South African Journal of Plant and Soil

ISSN: 0257-1862 (Print) 2167-034X (Online) Journal homepage: http://www.tandfonline.com/loi/tjps20

Evaluating maize yield variability and gaps in two agroecologies in northern Ghana using a crop simulation model

Dilys S MacCarthy, Samuel G Adiku, Bright S Freduah, Alpha Y Kamara, Stephen Narh & Alhassan L Abdulai

South African Journal of Plant and Soil 2017: 1–11
Printed in South Africa

This is the final version of the article that is published ahead of the print and online issue

SOUTH AFRICAN JOURNAL OF PLANT AND SOIL
ISSN 0257-1862 EISSN 2167-034X
http://dx.doi.org/10.1080/02571862.2017.1354407

Evaluating maize yield variability and gaps in two agroecologies in northern Ghana using a crop simulation model

Dilys S MacCarthy[1]*, Samuel G Adiku[2], Bright S Freduah[1], Alpha Y Kamara[3], Stephen Narh[1] and Alhassan L Abdulai[4]

[1] Soil and Irrigation Research Centre, School of Agriculture, College of Basic and Applied Sciences, University of Ghana, Kpong, Ghana
[2] Department of Soil Science, School of Agriculture, College of Basic and Applied Sciences, University of Ghana, Legon, Accra, Ghana
[3] International Institute of Tropical Agriculture, Kano, Nigeria
[4] Savanna Agricultural Research Institute, Nyankpala, Tamale, Ghana
* Corresponding author, email: dsmaccarthy@gmail.com

The yield gap and variability in maize under smallholder systems in two agroecologies in northern Ghana were evaluated using a decision support system for agrotechnology transfer (DSSAT). The model was used to assess (1) the potential yield of maize (Y_{POT}), (2) water-limited exploitable maize yield (Y_{WEX}), (3) nitrogen-limited yield (Y_{NI}), (4) farmer practice maize yield (Y_{CFP}) and (5) proposed enhanced nutrient use yield (enhanced farmer practice; Y_{EFP}). Effect of supplementary irrigation was also assessed on Y_{CFP} and Y_{EFP} conditions. Yield gaps were determined as the difference between Y_{POT} and Y_{CFP} or Y_{EFP} on the one hand, and between Y_{WEX} and Y_{CFP} or Y_{EFP} on the other hand. The yield gap based on potential yield ranged from 59% to 75% under CFP and narrowed to between 29% and 59% under EFP. With water-limited exploitable yields, the yield gap ranged from 53% to 65% under CFP, reducing to between 22% and 42% under EFP. The use of supplementary irrigation further reduced the yield gap. Improved fertiliser use and supplementary irrigation have the potential to increase yield and hence reduce the yield gap if effective policies and institutional structures are in place to provide farmers with credit facilities and farm inputs.

Keywords: crop simulation model, fertiliser use, maize, yield variability

Introduction

For many decades, maize (*Zea mays*) has been a major staple cereal in Ghana, with the main production zones limited to the southern parts of the country where rainfall is bimodal. Since the 1980s, it has been introduced into northern Ghana, which has a unimodal rainfall pattern, due to the breeding efforts and comparably higher yields than the traditional smaller grains. Despite its importance, maize productivity and yield in many production zones continue to be low with a national average of 1 700 kg ha^{-1} (MoFA 2011). However, Naab et al. (2015) showed that an application of nitrogen (N) at the rate of 120 kg ha^{-1} produced an average maize yield of about 3 600 kg ha^{-1} over a four-year period on-station in the northern zone of Ghana. The yield responses to fertiliser application suggest that soil productivity is the major constraint to maize production. Another factor constraining crop yield in this region is erratic rainfall distribution (Neumann et al. 2007; Laux et al. 2009). A study by MacCarthy et al. (2015) in the coastal savanna of Ghana also associated variability in rainfall distribution with variable crop yield. Hence, we conjecture that the interactions between soil management and water availability cannot be ignored as both determine plant growth and productivity and, hence, reduce maize yield gaps.

Even though climate risk has been identified as a major constraint to crop production for farmers, particularly in sub-Saharan Africa, quantified information on climate-induced risk and magnitude of yield gaps are scarce (van Ittersum and Rabbinge 1997; Kassie et al. 2014). Hence, there is the demand for the quantification of impact of climate variability on yield in the region (Muller et al. 2011; Kassie et al. 2014).

The evaluation of soil–weather interactions on maize production will require a holistic approach involving several soil–water–management interactions that would defy single-year field experimentation. Furthermore, whether farmers would be willing to adopt an enhanced management would depend not only on increased yields but also on the profitability of the strategy. For this, using decision support tools (DST) approaches are more appropriate and will better elicit the understanding of soil–plant–atmosphere interactions. The use of DST to quantify climate-induced yield variability in Africa is rather limited, even though they are useful in data-scarce environments and can reduce the cost associated with long-term experiments. The decision support system for agrotechnology transfer – cropping systems model (DSSAT-CSM; Jones et al. 2003) was used to evaluate the effects of different soil–environment–management interactions of crop growth and yield. Economic models such as stochastic dominance (Anderson et al. 1977) were used to assess the economic superiority of different management practices. The aim of the present study was to (1) assess the impact of climate variability on the yield of maize in northern Ghana and (2) analyse the existing yield gap of maize in smallholder systems in maize producing areas in two agroecologies of northern Ghana.

Materials and methods

Description of study area

The study sites were located in the three northern regions of Ghana, namely (1) Tamale and Yendi (9.40° N, 0.84° W and 9.44° N, 0.01° W, respectively) in the Northern Region, (2) Wa and Jirapa (10.06° N, 2.50° W and 10.52° N, 2.70° W, respectively) in the Upper West Region and (3) (10.89° N, 1.09° W and 10.78° N, 0.85° W, respectively) Navrongo and Bolgatanga in the Upper East Region (Figure 1). The Northern and Upper West Regions fall within the Guinea Savanna agroecological zone, whereas the Upper East region falls within the Sudan Savanna zone. The dominant soil type of the Upper West Region is classified as Ferric Lixisol (FAO classification), whereas those of the Tamale and Yendi sites are Alfisol and Ferric Luvisol, (FAO classification), respectively (Brammer 1962; Naab et al. 2015). The soils of northern Ghana are generally coarse-textured and often shallow (<60 cm) with low fertility. The cropping system is cereal–legume based.

Description of model and evaluation

The DSSAT-CSM crop simulation model, which comprises a suite of modules that are process based, mechanistic and crop management oriented (Jones et al. 2003), was used in the present study. The model utilises data on daily weather (rainfall, minimum and maximum temperature, and solar radiation), soil profile information and crop genetic coefficients to simulate crop growth and yield. The phasic and morphological developments of the crop are simulated using daily temperature, day length and genetic characteristics (Jones and Thornton 2003). Whereas optimal plant growth and development is influenced by photosynthetic capacity, radiation capture, thermal time and photoperiod sensitivity, actual growth and development are constrained by water and nutrient stress as well as suboptimal temperatures (Soler et al. 2007). Details on the CERES-Maize module of DSSAT are available in Jones and Kiniry (1986). The water and nutrient balance submodules reduce growth via stress factors. Nitrogen availability emanates from either organic matter mineralisation or from fertiliser/manure application. Soil organic matter (SOM) mineralisation and nutrient release is simulated using the Century model embedded in DSSAT (Gijsman et al. 2002). Briefly, the Century model defines SOM into three pools: SOM1, which is the active microbial pool with rapid turnover (days to months); SOM2, which is an intermediate pool with a slow turnover (years); and a passive or recalcitrant

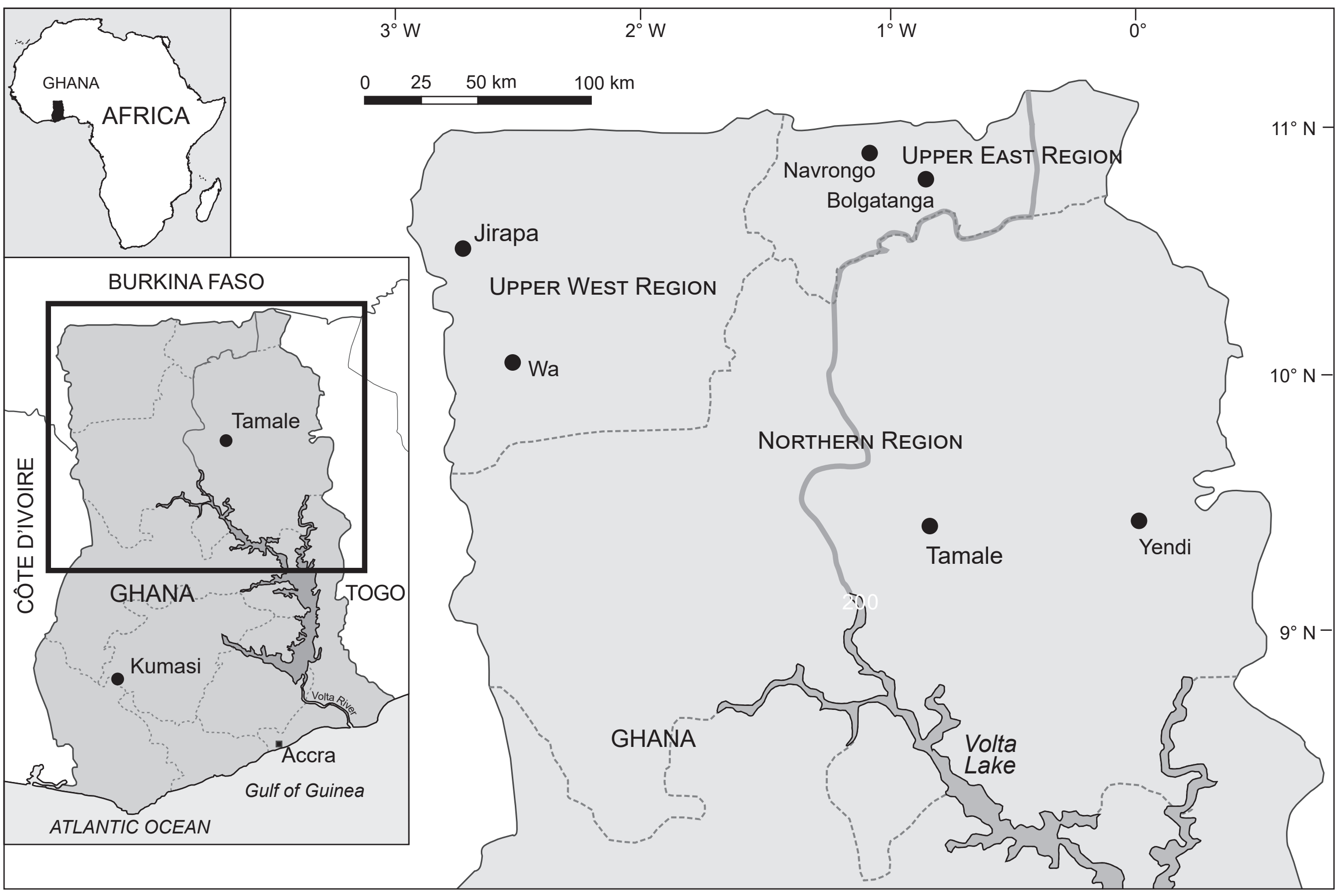

Figure 1: Map of northern Ghana illustrating the location of the study sites

pool, SOM3, which is very stable with turnover times of hundreds to thousands of years. Further details on organic matter types and partitioning are available in Porter et al. (2010). Daily water balance is calculated as a function of rainfall, irrigation, transpiration, soil evaporation, drainage and runoff. Movement of water from one layer to the next layer follows a cascading bucket approach described by Richtie (1998). The calculation of evapotranspiration follows Priestly-Tailor (Jones et al. 2003).

The CERES-Maize module has been widely tested and used in West Africa. In Ghana, CERES-Maize has been extensively calibrated and evaluated (e.g. Dzotsi et al. 2010; MacCarthy et al. 2012) and has been found to perform well in predicting maize response to a host of soil–water–management conditions across several agro-ecological zones.

In the present study, a further evaluation of the maize model was carried out using data collected from on-farm field trials in three communities (Kpallusogu, Gbullahigu and Dimabi) in northern Ghana. There were five treatments (control, 5 000 kg ha^{-1} manure, 60 kg N ha^{-1}, 2 500 kg ha^{-1} manure + 30 kg N ha^{-1}, and 120 kg N ha^{-1}) at each site arranged in a complete randomised design. The input soil data are shown in Table 1. The treatments with manure had the manure incorporated a week prior to sowing. The on-farm field trials were planted on 3, 5 and 28 July 2014. Fertilisers were applied in two splits. Basal fertiliser was applied on 22 and 23 July and on 18 August, and a topdressing applied on 10 and 11 August and 6 September at Kpallusogu, Gbullahigu and Dimabi, respectively. The plants were sown at a spacing of 80 cm × 40 cm. Data were collected on crop phenology, grain and biomass yield.

Simulation runs

The validated CERES-Maize was employed to simulate the potential and actual maize yields at the six sites for a range of soil–water–management situations using multi-year (30 years: 1980–2009) weather data, which were obtained from the Ghana Meteorological Agency. The management options include planting date, fertiliser and manure application. Planting density was set at 35 000 and 66 000 plants ha^{-1} for farmer and potential yields, respectively.

Three simulated sowing options were evaluated, namely early sowing window (from third week of May to the second week of June), mid sowing (from the third week of June to the first week of July) and late planting (from the second week of July to the fourth week of July). Sowing was effected after three consecutive rainfall events that add up to a minimum of 30 mm. The soil management option involved fertiliser and manure application. Mineral fertiliser was split-applied with the first half at 10 d after emergence and the remainder on 36 d after emergence. Simulations were done for the current farmer practice (CFP) yield, Y_{CFP}, with the input level of 30 kg N ha^{-1} plus 1 000 kg ha^{-1} manure, based on previous farmer surveys using a planting density of 35 000 plants ha^{-1}. We also defined an enhanced farmer practice (EFP) yield, Y_{EFP}, for the case of a farmer who would apply 60 kg N ha^{-1}

Table 1: Soil parameters used in simulations for all 6 sites in the three Northern regions of Ghana. L = Depth of the soil layer, LL = lower limit, DUL = field capacity, SAT = saturated water content, BD = bulk density, OC = organic carbon

Location	L (cm)	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SAT (cm^3 cm^{-3})	BD (g cm^{-3})	OC (%)	pH
Navrongo	5	0.069	0.137	0.401	1.52	0.48	5.1
	10	0.072	0.137	0.394	1.54	0.42	5.2
	20	0.076	0.137	0.388	1.56	0.36	5.2
	30	0.076	0.142	0.391	1.55	0.36	5.4
	40	0.096	0.170	0.388	1.56	0.36	5.2
	50	0.113	0.181	0.374	1.60	0.24	5.3
	60	0.119	0.193	0.387	1.56	0.48	5.3
Bolgatanga	22	0.058	0.126	0.460	1.36	0.37	5.7
	40	0.074	0.146	0.431	1.44	0.29	6.0
	60	0.114	0.196	0.450	1.39	0.22	6.1
Wa	5	0.085	0.155	0.383	1.54	0.49	6.3
	20	0.085	0.155	0.383	1.54	0.49	6.3
	40	0.122	0.190	0.362	1.57	0.48	6.3
	60	0.124	0.170	0.204	1.52	0.51	5.9
Jirapa	5	0.052	0.176	0.359	1.61	0.70	6.5
	15	0.052	0.176	0.359	1.61	0.70	6.5
	30	0.052	0.176	0.359	1.61	0.66	6.5
	45	0.073	0.192	0.360	1.61	0.58	6.5
	60	0.073	0.192	0.360	1.61	0.58	6.5
Tamale	15	0.012	0.176	0.359	1.34	0.51	5.1
	30	0.016	0.176	0.359	1.64	0.48	5.3
	45	0.027	0.192	0.360	1.70	0.24	5.7
	60	0.045	0.192	0.360	1.78	0.10	6.2
Yendi	15	0.125	0.198	0.294	1.34	0.64	7.4
	30	0.117	0.226	0.323	1.64	0.54	6.3
	45	0.117	0.226	0.323	1.70	0.14	4.8
	60	0.138	0.250	0.332	1.78	0.64	5.1

plus 2 000 kg ha^{-1} manure. Details of these scenarios are provided in Table 2. Impact of supplementary irrigation (SI) was also assessed on CFP and EFP. Automatic irrigation was provided when soil moisture was below half the field capacity of the soil. Furthermore, the potential grain yield, Y_{POT}, was simulated for an environment with water and nutrient stress-free conditions and where all other biotic stresses were effectively controlled and with a planting density of 66 000 plants ha^{-1}. The water-limited exploitable yield (rain-fed), Y_{WEX}, was simulated using the same conditions as the potential but using historical weather data (1980–2009) for the respective sites. We also simulated a nutrient-stressed but water non-limited yield, Y_{NL}. Following van Ittersum and Rabbinge (1997), two different approaches were used to determine yield gaps; (1) difference between Y_{POT} and Y_{CFP} and Y_{EFP} and (2) difference between (Y_{WEX}) and Y_{CFP} and $Y_{EFP.}$

Evaluation of model performance

The root mean square error (RMSE) and Willmott *d*-index were used to evaluate the performance of the model in representing phenology, biomass and grain production.

RMSE is defined as:

$$\text{RMSE} = \left[\frac{1}{n}\sum\left(\text{yield}_{\text{simulated}_i} - \text{yield}_{\text{observed}_i}\right)^2\right]^{0.5}$$

The lower the RMSE, the better the model performance and its minimum value of zero implies a perfect model performance.

The Willmott *d*-value ranges from 0 to 1. One indicates a perfect model, whereas 0 indicates poor model performance (Wilmott 1981). It is defined as:

$$d\text{-value} = 1 - \frac{\sum_{i=1}^{n}(\text{Observed}_i - \text{Simulated}_i)}{\sum_{i=1}^{n}\left(\left|\text{Simulated}_i - \text{Mean}_{\text{observed}}\right| + \left|\text{Observed}_i - \text{Mean}_{\text{observed}}\right|\right)}$$

Data analysis

Analysis of variance was used to assess differences between yields among the different management systems.

Economic analysis of the various management options was derived from 30-year simulated yields for the CFP and EFP with and without supplementary irrigation at each site and converted the yields to gross margins (GM) as GM = (grain yield × selling price) – input cost). Maize selling price and input (fertiliser, seed, land preparation, labour and irrigation [where it was applied]) costs for the period 1980 to 2009 were obtained from the Statistics Division of the Ministry of Food and Agriculture, Ghana. The prices and costs were adjusted to a constant Ghana Cedi using the consumer price index published by the Ghana Statistical Services. The cumulative distribution function (CDF) of the GMs were compared pairwise using the first stochastic dominance (FSD) concept in that more is preferred to less. Thus, the CDF of the GM for a particular management option that lies to the right of the other was considered more profitable (Anderson et al. 1977).

Results

Weather variation across the sites

The maximum temperatures (T_{max}) ranged from 33.8 °C to 35.2 °C across sites (Table 3). Minimum annual temperature (T_{min}) ranged from 22.4 °C to 23.1 °C across sites. Temperature generally increased northwards with the Northern Region being cooler than the Upper East and Upper West Regions. Annual temperature variability was higher within T_{max} than in T_{min}. Within the growing season (May–September), Yendi in the Northern Region recorded the lowest average temperature for both T_{max} and T_{min} with temperatures of 31.4 °C and 22.6 °C, respectively. Variability in T_{max} and T_{min} was also small for Yendi compared with the other sites (4.9% and 3.4% for T_{max}

Table 2: Summary input for scenarios simulated in the study. SI = supplementary irrigation

Scenario	Acronym	Plant population (plants ha^{-1})	Nitrogen applied (kg ha^{-1})	Water applied
Potential yield	Y_{POT}	66 000	No limitation[a]	No limitation[b]
Water-limited exploitable yield	Y_{WEX}	66 000	No limitation	Rain-fed
Nutrient-limited yield	Y_{NL}	66 000	30 + 1 t manure ha^{-1}	No limitation[b]
Current farmer practice	Y_{CFP}	35 000	30 + 1 t manure ha^{-1}	Rain-fed
Enhanced farmer practice	Y_{EFP}	35 000	60 + 2 t manure ha^{-1}	Rain-fed
Current farmer practice + Supplementary irrigation	Y_{CFP+SI}	35 000	30 + 1 t manure ha^{-1}	Rain-fed + SI
Enhanced farmer practice + Supplementary irrigation	Y_{EFP+SI}	35 000	60 + 2 t manure ha^{-1}	Rain-fed + SI

[a] and [b] Model setup to assume sufficiency of nitrogen and water, respectively

Table 3: Summary statistics of weather (30 years, 1980–2009) parameters of six locations in northern Ghana

Site	Region	Average seasonal rainfall (mm)	Average seasonal T_{max} (°C)	Average seasonal T_{min} (°C)	Average length of growing season (d)	Average length of longest dry spells (d)
Tamale	Northern	859	31.6	23.2	158	14
Yendi	Northern	958	31.4	22.6	163	13
Bolgatanga	Upper East	804	32.3	23.5	152	15
Navrongo	Upper East	860	32.7	23.5	144	16
Jirapa	Upper West	809	32.7	23.6	154	12
Wa	Upper West	809	31.3	22.7	154	13

and T_{min}, respectively). Jirapa in the Upper West Region recorded the highest temperatures for the growing season with an average temperature of 32.7 °C and 23.6 °C for T_{max} and T_{min}, respectively. Bolgatanga in the Upper East Region was the second warmest after Jirapa with an average growing-season mean temperature of 27.9 °C.

With regard to rainfall, Yendi was the wettest site with mean in-season rainfall of 958 mm over the 30-year historical period (1980–2009). Tamale was the second wettest (in-season rainfall of 860 mm). Wa was the driest site with annual in-season rainfall of 809 mm. Tamale and Yendi showed the highest inter-year variability in rainfall of 19% and 18%, respectively. The onset of rainfall was generally earliest in the Northern Region (Tamale and Yendi). Growing-season length was shortest at Navrongo, whilst Yendi and Tamale had the longest growing-season lengths averaging 160 d. Navrongo (in the Upper East Region) showed the longest dry spell lengths with a yearly average of about 16 d, whereas Wa had the shortest dry spell duration of 12 d.

Model evaluation

Anthesis was predicted with a RMSE of 2.4 d, while duration to maturity was simulated with RMSE of 3.6 d. Grain and total biomass yield were also reasonably simulated with Willmott's *d*-index of 0.85 and 0.88, respectively.

Potential yield

The potential maize yield varied among years and across locations. For example, at Tamale, the lowest and highest values of Y_{POT} were 3 500 and 6 880 kg ha^{-1}, respectively with a median value of 4 700 kg ha^{-1} (Figure 2). For Wa, the lowest, highest and median yields were 3 000, 5 500 and 4 500 kg ha^{-1}, respectively. The simulated range of potential maize yields was greatest at Navrongo, ranging from about 2 548 to 6 000 kg ha^{-1} but with the lowest median value of about 4 000 kg ha^{-1} (Figure 2). The least Y_{POT} ranged between 2 548 and 2 759 kg ha^{-1} across planting dates, sites and years. Variability in Y_{POT} across sites was between 18% and 20%.

Potential yields also varied across sowing dates at each of the sites (Figure 3). For instance, in Tamale, mean Y_{POT} varied between 5 216 kg ha^{-1} with early planting to 4 498 kg ha^{-1} with late planting. Variability in simulated yields ranged between 16% and 20%. In Navrongo, mean Y_{POT} ranged from 4 261 kg ha^{-1} with early planting to 3 700 kg ha^{-1} with late planting. Variability in Y_{POT} ranged between 18% and 26%.

Exploitable yields

The mean simulated water-limited exploitable yield Y_{WEX} (for rain-fed but non-limiting nitrogen conditions) varied from between 3 982 kg ha^{-1} in Yendi to 2 947 kg ha^{-1} in Navrongo (Table 4). The simulated modal Y_{WEX} across planting dates and years was 4 136 kg ha^{-1} at Yendi and 2 853 kg ha^{-1} at Navrongo. The minimum Y_{WEX} across sites, planting dates and years ranged between 1 024 kg ha^{-1} in Yendi and 451 kg ha^{-1} in Navrongo. Variability in Y_{WEX} ranged between 22% at Yendi and 35% in Bolgatanga

The Y_{WEX} also varied across planting dates in each of the study sites. In Tamale, for example, mean Y_{WEX}

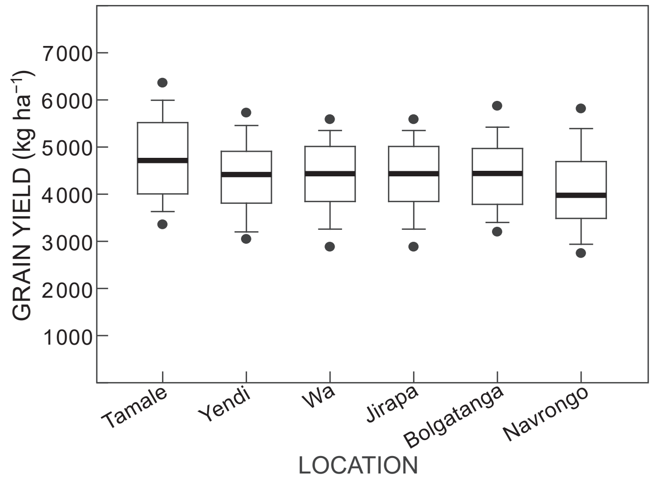

Figure 2: Variability in simulated potential yield of maize in six locations in northern Ghana. Each box indicates the 25th, 50th and 75th percentiles, error bars indicate the 10th and 90th percentiles, and solid circles represents the 5th and 95th percentiles

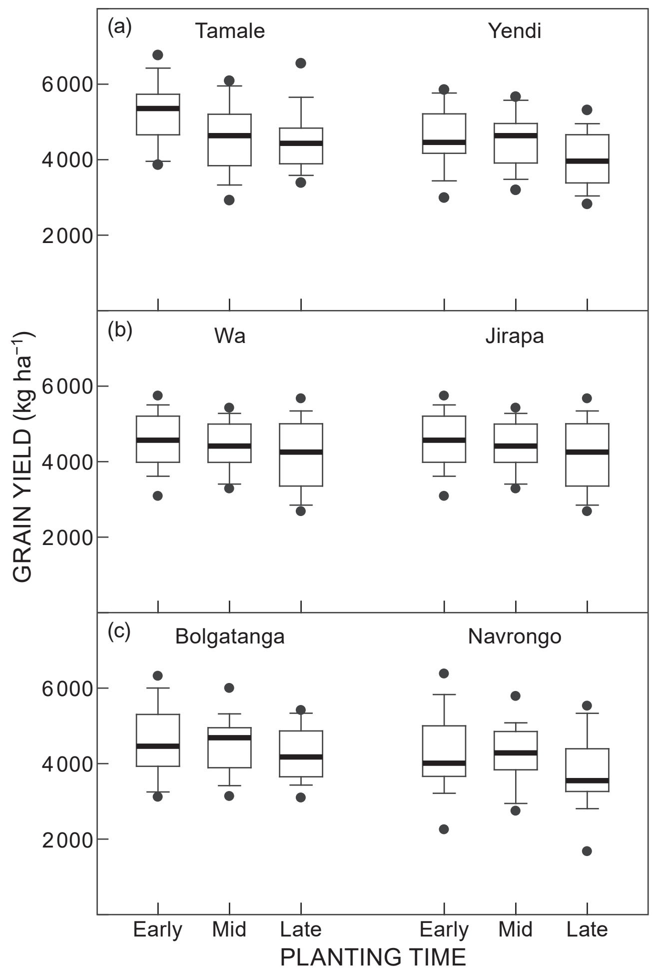

Figure 3: Variation of simulated potential yields within sites for different planting windows for the (a) Northern, (b) Upper West and (c) Upper East regions of Ghana. Each box indicates the 25th, 50th and 75th percentiles, error bars indicate the 10th and 90th percentiles and solid circles represent the 5th and 95th percentiles

varied between 4 362 kg ha^{-1} in the mid-planting window to 3 262 kg ha^{-1} for the late planting window. Variability in yields also ranged between 29% in the early planting window to 17% with late planting. In Navrongo, mean of Y_{WEX} varied between 3 151 kg ha^{-1} in the mid-planting window and 2 711 kg ha^{-1} in the late planting window. Annual variability of Y_{WEX} at the Navrongo site ranged from 33% for the late planting window to 26% for the mid-planting window. In general, maize grain yield was correlated significantly with in-season total rainfall for three of the six sites studied (Table 5). The correlations between simulated evapotranspiration and grain yield were, however, significant across sites.

Nitrogen-limited yields

Under N-limited (not water-limited) conditions (Y_{NL}), simulated yield across the sites ranged from 2 388 kg ha^{-1} in Tamale to 1 935 kg ha^{-1} in Navrongo. Variability in grain yield across sites and planting windows ranged between 18% in Yendi to 25% in Navrongo, which are much lower than those obtained under water-limited conditions (Figure 4). Mean grain yields also varied across planting windows. When only N was limiting, the simulated grain yields were lower than the condition in which only water was limiting (Figure 4).

Table 4: Analysis of percentage yield gaps between potential grain yield and farmer practice as well as enhanced farmer practice with and without supplementary irrigation. POT = potential yield, CFP = current farmer practice, EFP = enhanced farmer practices SI = supplementary irrigation. Values in parentheses are the standard error

Site	Y_{POT} (kg ha^{-1})	Gap Y_{CFP} (%)	Gap Y_{EFP} (%)	Gap Y_{CFP+SI} (%)	Gap Y_{EFP+SI} (%)
Potential yield-based gaps					
Tamale	4 763 (± 96)	62	36	56	26
Yendi	4 422 (± 82)	59	30	57	29
Wa	4 364 (± 82)	72	53	63	36
Jirapa	4 234 (± 80)	71	50	68	40
Bolgatanga	4 449 (± 85)	75	59	72	48
Navrongo	4 073 (± 102)	73	54	69	45
Water-limited exploitable yield-based gaps					
Tamale	3 918 (± 122)	52	23	46	10
Yendi	3 982 (± 92)	55	22	53	21
Wa	2 960 (± 105)	59	31	46	6
Jirapa	3 530 (± 118)	65	38	62	28
Bolgatanga	3 098 (± 113)	65	41	60	25
Navrongo	2 947 (± 106)	62	37	57	24

Table 5: Correlation between grain yield and in-season rainfall amounts and simulated evapotranspiration

Sites	In-season total rainfall amount	Evapotranspiration
Tamale	0.40*	0.60**
Yendi	0.08	0.41*
Navrongo	0.45*	0.62**
Bolgatanga	0.35	0.58**
Wa	0.38*	0.48**
Jirapa	0.15	0.39**

* $p < 0.05$, ** $p < 0.01$

Simulated yields under current farmer practice

The mean simulated yields under the farmer practice, Y_{CFP}, across sites and sowing windows ranged from 1 097 kg ha^{-1} at Bolgatanga to 1 830 kg ha^{-1} at Tamale (Table 6). Overall, most farmers produced an average of 1 300 kg ha^{-1} (CV = 30%). Among all of the sites, Yendi appeared to be the site with the highest maize production with the least variability under farmer-managed conditions. For example, the mean Y_{CFP} ranged from 1 830 kg ha^{-1} (at Bolgatanga) to 3 088 kg ha^{-1} (at Yendi) representing a yield gap based on potential yield of 56–72% and 59–75% with and without supplementary irrigation, respectively (Table 4). Simulated maize yields in Yendi showed least variability.

Enhanced farmer practice

Simulated mean yields under enhanced farmer practices, Y_{EFP}, varied across sites and sowing windows ranging between 3 088 kg ha^{-1} in Yendi to 1 817 kg ha^{-1} in

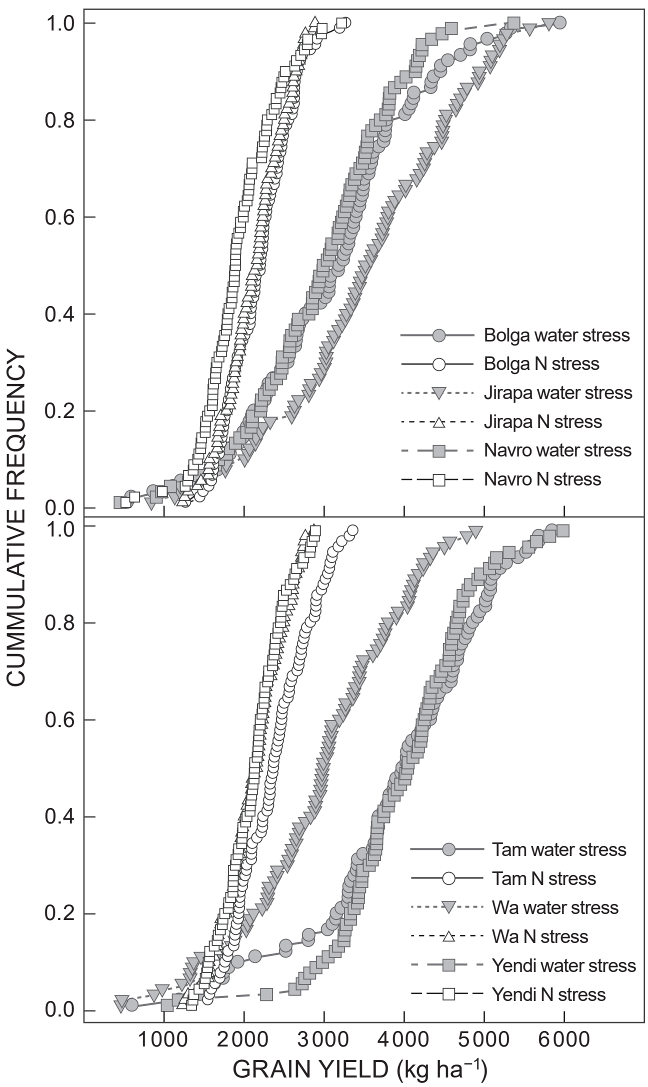

Figure 4: Comparison of simulated yields under water-limited (rain-fed, no nitrogen [N] stress) and N-limited (30 kg N ha^{-1} and no water stress) across the six sites over 30 years and three sowing windows. Tam = Tamale, Bolga = Bolgatanga, Navro = Navrongo

Navrongo (Table 6). The highest Y_{EFP} was 5 173 kg ha^{-1} in Tamale, whereas the lowest Y_{EFP} of 2 992 kg ha^{-1} was obtained in Navrongo. The lowest Y_{EFP} simulated yield under enhanced farmer practices across sites ranged from 459 kg ha^{-1} in Jirapa to 1 399 kg ha^{-1} in Yendi. Variability in the yields obtained under enhanced farmer practices across the sites ranged from 30% to 22%. The use of enhanced farmer practices compared with farmer practices resulted in yield increases (Figure 5) of between 75% in Jirapa to 65% in Tamale. The yield gaps based on potential yields were 26–48% and 36–59% with and without supplementary irrigation, respectively (Table 4).

Impact of supplementary irrigation on CFP and EFP

The use of supplementary irrigation generally resulted in positive grain yield of between 1% and 76% across planting windows and sites under both CFP and EFP conditions. The benefits of irrigation were least visible at the Yendi site (Table 7). The increases in yield due to supplementary irrigation also varied across planting dates with the plants grown in the early planting window benefiting more than those grown in the mid and late planting windows. Variability in maize yield also decreased with the use of supplementary irrigation. The minimum guaranteed yield under both CFP and EFP was also generally higher under supplementary irrigation.

Economic analysis of enhanced nutrient use

Gross margins derived from maize production under CFP and EFP at the six sites varied among sites and within the planting dates (Figure 6). The CDFs of GM obtained for the EFP were consistently dominant over those obtained from the CFP across the study sites. Rose and Adiku (2001) proposed the use of the median GM as a measure of long-term profitability of a management option. In this regard, the highest median GM under CFP was US$185.00 ha^{-1} for early planting in Yendi, whereas the least median GM was US$67.00 ha^{-1} for late planting in Navrongo. For the EFP, the highest median GM was US$315.00 ha^{-1} for early planting in Yendi, whereas the least median GM of US$99.00 ha^{-1} was obtained at Bolgatanga under late planting. Thus, it was also evident

Table 6: Summary yield statistics of simulated maize yields at six sites in the three northern regions of Ghana under nitrogen-varied fertiliser and irrigation conditions. CFP = current farmer practice, EFP = enhanced farmer practice SI = supplementary irrigation. Values in parentheses are the standard error

Parameter	CFP	CFP + SI	EFP	EFP + SI
		Tamale		
Mean (kg ha^{-1})	1 830 (± 50)	2 098 (± 56)	3 031 (± 87)	3 529 (± 77)
Mode (kg ha^{-1})	1 830	2 699	3 053	4 020
Max (kg ha^{-1})	3 148	3 449	5 173	5 953
Min (kg ha^{-1})	381	1 170	573	2 156
CV (%)	26	23	28	22
		Yendi		
Mean (kg ha^{-1})	1 801 (± 44)	1 882 (± 48)	3 088 (± 73)	3 158 (± 77)
Mode (kg ha^{-1})	1 718	2 372	3 078	-
Max (kg ha^{-1})	2 949	2 949	4 894	4 782
Min (kg ha^{-1})	776	775	1399	1 390
CV (%)	23	24	22	23
		Wa		
Mean (kg ha^{-1})	1 228 (± 39)	1 602 (± 40)	2 056 (± 66)	2 792 (± 66)
Mode (kg ha^{-1})	1 129		1 921	1 940
Max (kg ha^{-1})	1 951	2 630	3 599	4 168
Min (kg ha^{-1})	309	506	504	854
CV (%)	30	24	30	22
		Jirapa		
Mean (kg ha^{-1})	1251 (± 35)	1 350 (± 34)	2 196 (± 61)	2 527 (± 56)
Mode (kg ha^{-1})	1 143		1 651	2 325
Max (kg ha^{-1})	2 250	2 246	3 269	3 999
Min (kg ha^{-1})	267	479	459	958
CV (%)	27	27	26	21
		Bolgatanga		
Mean (kg ha^{-1})	1 097 (± 32)	1 253 (± 27)	1 817 (± 55)	2 321 (± 47)
Mode (kg ha^{-1})	1 198	858	2 497	2 422
Max (kg ha^{-1})	1 867	1 802	3 023	3 244
Min (kg ha^{-1})	342	511	753	1 014
CV (%)	27	21	29	19
		Navrongo		
Mean (kg ha^{-1})	1 112 (± 30)	1 279 (± 30)	1 858 (± 56)	2 249 (± 46)
Mode (kg ha^{-1})	786	1 295	2 305	2 355
Max (kg ha^{-1})	1 982	2 026	2 992	3 133
Min (kg ha^{-1})	345	701	659	1 336
CV (%)	27	22	28	19

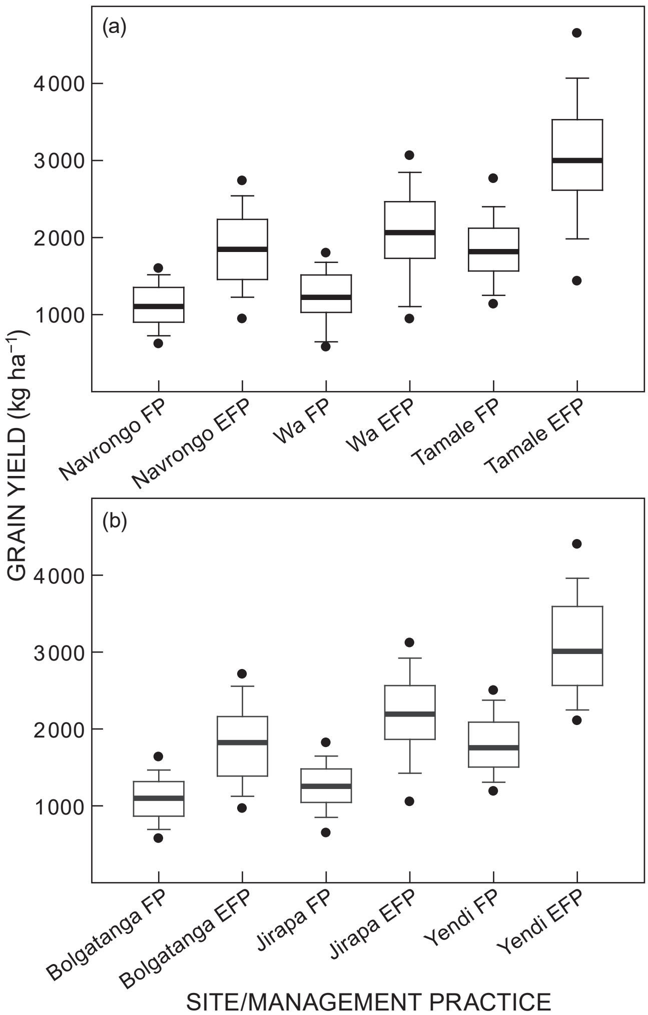

Figure 5: Comparison of simulated maize yield of farmer current farmer practice (CFP) and enhanced farmer practice (EFP) across all six sites. Each box indicates the 25th, 50th and 75th percentiles, error bars indicate the 10th and 90th percentiles, and solid circles represent the 5th and 95th percentiles

that the median GM obtained for the EFP was consistently higher than those obtained for the CFP across sites. In general, both the stochastic dominance and median GM indicate lowest profitability of maize production in Navrongo (Upper East Region) in contrast to the two sites in the Northern Region (Tamale and Yendi) where maize production would be more profitable.

Another measure of profitability of maize production is the variability of the GM. Variability in the GM was generally very high across sites, ranging from 40% in Tamale to 51% in Wa under CFP and from 43% at Yendi and Tamale to 58% in Bolgatanga. In summary, maize production appears to be more profitable in the Northern Region (Tamale and Yendi) than in the Upper West (Wa and Jirapa) and Upper East (Navrongo and Bolgatanga) regions.

Except for Yendi, the use of supplementary irrigation resulted in higher GM under both CFP and EFP across sites (Table 7). Even though the use of supplementary irrigation resulted in positive yield increases, the yield increases did not always result in increase in GM compared with the non-irrigated conditions. Thus, locations with relatively well-distributed rainfall and a longer growing season had a GM under irrigation lower than those sites with poorer rainfall distribution. The Yendi site showed reduction in mean GM by 3% for both CFP and EFP when supplementary irrigation was used. The GM obtained with supplementary irrigation was, however, generally higher compared with the non-irrigated yield.

Discussion

The CERES-Maize module of the DSSAT crop model suite generally performed well in capturing the yield patterns of the maize cultivar ‘Obatanpa’ (an intermediate-maturing cultivar) in the northern regions of Ghana. Previous validation tests gave a Willmott *d*-value of 0.98 (Dzotsi et al. 2010). In the present study, we obtained a *d*-value of 0.82. Based on this performance the model was deemed suitable for this study as grain yield and total biomass simulated by CERES-Maize was credible.

The use of crop growth simulation models to estimate

Table 7: Gross margin returns on maize grown with and without supplementary irrigation at sites in northern Ghana. CFP = current farmer practice, EFP = enhanced farmer practice, SI = supplementary irrigation

	CFP	EFP	CFP + SI	EFP + SI	CFP	EFP	CFP + SI	EFP + SI
Northern Region	Tamale				Yendi			
Mean (US$)	169	268	188	297	163	272	158	266
Median (US$)	148	254	182	295	164	267	156	264
Max (US$)	316	523	351	522	300	518	289	516
Min (US$)	43	42	68	104	46	89	46	77
Upper West Region	Wa				Jirapa			
Mean (US$)	102	161	129	228	105	177	103	201
Median (US$)	99	159	126	224	96	166	94	188
Max (US$)	193	312	253	442	196	353	220	408
Min (US$)	11	11	28	46	9	9	24	47
Upper East Region	Bolgatanga				Navrongo			
Mean (US$)	88	136	93	181	90	142	96	173
Median (US$)	80	117	87	167	83	130	89	154
Max (US$)	192	338	188	356	176	293	184	320
Min (US$)	14	25	17	31	18	30	30	46

yield gap has been suggested as more appropriate as it offers the most reliable way to estimate yield potential and water-limited or exploitable yield because it takes into consideration genetic, environment and management interaction and its effects on grain yield (Grassini et al. 2011; Laborte et al. 2012; van Ittersum et al. 2013).

The potential yield of maize varied with time of sowing across all sites. Generally, planting after the third week of July (late planting) resulted in the lowest average potential yield. Given that water and nutrients are non-limiting, the low yields under late planting could be attributed to the relative decline in solar radiation due to heavy cloud cover during the peak rainfall months of August and September. Thus, late planting of maize should be avoided unless the onset of rains for the season delays.

Under resource-limiting conditions, the average simulated yields were within the ranges reported by several studies (Dzotsi et al. 2010; Naab et al. 2015). While the highest yield potential was simulated for Tamale in the Northern Region, the least was simulated for Navrongo in the Upper East Region. Simulated grain yield variability was higher under water-limited (rain-fed) conditions than under

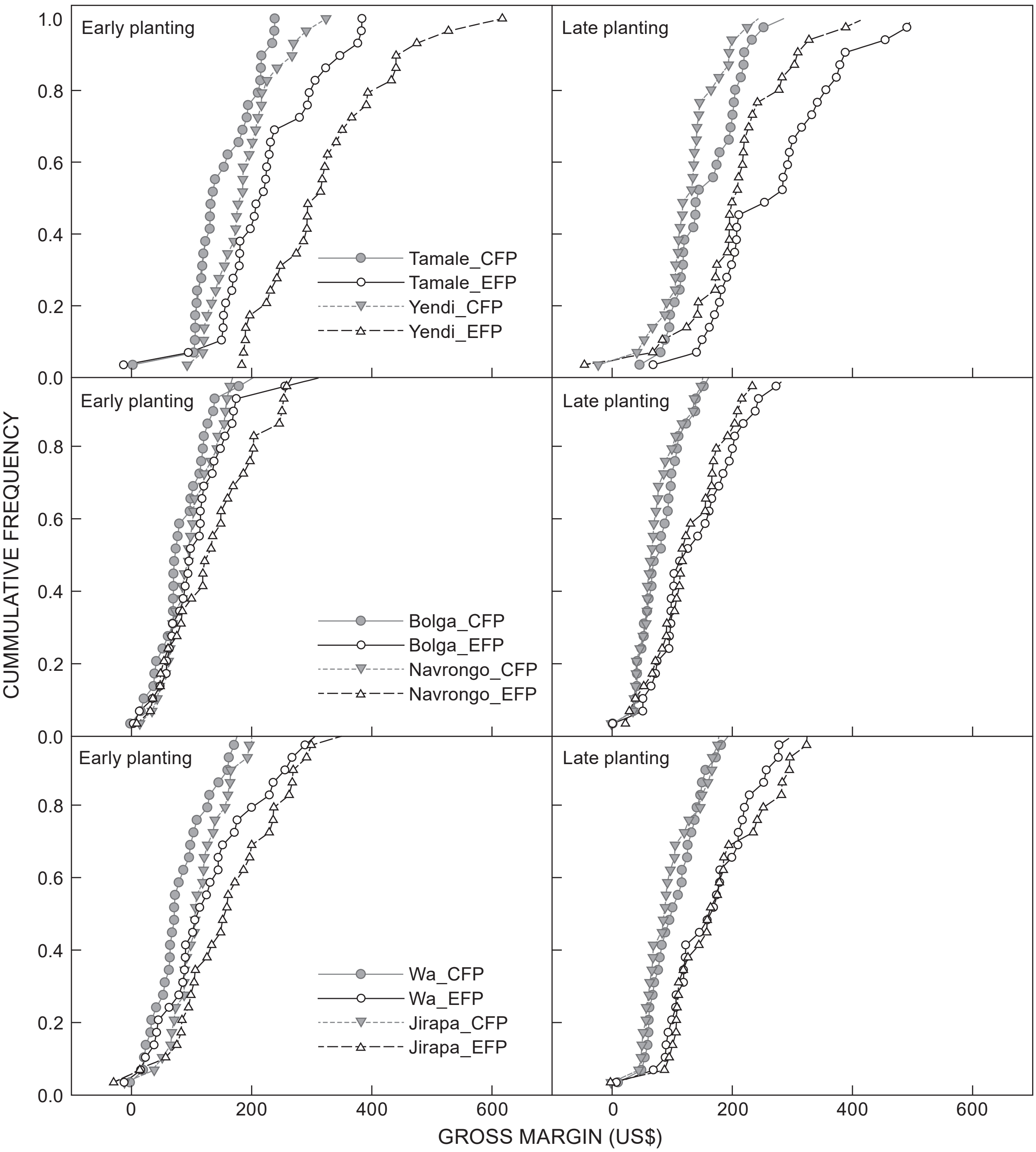

Figure 6: Comparison of estimated gross margins obtainable from current farmer practice (CFP) and enhanced farmer practice (EFP) across all six sites. CFP and EFP had inputs of 30 kg N ha^{-1} + 1 000 kg ha^{-1} manure and 60 kg N ha^{-1} + 2 000 kg ha^{-1} manure, respectively

nitrogen-stress conditions (when water was not limiting). This suggests that variability in rainfall distribution poses more risk to grain yield in the study area.

Yield gap analysis showed that yields under current farmer practice were 59–75% below the potential yields and between 53% and 65% of exploitable yields in northern Ghana, which could be further reduced with supplementary irrigation (Table 4). These values are comparably higher than those obtained by Kaisie et al. (2014) in a similar study in semi-arid Ethiopia. Rotter and Dreiser (1994) also reported values of between 40% and 60% for the Rift valley region of Kenya. The higher gap ratios under current farmer practice may be attributed to the low nutrient input, relatively degraded nature of the soils and the shallow depth, which also limits water-holding capacity (MacCarthy et al. 2017) and hence yields. In the case of the EFP, yield gaps ranged from 29% to 59% below the potential, and from 22% to 42% below exploitable yields, indicating a narrowing of the gap (Table 4).

The narrowing of the yield gap under enhanced farmer management confirms that an increase in inorganic fertiliser plus manure use in the region beyond the current farmer nutrient input (30 kg N ha^{-1} plus 1 000 kg ha^{-1} manure) would increase yields significantly, even under erratic rainfall conditions. The extent of narrowing in the yield gap with the enhanced farmer practice supports the earlier proposition by Muller et al. (2012) that yield gaps in sub-Saharan Africa can be closed especially by increased fertiliser use. Indeed, the economic analysis showed that farmers who opted for enhanced management could still cover their variable costs at 60 kg ha^{-1} of N fertiliser application. Thus, provided credit for inputs purchase is readily available, maize farming in northern Ghana could be a profitable venture with increased yields. Similarly, the cost of supplementary irrigation can be covered by increased grain yield except for the Yendi site.

Apart from the soil constraint, rainfall onset variability and within-season distribution (not total amount) are important determinants of crop yields in the northern regions of Ghana. As shown in this study, maize yields correlated significantly with within-seasonal evapotranspiration ($p < 0.05$) at most of the sites, but the correlation with total seasonal rainfall was weak ($p > 0.05$). Other studies have underscored the importance of rainfall variability for yield stability. Kassie et al. (2014), in a study undertaken in a semi-arid region of Ethiopia, attributed about 60% of maize yield variability to the uncertainty in rainfall. Muller et al. (2011) reported that rainfall variability was the main cause of yield variability in sub-Saharan Africa. The effects of rainfall variability on grain yield is often further aggravated by the low water storage capacity of the dominantly coarse-textured and shallow soils at the sites. Practices that reduce runoff and evaporative losses, such as residue retention and mulching, need be incorporated into farming practices, provided that other competing needs for residues can be met through other alternative means.

We have shown that the soil fertility constraint can be remedied by increased application of fertiliser and manure. Even though supplementary irrigation proved beneficial in five of the six sites studied, the benefits were lower than expected due to the sandy nature of the soils, thereby reducing efficient water use. To be able to operationalise irrigation of maize in these areas will require investment in irrigation infrastructure, which is currently scarcely available. Unless that is done, erratic rainfall distribution will continue to be a challenge, especially in the wake of climate change impact that acts to exacerbate rainfall variability. The erratic rainfall distribution would also reduce efficiency of fertiliser use, particularly if dry spells coincide with fertiliser application times. The efficiency of fertiliser use is also reduced when dry spells occur during the reproductive stage of the crop.

The use of supplementary irrigation has the potential to increase grain yield and also reduce yield variability in most of the sites studied. The present study also showed that yields varied depending on the planting window. Thus, foreknowledge of the weather could assist the farmer in the choice of planting time. Studies by MacCarthy et al. (2017) and Kassie et al. (2014) indicated the utility of climate forecast for efficient rain-water management in rain-fed agriculture. Climate forecast studies are limited in Ghana but there is some indication that seasonal onset and rainfall correlated with the El Niño–Southern Oscillation (Adiku and Stone 1995; Adiku et al. 2007; MacCarthy et al. 2017). In addition, the adoption of weather-based insurance schemes may provide some respite to farmers to protect them against climate-induced risks.

Other important yield-limiting factors, such as appropriate plant population and weed management among others, are critical for the efficient use of the increased fertiliser input. This is particularly relevant in our study areas where the average planting density is 35 000 plants ha^{-1} instead of the recommended 66 000 plants ha^{-1}. In general, our study showed that early planting and increased fertiliser application (60 kg N ha^{-1}) would be the recommendation for improved maize production in the northern regions of Ghana. There is also the need to employ soil management measures that will boost the soil water-holding capacity. The use of enhanced farmer practices should be encouraged because it provides higher yield and the monetary returns are equally superior to those under current farmer practices. This will, however, call for the provision of financial facilities for farmers to be able to access credit that will enable them to purchase suitable inputs and apply cultural practices at the appropriate time.

Conclusions

This study has shown that potential maize yields were highest in the Northern Region and least in the Upper East Region of Ghana. Similarly, yield gaps of maize increase as one moves from the Guinea Savanna to Sudan Savanna agroecology. Nutrient stress appeared to be more severe than water stress in the study sites. Supplementary irrigation together with enhanced nutrient application improved yields, particularly at sites with a shorter growing season and higher frequency of drought spells. Improved soil nutrient management and supplementary irrigation reduced the maize yield gap and also the inter-annual yield variability associated with maize production in smallholder systems in this study. Provided financial resources were accessible to farmers and irrigation facilities developed, there is a high probability that returns from maize farms with improved management would be higher than those under current farmer practice.

Acknowledgements — The authors are grateful to the SARD-SC Maize project, CRP MAIZE and CIMMYT/IITA whose financial support through Project A4032.09.34 made this research possible.

References

Adiku SGK, Mawunya FD, Jones JW, Yangyouru M. 2007. Can ENSO help in agricultural decision-making in Ghana? In: Sivakumar MVK, Hansen J (eds), *Climate prediction and agriculture: advances and challenges*. Berlin: Springer-Verlag. pp 205–212.

Adiku SGK, Stone RC. 1995. Using the Southern Oscillation index for improving rainfall prediction and agricultural water management in Ghana. *Agricultural Water Management* 29: 85–100.

Anderson JA, Dillon JL, Hardaker JB. 1977. *Agricultural decision analysis*. Ames: Iowa State University Press.

Brammer H. 1962. Soils of Ghana. In: Wills B (ed.), *Agriculture and land use in Ghana*. New York: Oxford University Press. pp 88–126.

Dzotsi KA, Jones JW, Adiku SGK, Naab JB, Singh U, Porter CH, Gijsman AJ. 2010. Modelling soil and plant phosphorus within DSSAT. *Ecological Modelling* 221: 2839–2849.

Gijsman AJ, Hoogenboom G, Parton WJ, Kerridge PC. 2002. Modifying DSSAT crop models for low input agricultural systems using a soil organic matter-residue module from CENTURY. *Agronomy Journal* 94: 462–474.

Grassini P, Thorburn J, Burr C, Cassman KG. 2011. High–yield irrigated maize in the Western U.S. Corn-Belt: I. On-farm yield, yield–potential, and impact of management practices. *Field Crops Research* 120: 142–150.

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT. 2003. The DSSAT cropping system model. *European Journal of Agronomy* 18: 235–265.

Jones JW, Kiniry JR. 1986. *CERES-Maize: a simulation model of maize growth and development.* College Station: Texas A&M University Press.

Jones PG, Thornton PK. 2003. The potential impacts of climate change in tropical agriculture: the case of maize in Africa and Latin America in 2055. *Global Environmental Change* 13: 51–59.

Kassie BT, van Ittersum MK, Hengsdijk H, Asseng S, Wolf J, Rötter RP. 2014. Climate-induced yield variability and yield gaps of maize (*Zea mays* L.) in the Central Rift Valley of Ethiopia. *Field Crops Research* 160: 41–53.

Laborte AG, de Bie CAJM, Smaling EMA, Moya PF, Boling AA, van Ittersum MK. 2012. Rice yields and yield gaps in Southeast Asia: past trends and future outlook. *European Journal of Agronomy* 36: 9–20.

Laux P, Wagner S, Wagner A, Jacobeit J, Bárdossy A, Kunstmann H. 2009. Modelling daily precipitation features in the Volta Basin of West Africa. *International Journal of Climatology* 29: 937–954.

MacCarthy DS, Adiku SGK, Freduah BS, Gbefo F, Kamara AY. 2017. Using CERES–Maize and ENSO as decision support tools to evaluate climate-sensitive farm management practices for maize production in the northern regions of Ghana. *Frontiers in Plant Science* 8: 31.

MacCarthy DS, Akponikpe PBI, Narh S, Tegbe R. 2015. Modelling the effect of seasonal climate variability on the efficiency of mineral fertilization on maize in the coastal savannah of Ghana. *Nutrient Cycling in Agroecosystems* 102: 45–64.

MacCarthy DS, Vlek PLG, Fosu-Mensah BY. 2012. The response of maize to N fertilization in a sub-humid region of Ghana: understanding the processes using a crop simulation model. In: Kihara J, Fatondji D, Jones JW, Hoogenboom G, Tabo R, Bationo A (eds), *Improving soil fertility recommendations in Africa using the Decision Support Systems for Agrotechnology Transfer (DSSAT)*. Dordrecht: Springer. pp 61–75.

MoFA (Ministry of Food and Agriculture). 2011. Agriculture in Ghana: facts and figures (2010). [s.l.]: Ministry of Food and Agriculture, Statistics, Research and Information Directorate.

Muller C, Cramer W, Hare WL, Lotze-Campen H. 2011. Climate change risk for African agriculture. *Proceedings of the National Academy of Sciences of the USA* 108: 4313–4315.

Muller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. 2012. Closing yield gaps through nutrient and water management. *Nature* 490: 254–257.

Naab JB, Mahama GY, Koo J, Jones JW, Boote KJ. 2015. Nitrogen and phosphorus fertilization with crop residue retention enhances crop productivity, soil organic carbon, and total soil nitrogen concentrations in sandy–loam soils in Ghana. *Nutrient Cycling in Agroecosystems* 102: 33–43.

Neumann R, Jung G, Laux P, Kunstman H. 2007. Climate trends of temperature, precipitation and river discharge in the Volta Basin of West Africa. *International Journal of River Basin Management* 5: 17–30.

Porter CH, Jones JW, Adiku SGK, Gijsman AJ, Gargiulo O, Naab JB. 2010. Modelling organic carbon and carbon–mediated soil processes in DSSAT V4.5. *Operational Research* 10: 274–278.

Ritchie JT. 1998. Soil water balance and plant water stress. In: Tsuji GY, Hoogenboom G, Thornton PK (eds), *Understanding options for agricultural production*. Dordrecht: Kluver Academic Publishers. pp 41–54.

Rose CW, Adiku SGK. 2001. Conceptual methodologies in agro-environmental systems. *Soil and Tillage Research* 58: 141–149.

Rotter RP, Dreiser C. 1994. Extrapolation of maize fertilizer trial results by using crop-growth simulation: results from Muranga District, Kenya. In: Fresco LO, Boume LSJ, van Keulen (eds), *The future of the land: mobilising and integrating knowledge for land use options*. Chichester: John Wiley and Sons. pp 249–260.

Soler CMT, Sentelhas PC, Hoogenboom G. 2007. Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *European Journal of Agronomy* 27: 165–177.

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. 2013. Yield gap analysis with local to global relevance—a review. *Field Crops Research* 143: 4–17.

van Ittersum MK, Rabbinge R. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52: 197–208.

Willmott CJ. 1981. On the validation of models. *Physical Geography* 2: 184–194.

Received 28 February 2017, revised 4 July 2017, accepted 8 July 2017
Associate Editor: Albert Materechera