stages were used to parameterize the model using data collected under optimum growth conditions. The N and P concentration values were used to modify the maximum and minimum values for the maize model. Daily weather data (rainfall, minimum and maximum temperature, and solar radiation), for the study area, were collected from a near-by weather station, which is about 0.1 km from the Agricultural College site and 2.5 km from the Ejura farm site, was used in the meteorological module for model parameterization and evaluation. The minor season was affected by early drought as shown in Fig. 1.

Maize module

The growth, phenology and yield data collected in the field experiments were used to parameterize the maize

Table 1 Soil properties used for modelling maize yield in the study area

Soil layer Layer thickness (mm)	1 150	2 150	3 150	4 150	5 150	6 150	7 150	8 150	9 150
Soil parameters									
Haplic Lixisol (Expt. 1 and 3)									
BD (g cm^{-3})	1.50	1.55	1.54	1.54	1.44	1.50	1.40	1.40	1.40
SAT (cm cm^{-1})	0.401	0.388	0.387	0.394	0.398	0.409	0.457	0.457	0.461
DUL (cm cm^{-1})	0.310	0.318	0.311	0.308	0.344	0.359	0.407	0.407	0.407
LL (cm cm^{-1})	0.106	0.167	0.228	0.280	0.281	0.283	0.283	0.283	0.283
Soil C parameters									
Organic C (%)	1.1	0.68	0.51	0.46	0.42	0.38	0.28	0.28	0.28
Finert[a]	0.30	0.50	0.60	0.75	0.90	0.99	0.99	0.99	0.99
Fbiom[b]	0.035	0.025	0.015	0.01	0.01	0.01	0.01	0.01	0.01
Soil P parameters									
Labile P (mg/kg)	12.7	6.5	3.4	2.0	1.7	1.5	0.9	0.9	0.9
P sorption[c] (mg/kg)	50	125	150	200	200	200	200	200	200
Haplic Lixisol (Expt. 2)									
BD (g cm^{-3})	1.63	1.61	1.63	1.64	1.54	1.50	1.45	1.45	1.45
SAT (cm cm^{-1})	0.365	0.368	0.350	0.358	0.294	0.249	0.257	0.257	0.257
DUL (cm cm^{-1})	0.210	0.218	0.211	0.208	0.204	0.219	0.207	0.207	0.207
LL (cm cm^{-1})	0.080	0.161	0.198	0.069	0.260	0.257	0.258	0.258	0.258
Soil–C parameters									
Organic C (%)	0.58	0.55	0.51	0.46	0.42	0.38	0.34	0.34	0.34
Finert[a]	0.30	0.50	0.60	0.75	0.90	0.99	0.99	0.99	0.99
Fbiom[b]	0.035	0.025	0.015	0.01	0.01	0.01	0.01	0.01	0.01
Soil P parameters									
Labile P (mg kg^{-1})	9.4	4.8	2.3	1.8	1.4	1.1	1.0	1.0	1.0
P sorption[c] (mg kg^{-1})	50	150	200	200	200	200	200	200	200
Plinthosol (Expt. 4)									
BD (g cm^{-3})	1.57	1.55	1.58	1.56	1.56	1.66	1.73	1.73	1.73
SAT (cm cm^{-1})	0.384	0.392	0.381	0.389	0.266	0.254	0.232	0.232	0.231
DUL (cm cm^{-1})	0.203	0.212	0.201	0.197	0.195	0.189	0.189	0.198	0.189
LL (cm cm^{-1})	0.078	0.084	0.117	0.123	0.121	0.120	0.118	0.118	0.118
Soil–C parameters									
Organic C (%)	0.55	0.53	0.40	0.40	0.35	0.04	0.04	0.04	0.04
Finert[a]	0.30	0.50	0.60	0.75	0.90	0.99	0.99	0.99	0.99
Fbiom[b]	0.035	0.025	0.015	0.01	0.01	0.01	0.01	0.01	0.01
Soil P parameters									
Labile P (mg kg^{-1})	9.1	5.5	4.5	3.4	1.4	1.1	1.0	1.0	1.0
P sorption[c] (mg kg^{-1})	75	150	400	400	400	400	400	400	400

BD Bulk density, *SAT* volumetric water content at saturation, *DUL* drained upper limit

[a] Finert defines the proportion of the soil organic matter that is not susceptible to decomposition

[b] Fbiom is the proportion of the decomposable soil organic matter that is initially present in the more rapidly decomposing pool

[c] Sorption is the P sorbed at a concentration in solution of 0.2 mg l^{-1}

module. Thermal time accumulations were derived from observed phenology and weather data, using the algorithm described in Jones and Kiniry (1986). Data from each cultivar were used to estimate the genetic coefficient related to thermal time accumulations for the critical growth stages.

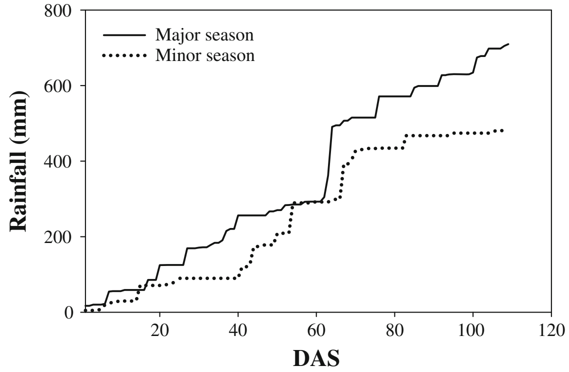

Fig. 1 Cumulative rainfall during major and minor season in Ejura, Ghana (2008)

The maize cultivars used in the experiment had not been previously modeled with APSIM. For the short- (Dorke) and medium-season duration cultivar (Obatanpa), the parameter set selected was SC709, a late-maturing hybrid from Zimbabwe for Obatanpa and hybrid 511 from Kenya for Dorke. In order to improve the fit between simulated and observed values for physiological maturity dates and yield for Obatanpa cultivar, the thermal time between Flowering stage and maturity (tt_flower_to_maturity) was increased from 760 to 830 °C days (Table 2). In addition, the maximum head grain number (head_grain_no_max) was reduced from 600 to 520, and the grain growth rate (grain_gth_rate) from 9 to 8. For the second cultivar (Dorke), the head grain maximum number (head_grain_no_max) was reduced from 450 to 420 and the grain growth rate (grain_gth_rate) was set at 8 mg day^{-1}.

The fraction of dry matter translocated to stem, that goes to developing the head, was adjusted from the default value of 0.17 to 0.19, as using the default slightly under predicted grain yield. Table 2 presents the genetic coefficient for the maize cultivars Obatanpa and Dorke used in APSIM. With the use of the soil data (Table 1; Haplic Lixisol (Expt. 2)), management data and weather data, APSIM model was run to predicted tasseling date, biomass and grain yield, which were compared with measured values.

Long-term simulation experiment

The sowing window used was 15 March to 10 May and sowing at soil depth of 50 mm, with a planting density of 6.7. Sowing was done when rainfall within

Table 2 Genetic parameters for the maize cultivars Obatanpa and Dorke used in APSIM

Parameters	Value	Units
Obatanpa cultivar		
Thermal time accumulation		
Duration from emergence to end of juvenile	300	°C day
Duration—end of juvenile to flowering initiation	20	°C day
Duration—flag leaf to flowering stage	10	°C day
Duration—flowering to start of grain filling	170	°C day
Duration, flowering to maturity	830	°C day
Duration—maturity to seed ripening	1	°C day
Photoperiod		
Day length photoperiod to inhibit flowering	12.5	H
Day length photoperiod for insensitivity	24.0	H
Photoperiod slope	23.0	°C/H
Grain maximum number per head	520	
Grain growth rate	8	mg/day
Base temperature	8	°C day
Dorke cultivar		
Duration from emergence to end of juvenile	285	°C day
Duration—end of juvenile to flowering initiation	20	°C day
Duration—flag leaf to flowering stage	10	°C day
Duration—flowering to start of grain filling	170	°C day
Duration, flowering to maturity	700	°C day
Duration—maturity to seed ripening	1	°C day
Photoperiod		
Day length photoperiod to inhibit flowering	12.5	H
Day length photoperiod for insensitivity	24.0	H
Photoperiod slope	10.0	°C/H
Grain maximum number per head	420	
Grain growth rate	8	mg/day
Base temperature	8	°C day

5 days is 20 mm. Seven rates of nitrogen fertilizer (0, 20, 40, 60, 80 100 and 120 kg N ha^{-1}) and two rates of phosphorus fertilizer (0 and 30 kg P ha^{-1}) were used. The N fertilizer concentrations were split applied. The first halves were applied 10 days after sowing, together with the full rate of P and the remaining halves applied 45 days after sowing. Initial soil conditions were reset at the beginning of each year. Soil organic C was reset to the starting value for the soil at the beginning of each season. Soil data (Table 1) for experiment 1 and 3 was used for the scenario analysis.

Statistical analysis

The performance of the model in predicting the grain yield, total biomass, N and P uptake of maize was evaluated using the square of the correlation coefficient (R^2), root mean square error (RMSE), and modified coefficient of efficiency (E1) (Willmott et al. 1985).The calculations were as follow:

1. Root mean square error (RMSE):

$$RMSE = \left[n^{-1}\sum(yield_{sim} - yield_{meas})^2\right]^{0.5}$$

where n is the number of replications, sim and meas denote simulated and measured total biomass, grain yield, N and P uptake for each replicate.

2. The modified coefficient of efficiency, E_1, was calculated as:

$$E1 = 1 - \frac{\sum_{i=1}^{n}|Observed_i - Simulated_i|}{\sum_{i=i}^{n}|Observed_i - Mean_{obs}|}$$

E_1 values range from -1 to 1, with higher values indicating better agreement between model simulations and observations.

$E_1 = 1$ describes a perfect fit of observed and simulated data whilst $E_1 = 0$ indicates the simulated data and describes the observations as well as the average of the observed data. In the modified version, squared difference terms are replaced by their respective absolute values, hence reducing the sensitivity of the coefficient to outliers, as in the original coefficient (Legates and McCabe 1999). *T* test was used to determine significant differences at $p < 0.05$.

Table 3 Effect of nitrogen and phosphorus fertilizer on Obatanpa maize grain yield at Ejura during the major and minor season, 2008

Treatment	N	P	Expt. 1	Expt. 2	Expt. 3	Expt. 4
Combination	(kg ha^{-1})		yield (kg ha^{-1})			
N1P1	0	0	1,623	1,258	1,285	918
N1P2	0	30	1,624	1,329	1,277	1,125
N1P3	0	60	1,699	1,379	1,355	1,222
N2P1	40	0	2,869	2,385	2,544	1,657
N2P2	40	30	3,625	3,010	3,206	2,672
N2P3	40	60	3,813	3,020	3,560	2,937
N3P1	80	0	3,757	3,260	3,269	2,649
N3P2	80	30	4,805	4,263	4,199	3,651
N3P3	80	60	4,903	4,482	4,509	3,735
N4P1	120	0	3,951	3,563	3,686	3,006
N4P2	120	30	4,953	4,597	4,462	3,881
N4P3	120	60	4,913	4,503	4,557	3,985
Mean			3,545	3,088	3,159	2,622
Effects			F-probability			
N			**	**	**	**
P			**	**	**	**
N * P			**	**	**	*

Expt. 1 Ejura farm major season; *Expt. 2* Agric college major season; *Expt. 3* Ejura farm minor; *Expt. 4* Agric college minor season; *NS* non-significant; *, ** significant at 0.05 and 0.01, respectively

Results

Soil data

Soil organic carbon content of the top soils (0–15 cm) at the experimental sites were 1.1 % (for experiments 1 and 3), 0.58 % (experiment 2) and 0.55 % (experiment 4) with standard deviations of 0.2, 0.06 and 0.1 respectively. The mean values of top soil labile P were 12.7, 9.4 and 9.1 mg kg^{-1} for experiments 1 and 3, 2 and 4 respectively with their respective standard deviations of 1.6, 1.1 and 1.2 mg kg^{-1}. The mean lower limit water content of the soils were 0.106, 0.086 and 0.078 cm cm^{-1} in experiments 1 and 3, 2 and 4 respectively with their respective standard deviations of 0.018, 0.024 and 0.020. The mean drain upper limit were 0.310, 210 and 203 cm cm^{-1} in experiments 1 and 3, 2 and 4 respectively, with their standard deviations of 0.041, 0.053 and 0.049.

Measured grain yield, total biomass yield and grain N uptake

Generally, N significantly ($p < 0.01$) increased grain yield of Obatanpa maize up to 80 kg N ha^{-1}. There was no effect of N beyond 80 kg N ha^{-1} if there was no P application. Table 3 presents grain yield of Obatanpa during major and minor seasons. Grain yield in Expt. 1 (Ejura farm major season) responded positively to N application, with yields ranging from 1,623 kg ha^{-1} in N1P1 (control) to a maximum yield of 4,953 kg ha^{-1} in N4P2 (120 kg N ha^{-1} and 30 kg P ha^{-1}). There was significant increase ($p < 0.01$) in grain yield when N was applied irrespective of the application of P. There was no significant response to P beyond 30 kg P ha^{-1}. Significant ($p < 0.01$) interactive effects of N and P mineral fertilizer on grain yield were observed. In Expt. 2, N and P significantly increased ($p < 0.01$) grain yields at all levels of N. The positive interactive effect of N and P was also significant ($p < 0.01$). Application of N fertilizer increased grain yields ranging from 1,258 in N1P1 to 4,597 kg ha^{-1} in N4P2 (Table 3). Similar trends were observed in Expt. 3 and 4 where grain yields ranged from 1,277 kg ha^{-1} in N1P2, to a maximum of 4,557 kg ha^{-1} in N4P3 in experiment 3 and 918 in the N1P1 to 3,985 kg ha^{-1} in experiment 4. In the Dorke cultivar also (Table 4), N and P and their interactive effect significantly increased grain yield at all levels of N. Grain yields ranged from 824 kg ha^{-1} in the control (Expt. 4) during the minor season to a maximum value of 4,267 kg ha^{-1} in N4P2 (Expt. 1) during the major season.

Nitrogen and P significantly ($p < 0.01$) increased total dry matter (TDM) production at all levels of N in both cultivars. In Obatanpa, Total biomass yield ranged from a minimum of 4,846 kg ha^{-1} (N1P1) to a maximum of 11,320 kg ha^{-1} (N4P3) while in Dorke maize cultivar, TDM ranged from a minimum of 2,858 kg ha^{-1}, in N1P1 (Expt. 4) to a maximum of 10,420 kg ha^{-1} in N4P3 (Expt. 1). In all experiments, significant ($p < 0.01$) increase in grain N uptake in Obatanpa were observed with the application of N and P inorganic fertilizers. Grain N uptake ranged from 12 kg ha^{-1} in the control, during the minor season (Expt. 4) to a maximum of 79 kg ha^{-1} in N4P3, during the major season (Expt. 1). Similar trend was observed in Dorke maize cultivar where grain N uptake ranged from a minimum of 11 kg ha^{-1} in the control during the minor season (Expt. 4) to a maximum of 68 kg ha^{-1} in N4P2 during the major season (Expt.1). In both cultivars, grain N uptake was higher during the major season.

Table 4 Effect of nitrogen and phosphorus fertilizer on Dorke grain yield at Ejura during the major and minor season 2008

Treatment	N	P	Expt. 1	Expt. 2	Expt. 3	Expt. 4
Combination	(kg ha^{-1})		Grain yield (kg ha^{-1})			
N1P1	0	0	1,182	1,072	1,222	824
N1P2	0	30	1,240	1,228	1,263	1,026
N1P3	0	60	1,337	1,214	1,255	1,220
N2P1	40	0	2,616	2,112	2,142	1,517
N2P2	40	30	2,963	2,585	2,971	2,617
N2P3	40	60	3,283	2,812	3,076	2,818
N3P1	80	0	3,339	2,772	2,823	2,228
N3P2	80	30	3,965	3,440	3,717	3,288
N3P3	80	60	4,157	3,657	4,007	3,406
N4P1	120	0	3,677	3,106	3,186	2,518
N4P2	120	30	4,267	3,825	4,176	3,343
N4P3	120	60	4,187	3,906	4,019	3,560
Mean			3,018	2,644	2,821	2,364
Effects			F-probability			
N			**	**	**	**
P			**	**	**	**
N * P interaction			*	*	**	**

NS Non-significant; *, ** significant at 0.05 and 0.01, respectively

APSIM parameterization

Mean total biomass yields obtained under the experiment for model parameterisations were 10,524 and 10,120 kg ha^{-1} and grain yield were 4,552 and 3,850 kg ha^{-1} for Obatanpa and Dorke cultivars, respectively. The observed development stages of the crop, as illustrated in Fig. 2, were well presented by the model. The APSIM model adequately simulated the phenology, N and P uptake, grain and biomass yields. The model simulated total biomass adequately, with 1.1 and −2.0 percentage difference between the simulated and the observed for Obatanpa and Dorke cultivars, respectively. Percentage difference between simulated and observed grain yields were 4.5 and 4.1 for Obatanpa and Dorke cultivars respectively.

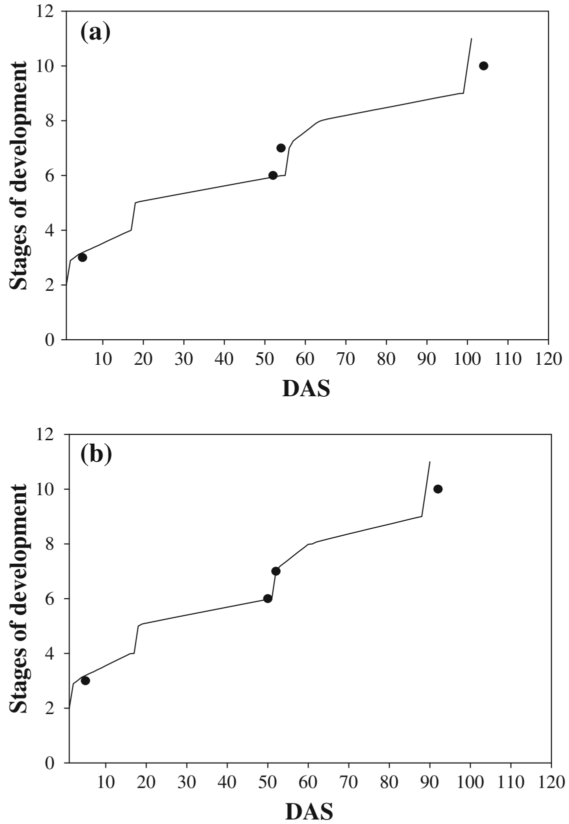

Fig. 2 Observed (*symbol*) and simulated (*line*) phenology of Obatanpa (**a**) and Dorke (**b**) maize cultivar from sowing to maturity for model parameterization

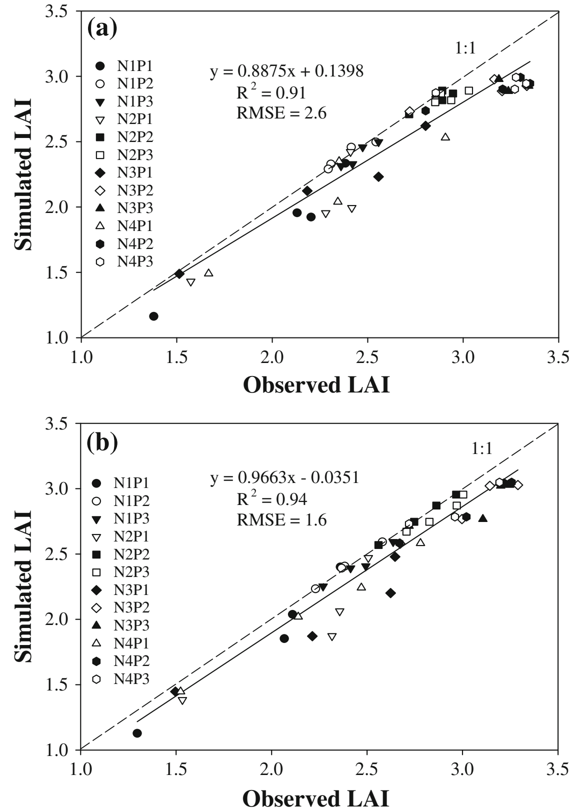

Fig. 3 Comparison of observed and simulated maximum LAI of Obatanpa (**a**) and Dorke (**b**) maize cultivars at Ejura, Ghana, 2008. N1, N2, N3 and N4 indicate 0, 40, 80 and 120 kg N ha^{-1}; P1, P2 and P3 are for 0, 30 and 60 kg P ha^{-1}

Evaluation of model performance

APSIM simulated number of days to tasseling of both cultivars, in response to inorganic fertilization well compared with the observed, with an overall RMSE of 1.5 and 1.4 days for Obatanpa and Dorke, respectively. In general, the model simulated crop duration, with RMSE values of 4.7 and 2.9 days for Obatanpa and Dorke, respectively. There was no significant ($p > 0.05$) difference between simulated and observed number of days taken for the crop to attain physiological maturity. The leaf area index simulation captured the response to N and P application, with coefficient of determinations (R^2) of 0.91 and 0.94 (Fig. 3) for Obatanpa and Dorke respectively. The model however, slightly under predicted LAI for both cultivars (Fig. 3). The APSIM-Maize model simulated time-series crop biomass accumulation, with good agreement with measured data (Fig. 4).

The measured total biomass ranged from a minimum of 2,858 kg ha^{-1} (control in Exp 4) to a maximum of 11,320 kg ha^{-1} with the application of 120 kg N ha^{-1} and 60 kg P ha^{-1} in Exp 1. There was a good agreement between the measured and simulated TDM, with overall R^2 values of 0.89 and 0.91 for Obatanpa and Dorke cultivars, respectively (Fig. 5). The RMSE values for TDM were 780 and 661 kg ha^{-1}, and model coefficients of efficiency (E1) were 0.68 and 0.70 for Obatanpa and Dorke, respectively.

In the Obatanpa cultivar, grain yield of maize ranged from 918 in the control (Expt. 4) to 4,953 kg ha^{-1} (Expt. 1) and that for the Dorke cultivar ranged from 824 to 4,267 kg ha^{-1}. The response of grain yield to different concentrations of inorganic N and P fertilizer applications were well presented by the model (Fig. 6). The RMSE values for grain yield ranged from 261 to 671 kg ha^{-1} and the modified coefficient of efficiency (E_1) of 0.63 and 0.62 for Obatanpa and Dorke, respectively. Grain yield simulation was generally better in the major season than in the minor season, with over estimation of grain yields, particularly at higher concentrations of N, in the minor season. In the minor season, both experimental sites were infested with stem borer, which led to a reduction in plant density and grain yield. Stress factors such as pests and diseases were not included in the model, hence were not reflected in the simulations. Generally, yields obtained during the major season were higher than yields in the minor season. This is, however, expected as higher rainfall amount was recorded during the major season than the minor season (Fig. 1). The application of 60 kg P ha^{-1} without N application did not result in increase in simulated grain yield.

Total N uptake was successfully simulated by the model for both cultivars for the different N and P fertilizer concentration (Fig. 7). However, there was a slight overestimation of total N uptake by the model, with over all RMSE values of 9.9 and 8.8 kg ha^{-1} for Obatanpa and Dorke, respectively. The model performed well with an overall correlation coefficient of 0.96 and modified coefficient of model efficiency of 0.71 and 0.72 for Obatanpa and Dorke, respectively. Similarly, total P uptake was well simulated by the model with overall R^2 of 0.86 and 0.85 for Obatanpa and Dorke, respectively (Fig. 8). However, the model underestimated total P uptake with a RMSE of 2.4 kg ha^{-1} for both cultivars.

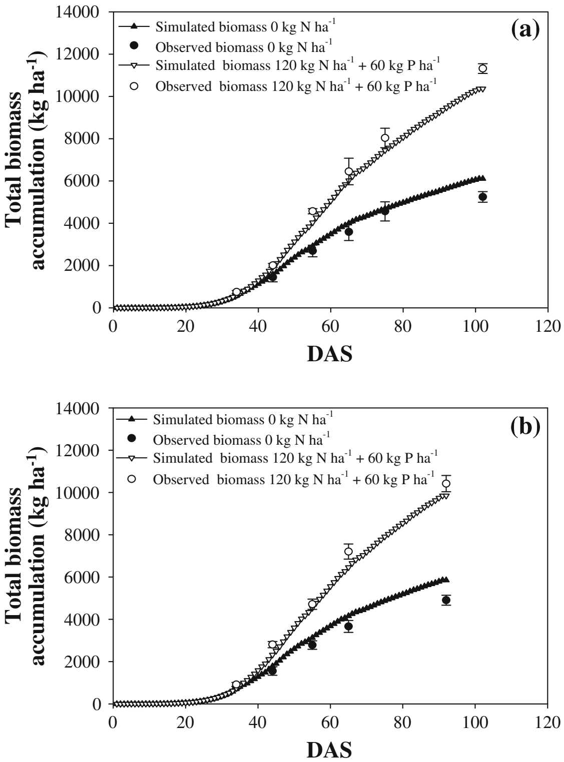

Fig. 4 Comparison of simulated and observed biomass accumulation of Obatanpa (**a**) and Dorke (**b**) maize cultivars in the major season on Haplic Lixisol in Ejura

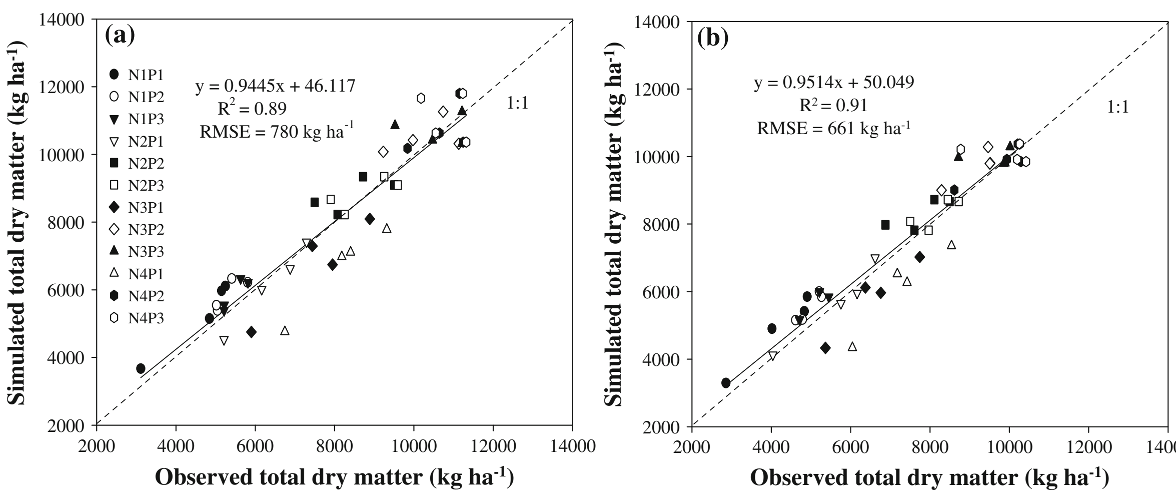

Fig. 5 Comparison of observed and simulated total dry matter of Obatanpa (**a**) and Dorke (**b**) maize for different treatments at Ejura, Ghana, 2008. N1, N2, N3 and N4 indicate 0, 40, 80 and 120 kg N ha^{-1}; P1, P2 and P3 are for 0, 30 and 60 kg P ha^{-1}

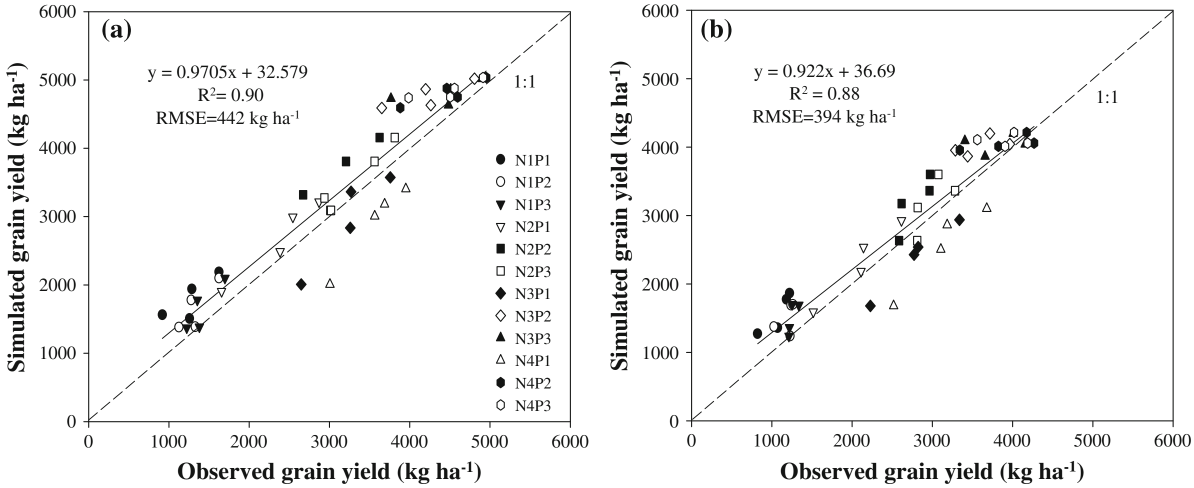

Fig. 6 Comparison of observed and simulated grain yield of Obatanpa (**a**) and Dorke (**b**) maize cultivars for different levels of N and P at Ejura, Ghana, 2008. (for legends see Fig. 5)

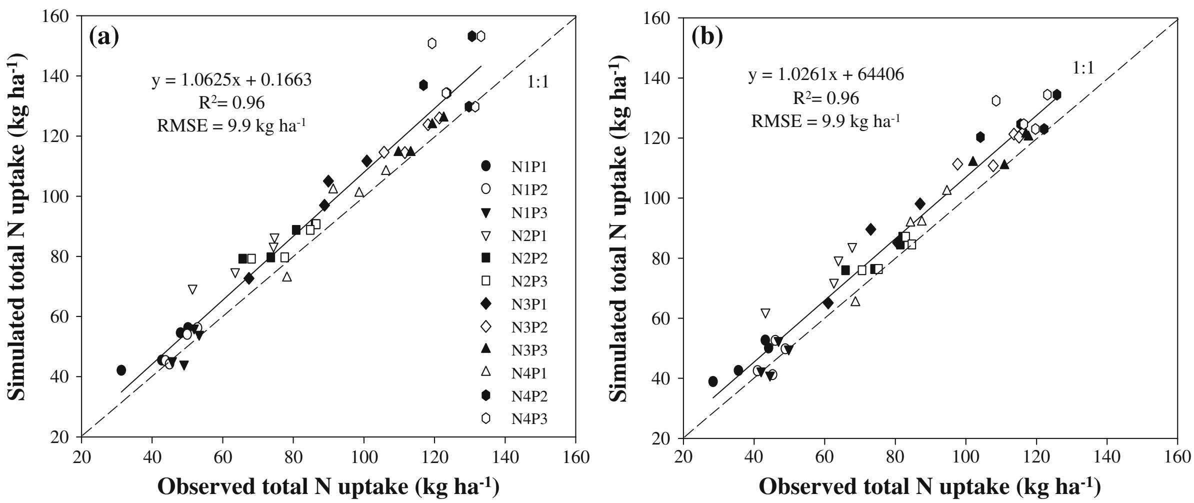

Fig. 7 Comparison of observed and simulated total N uptake of Obatanpa (**a**) and Dorke (**b**) maize for different N and P fertilizer rates at Ejura, Ghana 2008. (for legends see Fig. 5)

Long term N and P input scenario analysis

The effects of seasonal (major-minor) and varietal influences on maize response to N and P applications are presented below. Nitrogen and phosphorus had significant influence on grain yield as maximum and average long term grain yields increased in response to application of N and P in both cultivars. There was a significant response of grain yield to N inputs, irrespective of the application of P fertilizer (Figs. 9, 10, 11). However, when no N fertilizer was applied, there was no significant difference in grain yield between 0 and 30 kg P ha^{-1} application. Thus at this point N is a limiting factor and grain yield did not respond to applied P. There was a significant increase in yield variability over the years, with increasing rates of N application in both seasons. Applying 30 kg P ha^{-1} resulted in an increase in the variability in grain yield in the major season. In the minor season, however, applying P fertilizer rather reduced yield variability. Applying N fertilizer beyond 60 kg ha^{-1} only resulted in marginal increases in average yield for both

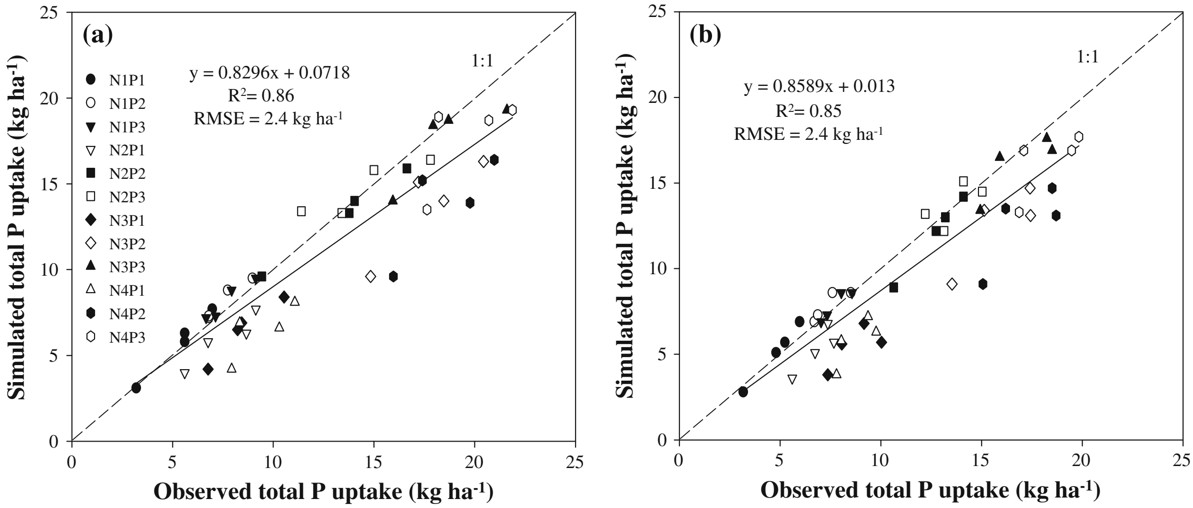

Fig. 8 Comparison of observed and simulated total P uptake of Obatanpa (**a**) and Dorke (**b**) maize for different N and P fertilizer rates at Ejura, Ghana 2008. (for legends see Fig. 5)

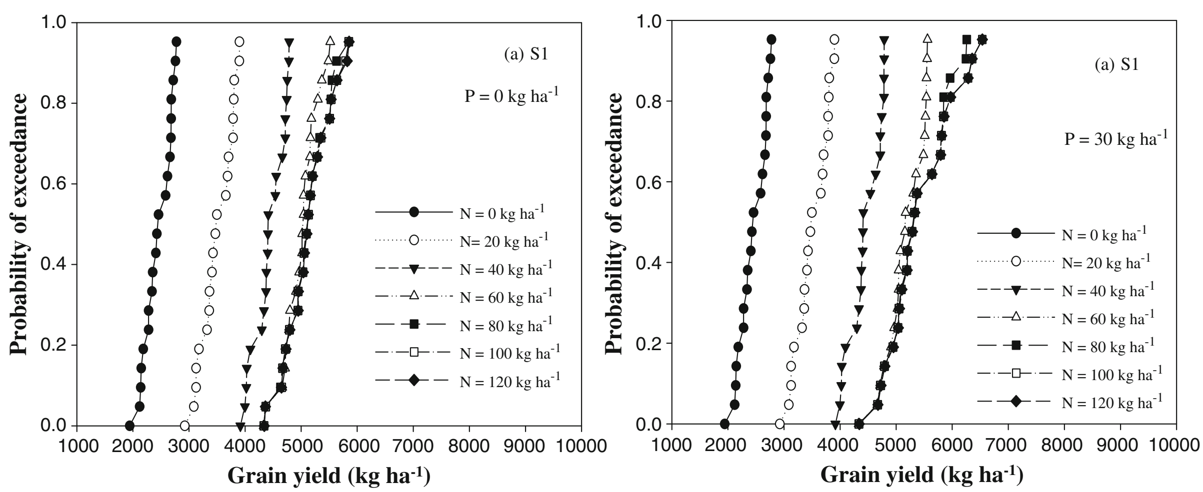

Fig. 9 Probability of exceedance of maize yield in response to N and P inputs at Ejura for Obatanpa (a) maize cultivar during major season (S1)

cultivars, over the simulation period and between the seasons (Figs. 9, 10, 11). With the application of 30 kg P ha^{-1}, grain yield increased with the application of N fertilizer.

Applying 60 kg N ha^{-1} and 30 kg P ha^{-1} resulted in an increase in long term average yield of 53 % (1,799 vs. 3,846 kg ha^{-1}) and 53 % (1,614 vs. 3,420 kg ha^{-1}) compared with yield without N fertilization for Obatanpa and Dorke cultivars respectively in the major season. The minimum grain yield increased from 1,337 to 1,958 and 1,242 to 1,418 kg ha^{-1} with the application of 60 kg N ha^{-1} and 30 kg P ha^{-1} for Obatanpa and Dorke respectively. Thus with the application of 60 kg N ha^{-1} farmers are guaranteed at least a yield of 1,958 and 1,418 kg ha^{-1} with an average of 3,972 and 3,467 for Obatanpa and Dorke respectively during the major season. An average yield of 4,459 and 4,011 kg ha^{-1} for Obatanpa and Dorke cultivars respectively, are guaranteed during the minor season. The responses of grain yield were higher during the minor season than the major season with the application of 60 kg N ha^{-1} and 30 kg P ha^{-1}. Standard deviation in yield increased from

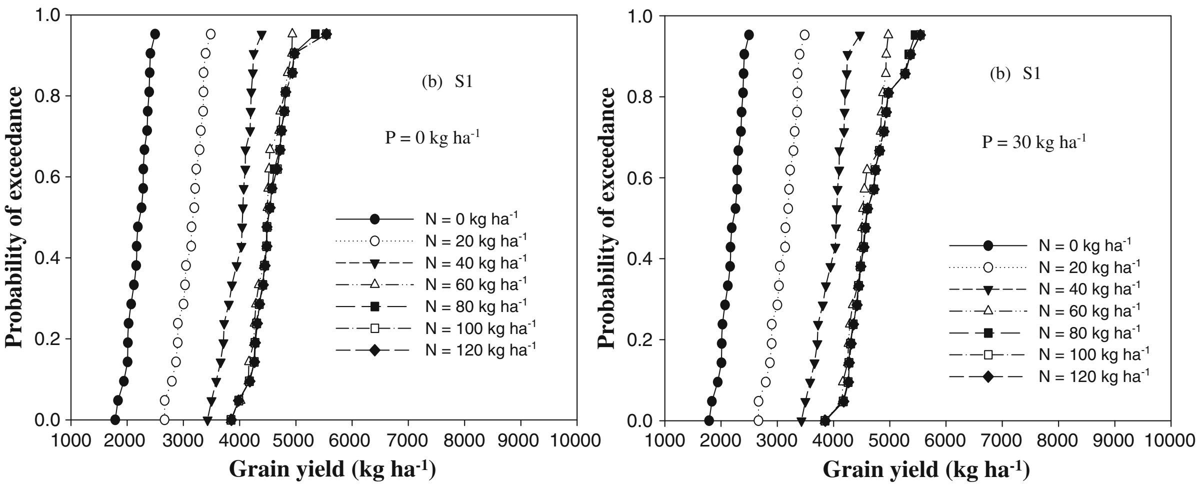

Fig. 10 Probability of exceedance of maize yield in response to N and P inputs at Ejura for Dorke (b) maize cultivars during major season (S1)

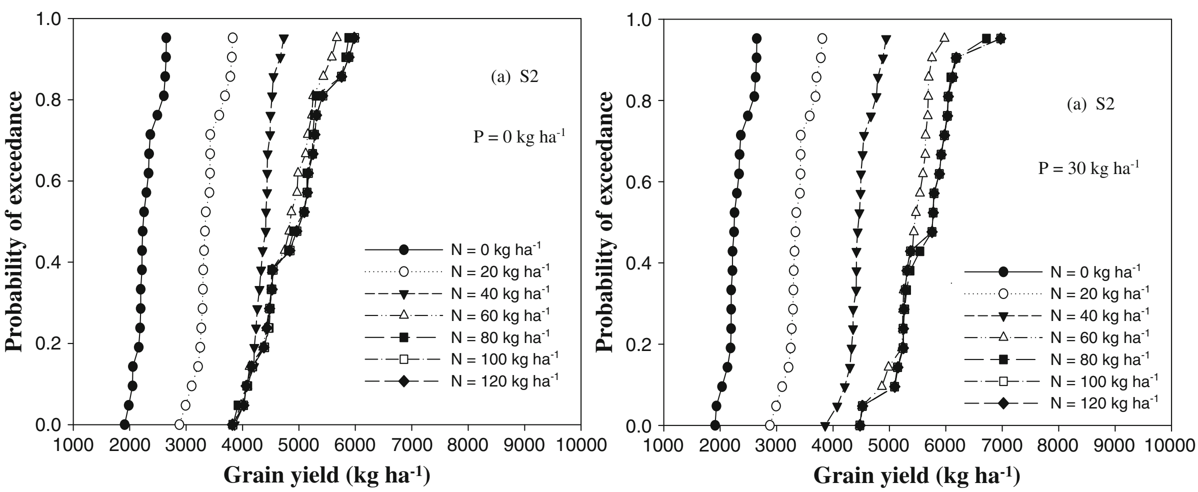

Fig. 11 Probability of exceedance of maize yield in response to N and P inputs at Ejura for Obatanpa (a) maize cultivar during the minor season (S2)

168 (0 kg N ha^{-1}) to 1,114 kg ha^{-1} (120 kg N ha^{-1}) in Obatanpa and 139 (0 kg N ha^{-1}) to 961 kg ha^{-1} (120 kg N ha^{-1}) in Dorke during the major season. During the minor season, standard deviation ranged from 167 to 1,055 kg ha^{-1} in Obatanpa and 125 to 858 kg ha^{-1} in Dorke.

The best years (giving the highest grain yields) with the application of 30 kg P ha^{-1} in the major season, were 1993 (with 20 and 40 kg N ha^{-1}) and 1997 (with 60–120 kg N ha^{-1}), for Obatanpa cultivar. The years 1983 and 1985 were the worst, giving the lowest grain yield during the minor and major seasons, respectively, for Obatanpa cultivar. With Dorke maize cultivar, the years 1983 (with 20–40 kg N ha^{-1}) and 1997 (with 60–120 kg N ha^{-1}) were the best giving the highest grain yield during the major season. The worst years, giving the lowest grain yields, were 1983 and 2000 for the minor and major seasons, respectively.

Discussion

Soil at experiments 1 and 3 were more fertile than those in experiments 2 and 4 as indicated in the soil organic carbon and labile P contents. The soils in experiments 2 and 4 are more sandy than those in experiments 1 and 3 as indicated from their lower limit water content values (Table 1). N and P and their interactive effect significantly influenced grain and biomass production of maize. The interactive effect of N and P on grain yield signifies the additional benefit of eliminating both constraints to plant growth. The application of 30 kg P ha^{-1} increased grain yield by an average of 21 % in Obatanpa and 23 % in Dorke. The trend in aboveground TDM production is similar to that of grain yield. Nitrogen and P and their combined effect significantly influenced total biomass production. Similar findings have been reported by Arthur (2009), Adiku et al. (2009), Kpongor (2007).

The influence of P nutrition on the growth of maize in Kenya was reported by Delve et al. 2009, and sorghum in semi-arid region in Ghana (MacCarthy et al. 2009). In this study, N was the most limiting soil nutrient as it is required in larger amounts than any other nutrient. The low amount of soil N was a result of the low soil organic carbon (SOC), which is due to partial or total removal of crop residues after harvest. Limited availability of extractable P reduced N use efficiency of plants. However, given the limited resource (mineral fertilizer) availability, farmers go in for N fertilizers as its return is higher than that of P (MacCarthy et al. 2009).

Evaluation of model performance

APSIM models has been developed for soils which are N and P-limiting, which is a characteristic of poor smallholder farms, hence making it suitable for this study. The study area is characterized by soils low in available P. Additionally, the soils have the capacity to sorp P from solution thereby making it unavailable for plant uptake. The sorption capacity of the soil are, however, rather moderate. The ability of the model to simulate the same number of degree days to reach maturity as that of the observed confirms the ability of the model to simulate the duration from sowing to physiological maturity. Days taken to reach physiological maturity were observed to have been prolonged at lower levels of N applications. However, this was not reflected in the model simulation results, which means it was not very sensitive to the effect of N and P stress on days to maturity. The low sensitivity of most simulation models have been reported by other authors (Gungula et al. 2003; MacCarthy et al. 2009) using DSSAT (Decision support system for Agro technological Transfer) for maize and APSIM for sorghum, respectively.

The good performance of the APSIM model in simulating grain and total biomass yield was reported by Delve et al. (2009), in their study on the influence of P on maize yield on contrasting soils in Kenya. Similarly, Whitbread et al. (2004) reported on the positive response of maize yield to P applications in their study on smallholder systems in Zimbabwe. MacCarthy et al. (2009) also indicated adequate performance of the model in simulating gain and biomass yield of sorghum, on contrasting soils in semi-arid Ghana. The yield of grain and biomass response to P application rates beyond 30 kg ha^{-1} did not yield additional increase in grain or biomass. Hence, applying 30 kg P ha^{-1} suffices plant requirements on this soil. The application of 60 kg P ha^{-1}, without N application, did not increase simulated grain yield. This indicates that below certain critical level of soil N, the application of P fertilizer will not result in increased yield.

The overestimation of total N uptake by the model was a result of the overestimation of the grain yield especially during the minor season. Asseng et al. (2000) reported a good correlation between measured and simulated grain N uptake of wheat in the Netherlands due to a good yield and total biomass simulation.

Long term N and P input scenario analysis

Based on the experimental dataset, grain yield can be expressed as an increasing function of N application rate (Fig. 6). In order to draw more general recommendations regarding N and P management, it was necessary to evaluate maize response to N and P under several climatic conditions. This was achieved by running the evaluated model over the 1980–2000 periods, which covers a wide range of climatic conditions using seven (7) rates of N application rates and two (2) rates of P.

Nitrogen and P had significant influence on grain yield as average long term grain yields increased in response to application of N and P input rates in both cultivars (Figs. 9, 10, 11). There was a significant response to N inputs in terms of grain yield irrespective of the application of P fertilizer (Figs. 9, 10, 11).

However, when no N fertilizer was applied, there was no significant difference in grain yield irrespective of P fertilization. Nitrogen is a more limiting factor for grain yield; therefore there was no response to increased application of P. When no P fertilizer was applied, grain yield were generally lower in response to added N rates compared to when P was applied. Similar observation was reported by MacCarthy et al. (2009) in long term simulation of sorghum response to nutrient in Semi-arid Ghana. This probably will be due to P stress effect with consequent restrictions on photosynthesis, leaf expansion, phenology and grain filling (Probert 2004). The cumulative probability of exceedence (Figs. 9, 10, 11) of the grain yield of Obatanpa cultivar in response to P input generally shifted to the right (higher grain yield) in both seasons. The responses were, however, more distinct in the minor season than in the major season. Applying P increased average yield of Obatanpa cultivar at all levels of N application in the minor season than in the major season. The additional benefit (increase in yield) from applying P ranged from −0.05 to 3.4 and −0.4 to 5.2 % in the major season for the Dorke and Obatanpa cultivars respectively. In the minor season, however, grain yield increased from −0.6 to 14.6 and 0.4 to 24.2 % for Dorke and Obatanpa cultivars respectively. Farmers will therefore reap more benefit using P fertilizer in the minor season, additionally, they will obtain higher benefit from P fertilization at higher levels of N fertilization.

The best years for Obatanpa (giving the highest grain yield) with the application of 30 kg P ha^{-1} in the major season were 1993 for lower rates of N (20 and 40 kg N ha^{-1}) and 1997 for medium to higher application rates (60–120 kg N ha^{-1}). This is probably due to sufficient and good distribution of rainfall within the cropping season. The worst years giving the lowest grain yield during the major season were 1987 (20 and 40 kg N ha^{-1}) and 1985 (60–120 kg N ha^{-1}) while the year 1983 was the worst year for all rates of N during the minor season. Grain yields were generally higher during the minor season than the major season; hence, investment in inputs (60 kg N ha^{-1} and 30 kg P ha^{-1}) by farmers during the minor season is likely to benefit them from higher grains yields than higher input during the major season. Analysis of stress factors indicated water stress during the flowering and grain filling stage of the crop in both seasons for these worst years (Figs. 12, 13). Although adequate nitrogen was available, water stress made it difficult for nutrient up take by the plant as nutrients are mostly absorbed through water medium. Water stress during flowering and grain filling stage has a significant influence on grain size, weight and hence yield.

For the Dorke cultivar, however, the worst years were 2000 and 1983 for major and minor seasons. These low yields could be due to lack of adequate moisture (Fig. 14) during the time of grain filling, thus affecting the grain size, weight and hence yield. It can be inferred from this study that the response of maize yield to inorganic fertilizer is season-specific. It depends very much on the amount and distribution

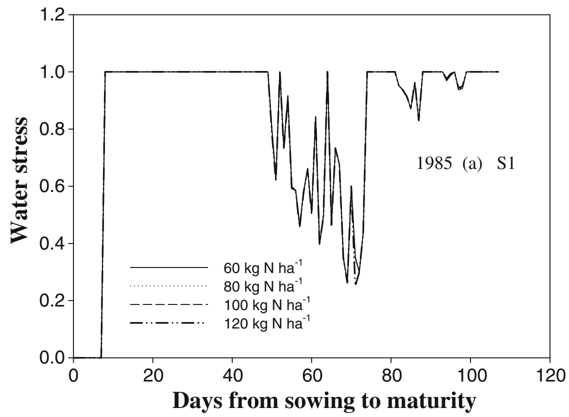

Fig. 12 Water stress in worse year (1985) in Obatanpa maize cultivar for different rates of N and 30 kg P ha^{-1} from sowing to maturity during the major season in Ejura, Ghana

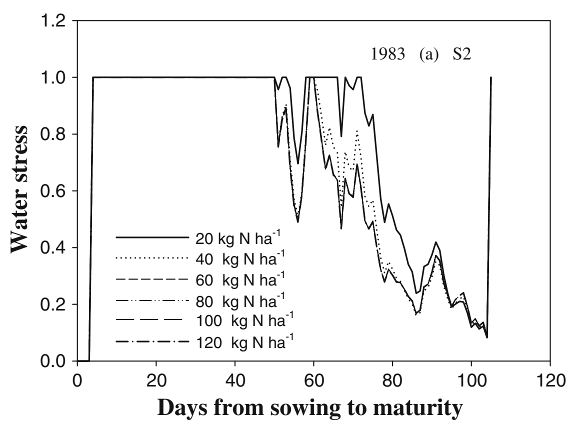

Fig. 13 Water stress in worse year (1983) in Obatanpa maize cultivar (a) for different rates of N and 30 kg P ha^{-1} from sowing to maturity during the minor season (S2) in Ejura, Ghana

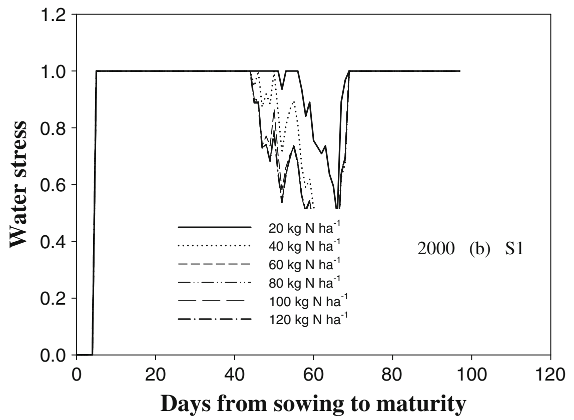

Fig. 14 Water stress in worse year (2000) in Dorke maize cultivar (b) for different rates of N and 30 kg P ha^{-1} from sowing to maturity during the major season (S1) in Ejura, Ghana

of rainfall within the season. From the results (Figs. 9, 10), application of 50 kg N ha^{-1} during the major season and an increase to 60 kg N ha^{-1} during the minor season with 30 kg P ha^{-1} will be beneficial to farmers as yield increase by 11.5 % during major season and 17.1 % during the minor season when N rate increased from 40 kg to 60 kg ha^{-1}.

The two cultivars responded differently in terms of yield to rainfall pattern for the various seasons and years. The two cultivars differ in their growth cycles and hence take different number of days to flower and reach maturity. The occurrence of drought spell at the time of flowering or grain filling of one cultivar will result in lower yield. Thus, well distributed in-season rainfall (which determines the availability of soil moisture in rain-fed systems) particularly at very sensitive growth stages (tasselling and grain filling) is critical for good yield. Similar results were reported by Akponikpe et al. (2010) in their study on nitrogen management for pearl millet in the Sahel to support agricultural decision making.

Conclusion

The APSIM-Maize model was successfully parameterized and evaluated for the sub-humid region of Ghana. It explicitly captured the effects of inorganic N and P fertilizer application on total dry matter, LAI, grain yield, N uptake as well as P uptake of Obatanpa and Dorke maize cultivars. The model adequately simulated total biomass, grain yield and N and P uptake with correlation coefficients above 0.84 for both Obatanpa and Dorke.

The evaluation of the APSIM-Maize model in this study confirms that this model can be used as a research tool in a variable agro-environment. The results suggest that it can be used to explore alternative ways of improving maize production in the region and the level of resource needed for optimum production. Moderate application of N (50 kg N ha^{-1} during the major season and 60 kg N ha^{-1} during the minor season) improved both the long term average and the maximum yield. The response to mineral fertilizer (N and P) applications varied between seasons and cultivars. This suggests the need to have a range of fertilizer recommendations to be applied based on seasonal weather forecast and the variety to be use. Increasing application of N fertilizer resulted in higher variability in grain yield. Applying P resulted in higher variability in yield in the major seasons and a reduction in yield variability in the minor season, suggesting a possible interactive effect between P and rainfall distribution. Higher response to P fertilization is more likely in the minor season and farmers will benefit from applying P fertilizer at higher concentrations of N fertilization.

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