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Monitoring and Modelling Analysis of Maize (*Zea mays* L.) Yield Gap in Smallholder Farming in Ghana

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Abstract: Modelling and multiple linear regression were used to explore the reason for low maize yield in the Atebubu-Amantin and West Mamprusi Districts of Ghana, West Africa. The study evaluated maize yields on twenty farms against measures of soil fertility, agronomic attributes and soil water availability. Correlations between yield, soil fertility, rain, crop density, and weed biomass, were low, and no single factor could explain the low yields. A 50-year virtual experiment was then set up using the Agricultural Production Systems Simulator (APSIM) to explore the interactions between climate, crop management (sowing date and nitrogen fertilization) and rooting depth on grain yield and nitrate (NO_3-N) dynamics. The analysis showed that a lack of optimal sowing dates that synchronize radiation, rainfall events and nitrogen (N) management with critical growth stages explained the low farm yields.

Keywords: soil water; radiation interception; smallholder farmers; leaching; APSIM

1. Introduction

In the past 50 years, global wheat, maize and rice yields has increased as a result of crop intensification involving improved varieties, increased fertilizer inputs, production of two or more crops per year on the same piece of land, and irrigation [1–4]. Increases in maize yield of sub-Saharan African smallholders, however, were insignificant and remained with the largest yield gap in the world [5]. On average, the yield gap is 20%–36% below potential yield [6–9]. The key factors causing low yield are biophysical and management practices that lead to frequent nutrient, water, pest and disease stresses [7,8]. In South-East Asia, achievable maize yield is still about 0.9 t ha^{-1} lower than potential yield, resulting from field management and climate change. Site-specific nutrient management and climate resilient germplasm has been observed to be a potential way forward for sustainable intensification of maize production by smallholder farmers [9–11]. Improving smallholder farmers' yield, especially in Africa and Asia, is a critical part of future global food security.

Maize is an important staple food in Ghana accounting for more than 50% of total cereal production in the country and is grown in all agro-ecological zones [12]. In northern Ghana, where the annual rainfall averages 900 mm, simulation modelling evaluated under water non-limiting conditions suggest that farmers' yields are 59–75% below the potential [13]. The low productivity is attributed to poor soil fertility, management and climate variability [13,14]. Closing the yield gaps for maize is a priority for agricultural researchers in Ghana.

Various interventions have been proposed to address the maize yield gap in smallholder farms in Ghana. Application of N and P fertilizer, retention of crop residues, adopting minimum tillage that enhances soil organic carbon, total soil N and P concentrations, are likely to increase yields to be closer to the water-limited yield potentials [15]. However, adoption of these management options has been constrained by socio-economic limitations that include high costs, labor constraints, high transport costs, lack of credit facilities and lack of knowledge and technology [16–18]. Even though many authors agreed that nutrient supply rather than water is the limiting factor for yield in Ghana, it is observed that reduced maize yield on well-fertilized soil is due to highly variable rainfall [19,20].

Maize breeding programs in Ghana endeavor to bridge the yield gap with improved varieties. However, the potential of the new genetic material can only be realized if crop management, soil water and agronomic management are optimal. Improved varieties have yield advantages over traditional varieties due to superior root architecture, which provides the crop with increased capacity to extract soil nutrients and water and withstand abiotic stresses [21]. Over 40 maize varieties have been released since 1983. Maize cv. Obatanpa (CSIR—Crops Research Institute of Ghana) is the dominant variety planted by farmers and has a grain yield potential of 6 t ha^{-1} [22,23]. Although most farmers have adopted Obatanpa, the current average yield of maize in Ghana stands at 1.99 t ha^{-1}, far below the potential yield of 6 t ha^{-1} [22,24].

The large yield gaps in African smallholder farming systems are due to the genetic-environment-management interactions [6]. Farmers' priorities regarding labor allocation during sowing, fertilizer application and weeding are the most important factors that affect the actual yield. For example, delayed sowing due to insufficient labor exposes critical stages of crop development to periods of drought, low radiation, extreme temperature and water deficits which limit yield potential [25,26]. It is, however, challenging to understand the complex interaction and to determine which constraint is more critical to yield increase when there are multiple interacting constraints [7].

Smallholder farmers in Ghana often achieve lower yield for given management practices, sites, and varieties. Several studies have shown the low maize yield is a result of interactions between three biophysical constraints: (i) poor soil fertility, (ii) low plant available water capacity, and (iii) the variability of climatic factors. Questions have been raised about whether the low crop yields are related to soil fertility, soil water, crop density, or competition from weeds. Another question is whether the interactions between in-crop rainfall, radiation, sowing time, soil water stress, NO_3-N leaching, and management are the main cause of low yield. It is, therefore, possible to hypothesize that coinciding sowing windows with high radiation growth period and rainfall on fertility unconstrained soils would improve maize yield. The interaction between these biophysical constraints can be explored using long-term field trials and simulation modelling [27]. Simulation models give the flexibility of evaluating management options over space and time with fewer resources as compared with field experiments [28–30]. The Agricultural Production Systems Simulator (APSIM) has been used in Sub Saharan Africa to explore opportunities related to soil fertility, sowing date, crop management and climate change in smallholder farming systems [31–39]. The objective of this research was to investigate the interaction of in-season rainfall, radiation, sowing date, N management, and root depth on grain yield and N dynamics, and examine the main constraints of maize production in West Mamprusi and Amatin Atebubu, in the Middle and Northern Ghana.

2. Materials and Methods

2.1. Site Description and Climate

The relationship between maize yield, soil water and fertility was investigated in the forest—savannah transition and the Guinea savannah agroecological zones of Ghana. The study was conducted at four locations in the 2012 and 2013 cropping seasons (Figure 1): Atebubu (7°45′ N, 0°59′ W), Amantin (7°32′ N, 1°12′ W) (Atebubu-Amantin district) are located in the forest–savannah transition zone, and Wungu (10°19′ N, 0°51′ W) and Wulugu (10°27′ N, 0°47′ W) (West Mamprusi districts) in the Guinea savannah agroecological zone of Ghana. The forest—savannah transition zone is characterized by well-distributed bimodal rainfall with an annual average of 1500 mm (Figure 2). The mean monthly temperature during the growing season ranges from 22 to 34 °C. The Guinea savannah agroecological zone is characterized by low, erratic and poorly distributed monomodal rainfall. The mean annual rainfall is 1100 mm and the daily mean minimum and maximum temperatures are 22 and 35 °C, respectively [24].

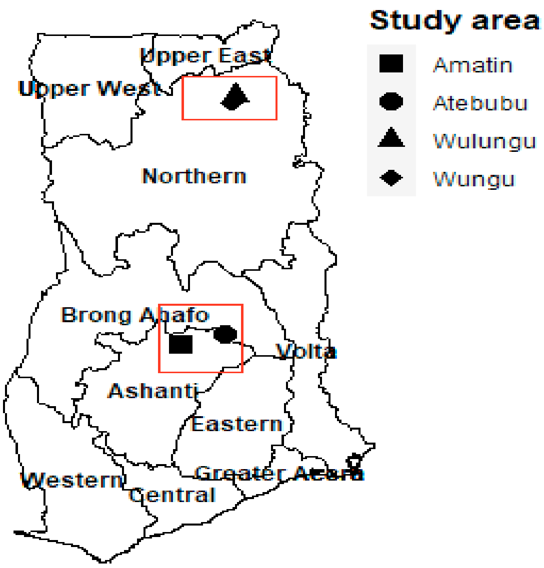

Figure 1. Location of the study areas in Ghana.

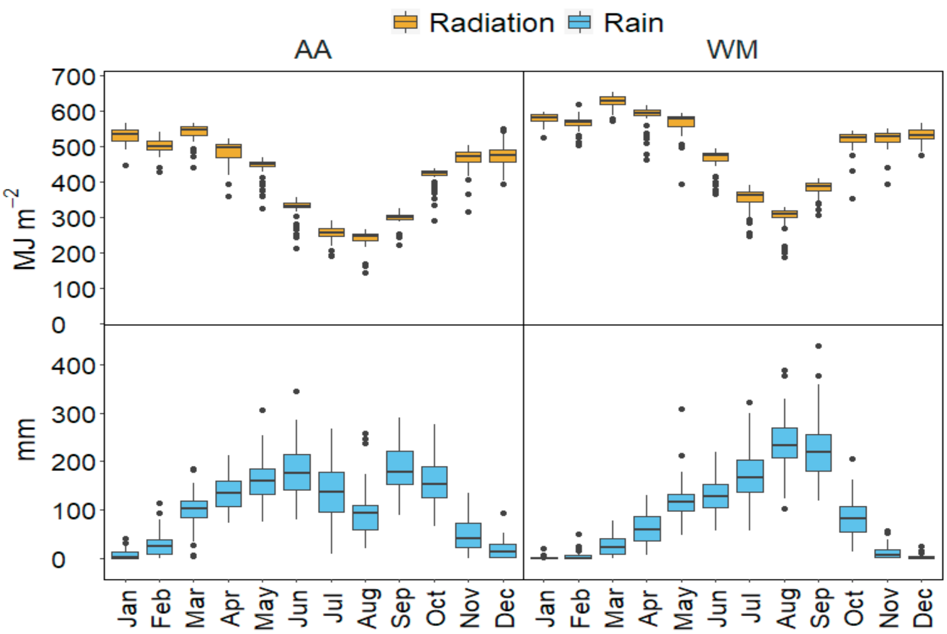

Figure 2. Long-term mean monthly total radiation and rainfall for Atebubu-Amantin (AA) and West Mamprusi (WM). The AA site has two seasons: major (Mar–Jul) and minor (Aug–Nov) season. The boxplot shows variability of rainfall and radiation. The lower horizontal line of the box represents the 25-percentile limit, and the upper horizontal line represents the 75-percentile limit. The line in the box represents the median radiation or rainfall. The dots below the 25 and above 75 percentile limits are outliers.

2.2. Field Measurements

2.2.1. Crop Data

Maize yields were measured on 20 farms from the center of two rows of each field. Farmers planted maize (cv. Obatanpa) in most of the study areas. Plant density (plant ha^{-1}) and weed pressure (kg ha^{-1}) were also recorded. The maize cobs were harvested 74–143 days after sowing. The sowing and harvesting dates and fertilizer rates applied by the farmers are summarized in Tables 1 and 2.

Table 1. Sowing date, harvesting date and fertilizer amount applied by the farmers in Atebubu-Amantin District.

Season	Sowing Date	Sowing (DOY) **	Harvest Date	Harvesting (DOY)	N Applied * (kg ha^{-1})	Days to Harvesting (Days)
Minor	31 July 2012	213	20 December 2012	355	0	143
Major	5 May 2012	126	9 September 2012	253	59	128
Minor	27 August 2013	239	20 December 2013	354	38	116
Major	14 April 2012	105	9 August 2012	222	65	118
Minor	7 September 2013	250	20 June 2013	354	0	104
Minor	5 August 2012	218	18 December 2012	353	65	136
Minor	6 August 2012	219	19 December 2012	354	101	136
Minor	8 September 2013	251	18 December 2013	352	19	102

* Total N applied represents N applied from compound fertilizer and ammonium sulfate. ** DOY = day of year.

Table 2. Sowing date, harvesting date and fertilizer amount applied by the farmers in West Mamprusi District.

Sowing Date	Sowing (DOY) **	Harvest Date	Harvesting (DOY)	N Applied * (kg ha^{-1})	Days to Harvesting (Days)
20 June 2012	172	3 November 2012	308	76	137
12 July 2013	193	13 September 2013	256	19	115
11 July 2012	193	30 November 2012	335	0	143
12 July 2013	193	23 September 2013	266	0	74
9 July 2012	191	20 November 2012	325	62	135
11 July 2013	192	5 November 2013	309	25	118
15 June 2012	167	1 November 2012	306	40	140
29 June 2013	180	5 October 2013	278	41	99

* Total N applied represents N applied from compound fertilizer and ammonium sulfate. ** DOY = day of year.

2.2.2. Soil Data

Soil fertility indices of total nitrogen (TN), pH, organic matter (SOC), soil phosphorus (P), and potassium (K) were measured in the 0–0.30 and 0.30–0.60 m zone on twenty farms. Total N was determined using the Kjeldahl method, soil pH was measured using a pH meter (1:1, H_2O), organic carbon (OC) using the Walkley and Black method [40,41]. Soil available P was determined using the Bray method [42], and available K using flame photometry [41]. Exchangeable cations were determined using the ammonium acetate method [41]. Soil properties are summarized in Table 3.

Soil matric potentials (ψ) were measured using Watermark sensors (Irrometer Co., Riverside, CA, USA) at 0.30, 0.60, and 0.80 m depths in ten farmers' field. A handheld watermark meter was used to read the sensors in the field. Additionally, Decagon 5TM (Decagon Devices, Inc., Pullman, WA, USA) soil water probes were installed at two farmers' fields in each of the two sites at 0–0.30 and 0.30–0.60 m to determine crop lower limit (LL) and drained upper limit (DUL) of the soils. The sensors were connected to a datalogger and data were recorded hourly. The lower limit (LL) was determined at the end of the season when crops had extracted all the water available to it from the soil, whereas DUL or field capacity is the maximum amount of water the soil can hold against gravity. Plant available water (PAW) was calculated as the difference between LL and DUL in mm for each depth (mm). Soil water characteristics of the farmers' field are summarized in Table 4. Two soil solution samplers were also installed at 0.30 and 0.60 m adjacent to each other and solutions were collected three times a week.

Soil NO_3-N concentration was measured by dipping test strips on each of the samples and reading the test strips with an RQflex Plus 10 [43].

Table 3. Soil physical and chemical properties of studied farmers' fields.

Site	Depth (m)	Exchangeable Cations (Centimol$^+$ kg^{-1})				Org. C (%)	pH	Total N (%)
		Ca^{2+}	Mg^{2+}	K^+	Na^+			
A	0.30	1.34	1.34	0.12	0.04	0.69	5.7	0.06
	0.60	2.14	0.53	0.16	0.05	0.11	5.3	0.01
B	0.30	2.67	0.53	0.03	0.02	0.75	5.6	0.06
	0.60	2.67	0.53	0.04	0.02	0.59	5.9	0.05
C	0.30	1.34	0.53	0.05	0.03	0.86	5.5	0.08
	0.60	1.34	0.53	0.03	0.02	0.48	5.4	0.04
D	0.30	3.20	1.34	0.09	0.03	0.96	6.0	0.08
	0.60	1.60	0.53	0.06	0.03	0.66	5.7	0.06
E	0.30	4.27	1.87	0.11	0.04	0.86	6.3	0.08
	0.60	2.14	1.60	0.05	0.03	0.73	5.8	0.07
F	0.30	1.34	0.80	0.04	0.02	0.57	5.8	0.05
	0.60	1.34	1.07	0.05	0.03	0.50	5.5	0.04
G	0.30	1.87	1.34	0.06	0.03	0.34	6.5	0.02
	0.60	1.60	1.07	0.05	0.03	0.18	6.5	0.02
H	0.30	2.40	1.07	0.19	0.05	1.19	6.17	0.06
	0.60	2.14	1.34	0.11	0.04	1.03	6.07	0.05
I	0.30	2.14	0.80	0.12	0.04	0.98	6.1	0.05
	0.60	1.60	1.07	0.11	0.04	0.71	5.9	0.04
J	0.30	4.01	0.80	0.26	0.07	0.82	6.26	0.07
	0.60	4.01	0.80	0.16	0.05	0.44	5.99	0.04

Table 4. Soil water characteristics of studied fields.

Site	Depth (m)	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	Bulk Density (g cm^{-3})	PAW (mm)
A	0.30	0.06	0.21	0.3	1.49	45
	0.60	0.06	0.21	0.3	1.58	45
B	0.30	0.06	0.21	0.3	1.45	45
	0.60	0.06	0.21	0.3	1.45	45
C	0.30	0.15	0.19	0.3	1.45	12
	0.60	0.12	0.17	0.3	1.52	15
D	0.30	0.15	0.19	0.3	1.41	12
	0.60	0.12	0.17	0.3	1.37	15
E	0.30	0.15	0.19	0.3	1.41	12
	0.60	0.12	0.17	0.3	1.43	15
F	0.30	0.10	0.24	0.3	1.49	42
	0.60	0.10	0.24	0.3	1.58	42
G	0.30	0.10	0.24	0.3	1.45	42
	0.60	0.10	0.24	0.3	1.45	42
H	0.30	0.12	0.20	0.3	1.45	24
	0.60	0.12	0.18	0.3	1.52	18
I	0.30	0.12	0.20	0.3	1.41	24
	0.60	0.12	0.18	0.3	1.48	18

LL, DUL and SAT, are saturated, Lower Limit and Drained Upper Limit of soil water respectively; PAW is Plant Available Water.

2.3. Modelling Using APSIM

We used the cultivar parameters suggested for maize (cv. Obatanpa) [37]. The crop management data (sowing date, harvest date, range of N applied) were taken from the farmers' field records (Table 1). A sowing density of 67,000 plants ha^{-1} and row spacing of 0.75 m were used in the model following recommended practices [44,45].

Although soil water content was measured in 10 farmers' fields (Table 4), a representative soil hydraulic profile with a fine soil layer using those measured and soil parameters reported by MacCarthy et al. [37] for northern Ghana was used in APSIM (Table 5). Soil water was assumed to be the same for soil layers 0 to 0.30 m and 0.30 to 1.20 m deep as measurements were taken only at 0.30 and 0.60 m. Water availability was also assumed to decrease with soil depth, particularly below 0.30 m (Table 5).

Table 5. Soil hydraulic properties used in Agricultural Production Systems Simulator (APSIM) for scenario simulations.

Soil Layers (m)	West Mamprusi (WM)				AA Major and AA Minor			
	LL **	DUL	SAT	Maize LL *	LL **	DUL	SAT	Maize LL *
0–0.10	0.06	0.24	0.3	0.06	0.1	0.21	0.3	0.1
0.10–0.20	0.06	0.24	0.3	0.06	0.1	0.21	0.3	0.1
0.20–0.30	0.06	0.24	0.3	0.06	0.1	0.21	0.3	0.1
0.30–0.45	0.07	0.24	0.3	0.07	0.11	0.21	0.3	0.11
0.45–0.60	0.07	0.24	0.3	0.08	0.11	0.2	0.3	0.12
0.60–0.90	0.07	0.22	0.3	0.10	0.11	0.19	0.3	0.13
0.90–1.20	0.07	0.20	0.3	0.12	0.11	0.18	0.3	0.14

* Maize LL (lower limit) indicates the extent to which maize can extract water from the soil. ** LL refers to permanent wilting point. All measurements are in mm mm^{-1}.

Soil albedo, soil drainage, and runoff curve number values reported by MacCarthy et al. [38] were adjusted for the site. Soil water above the drainage upper limit was assumed to drain within one day to the next layer. Oxygen stress that crops would have experienced when the soil is saturated was not considered. The only stress that was simulated in APSIM was the reduction in yield due to water, N, climatic factors and root depth.

The root exploration factor (*xfi*), which determines the ability of roots to grow, proliferate and extract water from each layer, was assumed to be non-limiting to yield (Table 6).

Table 6. APSIM root related soil input parameters used for scenario simulations.

Soil Parameters	Values
kl_i *	0–0.06
xf_{i} **	1

* A constant which is used to limit soil water extraction from a particular soil layer (m^3 m^{-3}). ** Root exploration factor used to consider physical constraints that slows down root advancement to different depths was considered non limiting. *i* refers to number of layers.

Modelling Scenarios

The model was run for 3 combinations of virtual experiments: (i) application of six N rates (0 to 125 kg N ha^{-1}, at 25 kg N ha^{-1} increments); (ii) root water extraction constrained at four rooting depths (0.30, 0.60, 0.90, and 1.20 m) using the soil parameter (*kl*) and (iii) seven sowing windows. For the 1.20 m rooting depth, root water extraction was considered non-limiting at all depths. For West Mamprusi (WM) and Amantin-Atebubu major season (AAMajor), five sowing months (March to July), whereas for Amantin-Atebubu minor season (AAMinor) two sowing months (August and September), were considered. For both sites, a sowing rule criterion was applied: sowing commenced after 25 mm of rainfall was recorded in the preceding five days. Simulations were carried out for each site using the maize (cv. *Obatanpa*) parameters, soil and long-term daily weather records (1950–2000; http://www.eu-watch.org/database). Soil water profiles were not reset to account for the effect of any rainfall after harvest and before next sowing.

For each site, biomass, yield, radiation interception, in-crop rainfall, sowing date, deep drainage, water stress, nitrogen stress and NO_3-N leaching were considered as predictors of yield and were extracted for analysis. Temperature's effects on crop thermal time were not separately included in the study because its effect on crop cycle was considered indirectly through crop yield. Multiple linear regression (MLR) analysis was used to identify the relationship between yield and the set of independent variables (rainfall, radiation, NO_3-N leaching, and drainage). We performed statistical analyses with R version 3.3.0 [46]. The analysis was done for all N applications considering grain yield and biomass as response variables and in-crop rainfall, radiation interception, sowing window, leaching, drainage, water stress, and nitrogen stress as predictors.

3. Results

3.1. Observed Yield, Soil Water and Nutrients

Surveys of farmers involved in the trial showed that N fertilizer applications varied between 0 and 101 kg ha^{-1} in the Atebubu-Amantin district (Table 1) and between 0 and 76 kg ha^{-1} in the West Mamprusi district (Table 2). The two sources of N fertilizer used were compound fertilizer (15-15-15 kg ha^{-1} N-$P_2 0_5$-K_2O) and ammonium sulfate [$(NH_4)_2SO_4$]. Ammonium sulfate was applied about six weeks after sowing as a top dressing.

The grain yield obtained by farmers plotted against explanatory variables of soil fertility, crop density, and weed pressure for the three sites is given in Figure 3. The soil was poor in terms of its fertility (P, N% and Org. C(%)), planting density varied among farmers (4 to 17 plants m^{-2}), 75% of the fields were acidic and the weed pressure (volume) also varied between 200 and 800 kg ha^{-1} dry matter. None of these explanatory variables correlated with the farmers' yields. Two farms that had very high plant densities in AAMajor (rainfall > 1000 mm) had poor yields, and none of the other variables measured could explain the low yields.

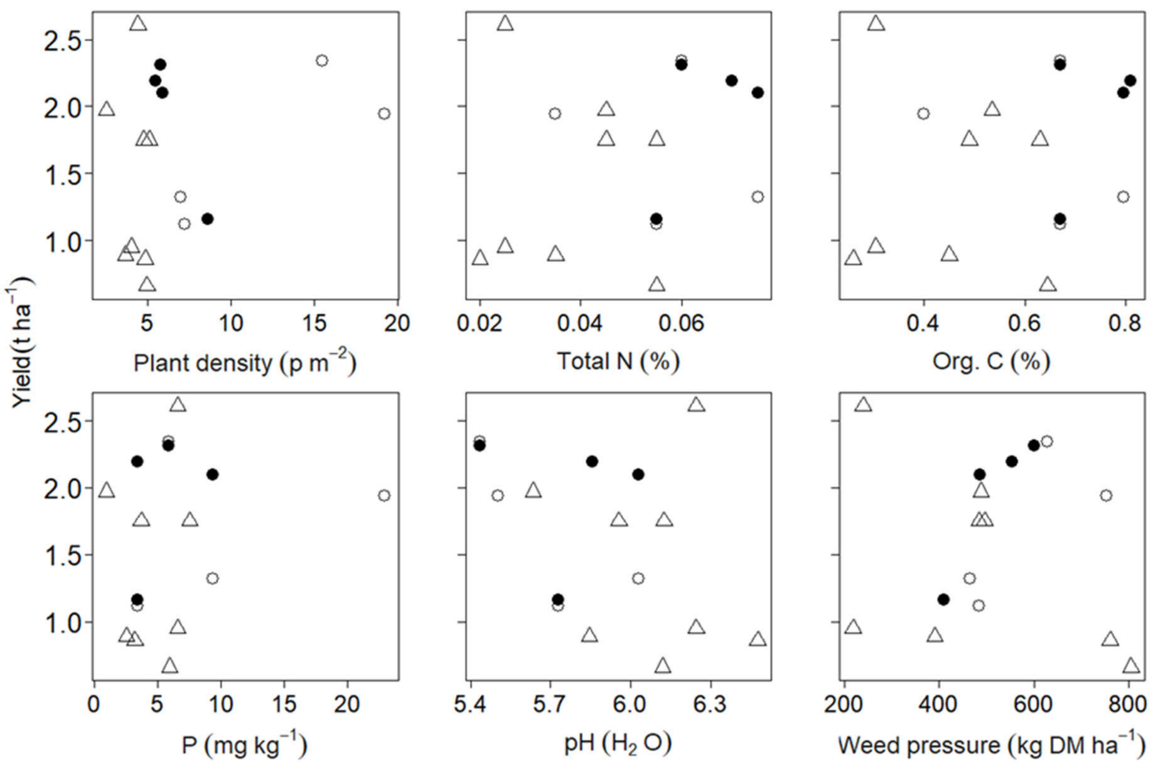

Figure 3. Grain yield (15% moisture content) of maize (t ha^{-1}) against soil nutrient, agronomic practices (plant density and weed pressure) for Amantin-Atebubu major season (AAMajor) (○), Amantin-Atebubu minor season (AAMinor) (•) and WM (△).

Figure 4 shows matric potentials (ψ) measured over time for the different sites. Matric potentials (ψ) between 0 and −25 kPa were considered as wet and the optimum soil water content is typically at field capacity, near −30 kPa in most agricultural soils. Figure 4b,d, and h show the soils to be generally wet and there was little, if any, water extraction from the sub-soil (0.60–0.80 m depth), as evidenced by no increase in the matric potential during the cropping season. The soil moisture measurements across the farmers' field showed very few crops used sub-soil moisture (Figure 4a–f). In the wetter zone (Atebubu-Amantin), 38% of the farmers planted between March and May, and 62% of the farmers planted between July and September (Table 2).

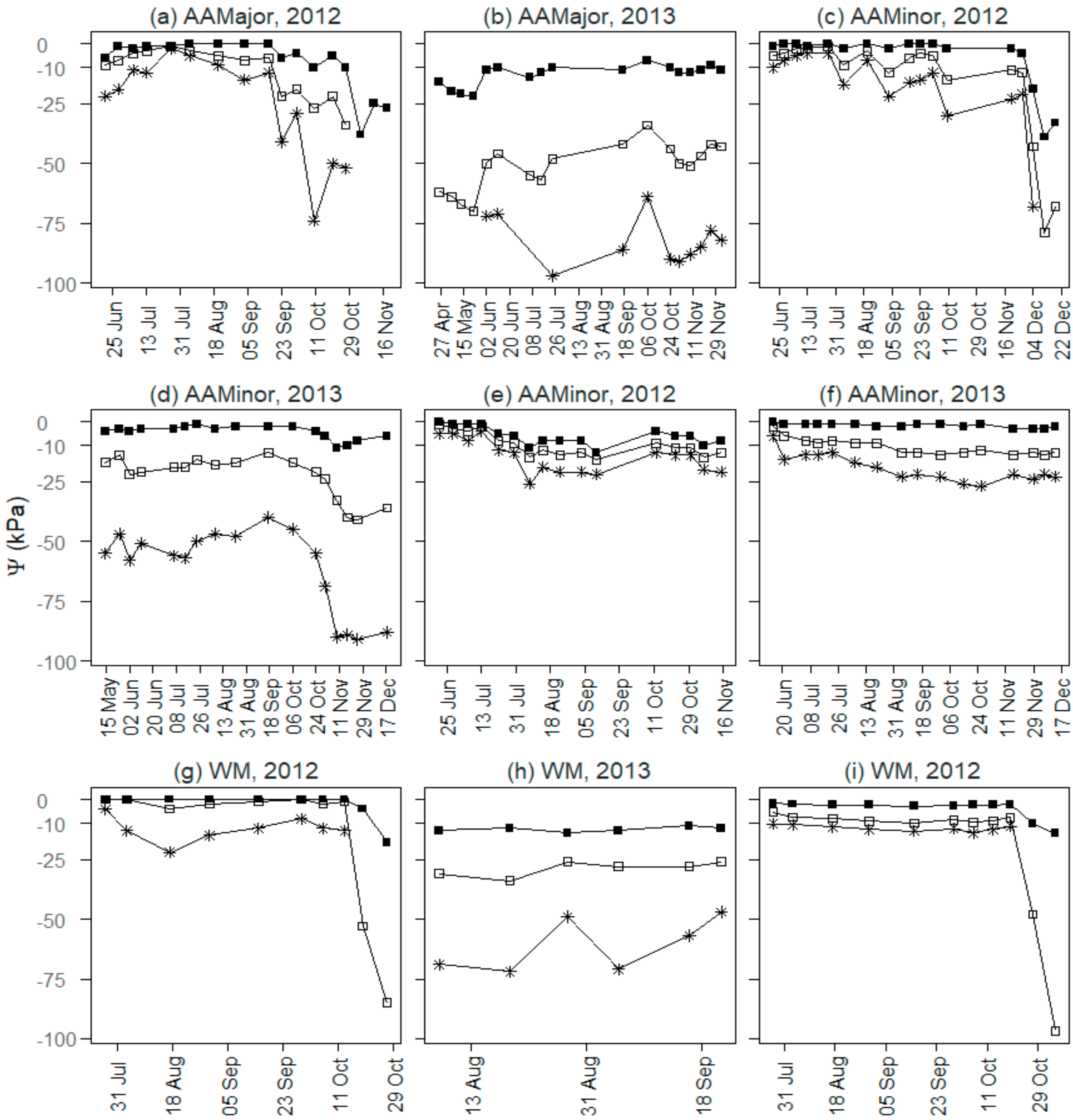

Figure 4. Average matric potential measured at three depths; 0.30 (✳), 0.60 (□), and 0.80 m (■) using watermark sensors in selected farmers' fields AA and WM sites. The growing period of the crops is indicated at the top of each plot.

Nitrate-N concentrations in farmers field at 0.30 and 0.60 m depth are shown in Figure 5. Of the farmers who applied fertilizer, 12.5% applied >75 kg N ha^{-1} and 25% applied 50–75 kg N ha^{-1}. Relatively high concentrations of NO_3-N (>60 mg L^{-1}) were observed at 0.60 m depth early in the growing season. Given that there was little water extraction at this depth, we argue that NO_3-N was not taken up by the crop (Figure 5). The wet profile (ψ > −25 kPa) and high NO_3-N collected by the suction cups at 0.60 m is evidence that water moved down the profile. Suction samples collect water samples only when ψ > −40 kPa [39] and provide further evidence to suggest that the water was moving down the profile and leaching the NO_3-N before it was taken up by the crop. The high NO_3-N concentration observed 85 days after planting in one field corresponded with the wet state at 0.30 m.

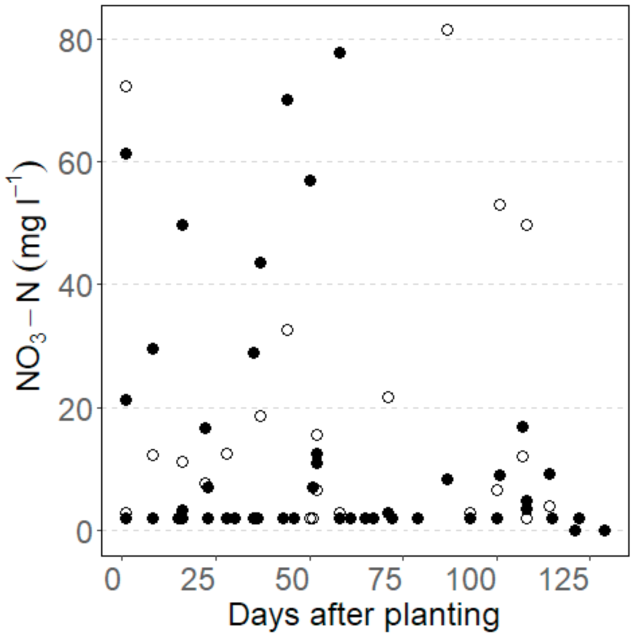

Figure 5. NO_3-N concentrations of a soil solution collected at 0.30 (○) and 0.60 m (•) depth using suction samplers in six farmers' fields.

3.2. Modelling Results

3.2.1. Yield, Sowing Date and Rooting Depth

Simulated yield showed high inter-annual variability with coefficient variation (CV) of 43%, 43%, 55% for West Mamprusi, Atebubu-Amantin major, and Atebubu-Amantin minor seasons, respectively. Higher grain yield was simulated when maize is sown in April in AAMajor and August in AAMinor for the 75 kg N ha^{-1} treatment (Figure 6). The reason for the higher yield in this sowing window is due to the high in-crop radiation and rainfall the crop receives at a critical stage (emergence to the start of grain-filling during the flowering period). For example, for AAMajor, the model simulated >3800 kg ha^{-1} when the average in crop radiation interception and rainfall for April is 543 MJ m^{-2} and 563 mm, and 632 MJ m^{-2} and 428 mm in WM, respectively. On the other hand, the yield was simulated to be <2500 kg ha^{-1} for the April planting and the average in-crop radiation interception and rainfall for the season was 353 MJ m^{-2} and 469 mm respectively, for AAMajor. The model also simulated a similar trend of yield for a given in-crop radiation interception and rainfall on WM and AAMinor. Higher biomass was simulated when maize was sown in April and May for WM, March, April, and May in AAMajor and August in AAMinor for the 75 kg N ha^{-1} treatment (Figure 7). The analysis showed that there is a 90% chance of getting a higher grain yield than the observed farmer yield when 75 kg N ha^{-1} is applied and for planting in April and May in AAMajor and WM (Figure 6). In AAMinor, there was only an 80% chance of getting higher yield than the average farmers' yield when maize was sown in August. The yield probability increased with the increase in root depth (Figure 8). A higher yield was simulated for 1.20 m followed by 0.90 m root depth. Simulated sowing and flowering date are compared for different sowing dates. The results show that crops that were sown early flowered early, and produced higher biomass and yield as compared with late sowing (Figure 9).

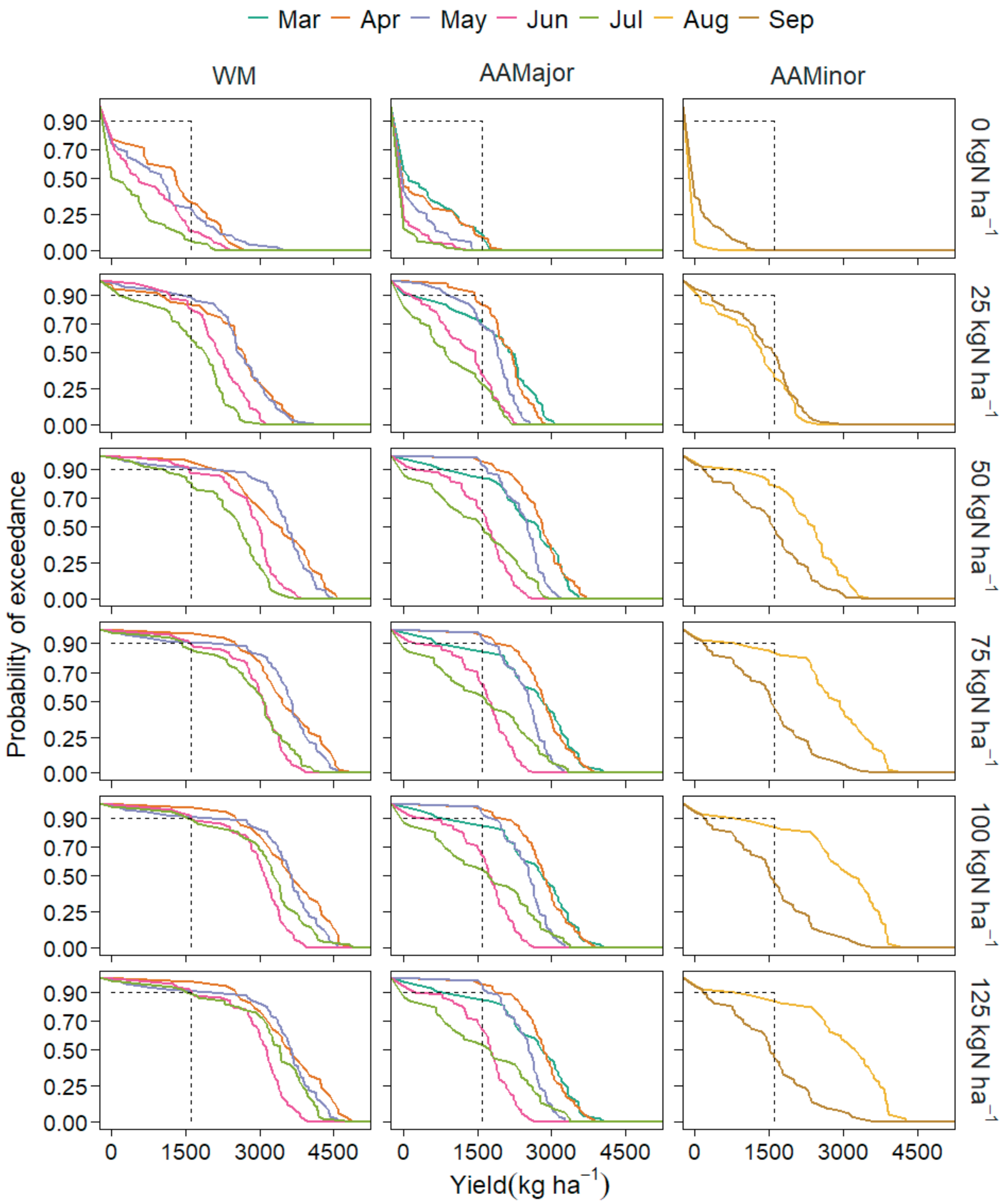

Figure 6. Simulated grain yield under 6 N rates, unconstrained root depth (reaches 1.20 m) and various sowing windows for West Mamprusi (WM), major season Atebubu-Amantin (AAMajor) and minor season Atebubu-Amantin (AAMinor). The vertical broken line at 1600 kg ha^{-1} denotes average observed farmers' yield for all the sites. The horizontal broken line represents the 90% probability that observed farmers' yield will be equaled or exceeded.

3.2.2. NO_3-N Leaching and Uptake, and Water Stress

The comparison of simulated yield, drainage, and leaching for three sites which received 75 kg N ha^{-1} is given in Figure 10. Each line in the graph represents simulated drainage and leaching for the three sites for different sowing windows and constricted soil depths. Simulated NO_3-N leaching varied between AAMinor, AAMajor and WM. High nitrate leaching (>50 kg ha^{-1}) was simulated for the July sowing window in AAMajor and WM and is probably be due to the high rainfall in July.

Similarly, yield regressed against drainage and leaching showed a decreasing trend with increase in drainage and leaching (Figure 11). The variation in daily drainage (not shown here) paralleled the variation in simulated NO_3-N leaching for the sites. Even though drainage largely depends on soil hydraulic properties, it decreased with the increased yield, higher biomass production, and crop water uptake.

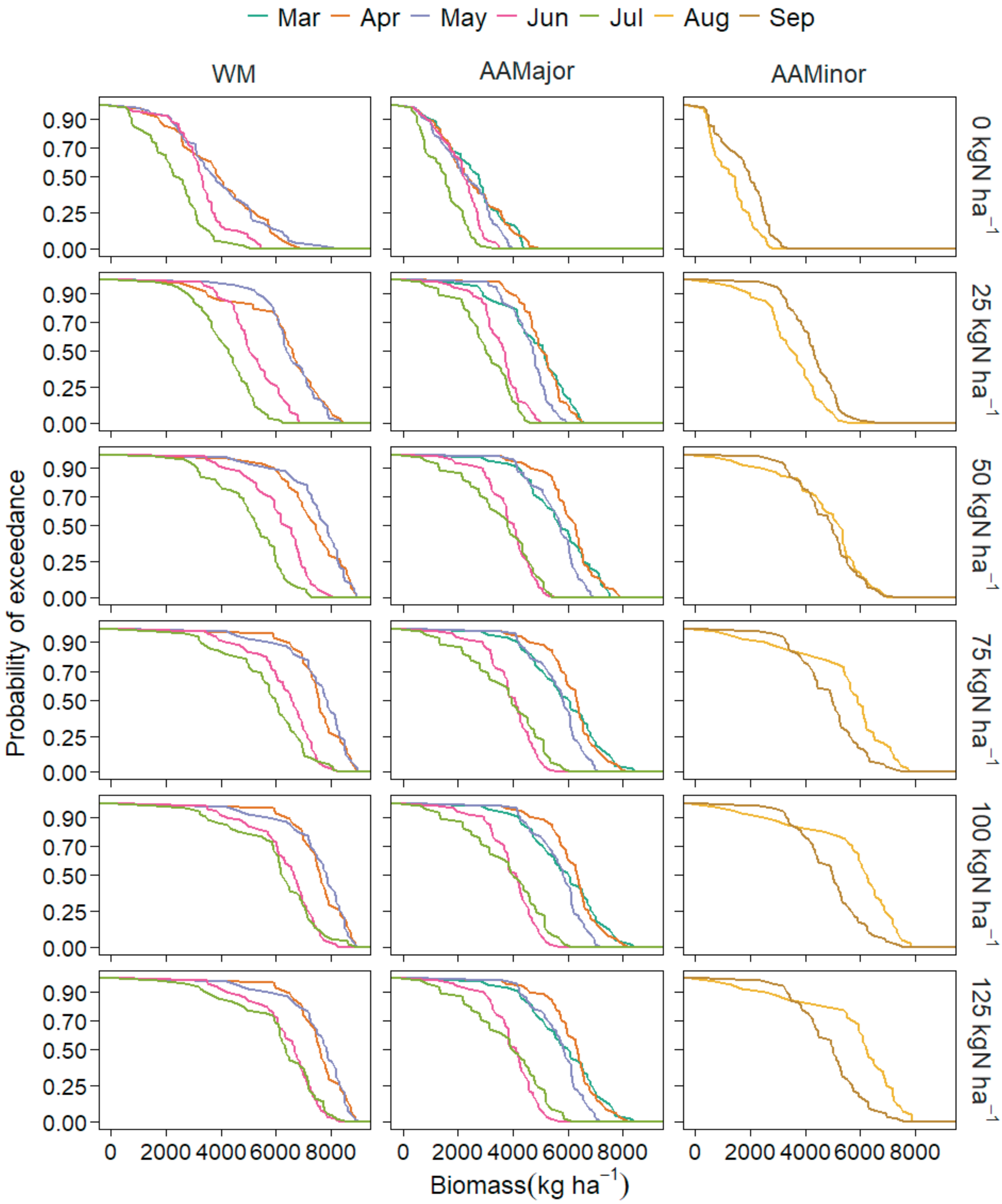

Figure 7. Simulated maize biomass under 6 N rates, various sowing windows, and rooting depth of 1.20 m for West Mamprusi (WM), major season Atebubu-Amantin (AAMajor) and minor season Atebubu-Amantin (AAMinor).

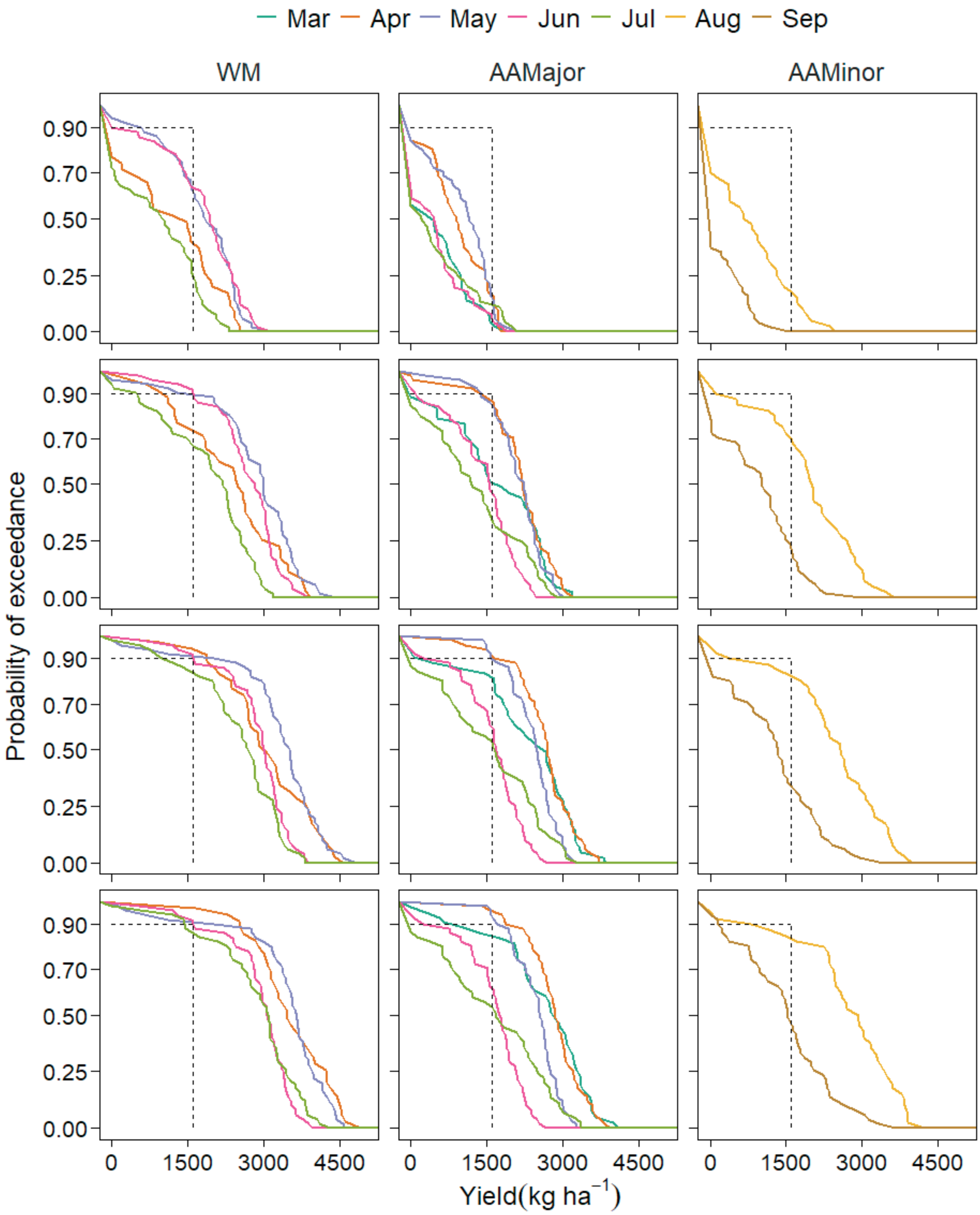

Figure 8. Simulated grain yield of maize fertilized 75 kg N rate, soil root penetration constrained at 30, 60, 90 and 1.20 m, and various sowing windows for West Mamprusi (WM), major season Atebubu-Amantin (AAMajor) and minor season Atebubu-Amantin (AAMinor). The vertical broken line denotes average measured farmers' yield for the sites. The horizontal broken line represents the 90% probability that observed farmers' yield will be equaled or exceeded.

The probability of NO_3-N uptake by maize for different root depths shows that more N is taken up as the depth of rooting is increased (Figure 12). The low yield at shallow root depth (0.3 m) is an indication of relatively poor accessibility to NO_3-N because of the shallow rooting depth set in the model. Under these conditions, there is less demand for N by the crop.

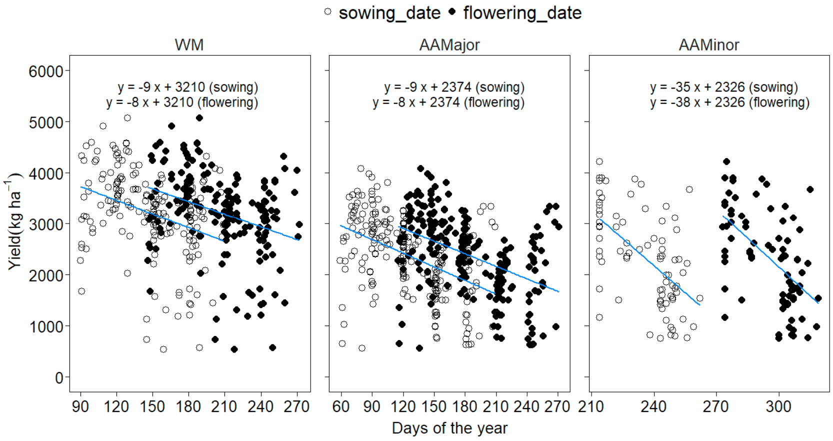

Figure 9. Simulated long term grain yield against sowing and flowering day of the year (April (91–121), May (121–152), June (152–182), July (182–2113), August (210–244), September (244–274), October (274–300)) for 75 kg N ha^{-1} and 1.20 m rooting depth. Maize below 500 kg ha^{-1} was considered as crop failure. Intercepts of the regression equations are centered around mean yield. The slope indicates the amount of yield (y) (kg ha^{-1}) that declines for each day a sowing or flowering (x) delays.

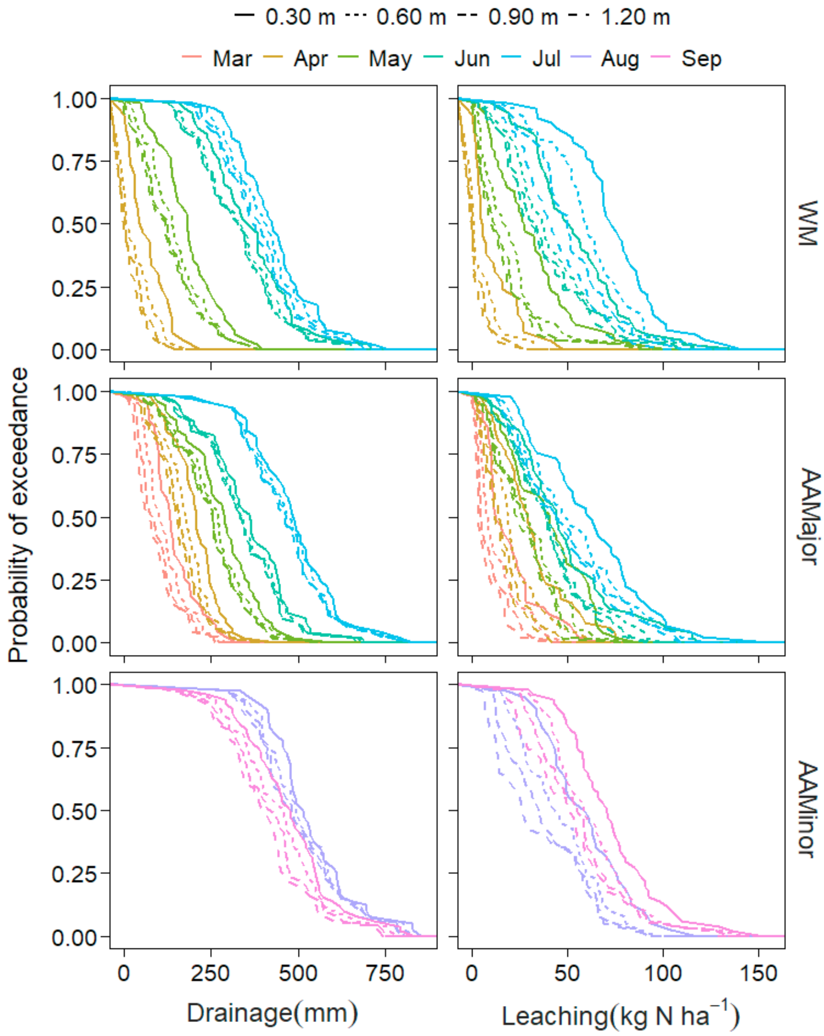

Figure 10. Simulated NO_3-N leaching and drainage for 75 kg N ha^{-1} rate, different sowing window and constricted rooting depth.

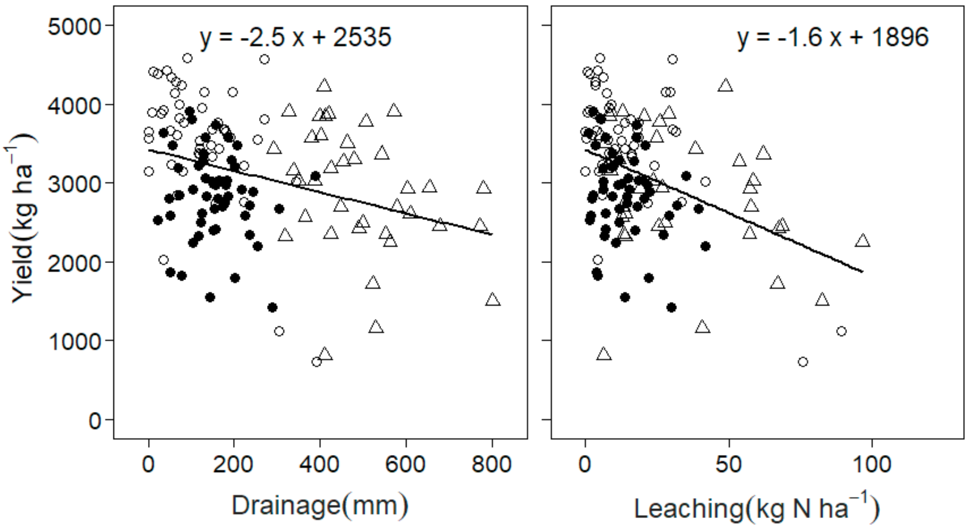

Figure 11. Simulated long-term NO_3-N leaching and drainage for 75 kg N ha^{-1} of AAMajor (○), AAMinor (●), and WM (△) for April, August, and May sowing windows respectively.

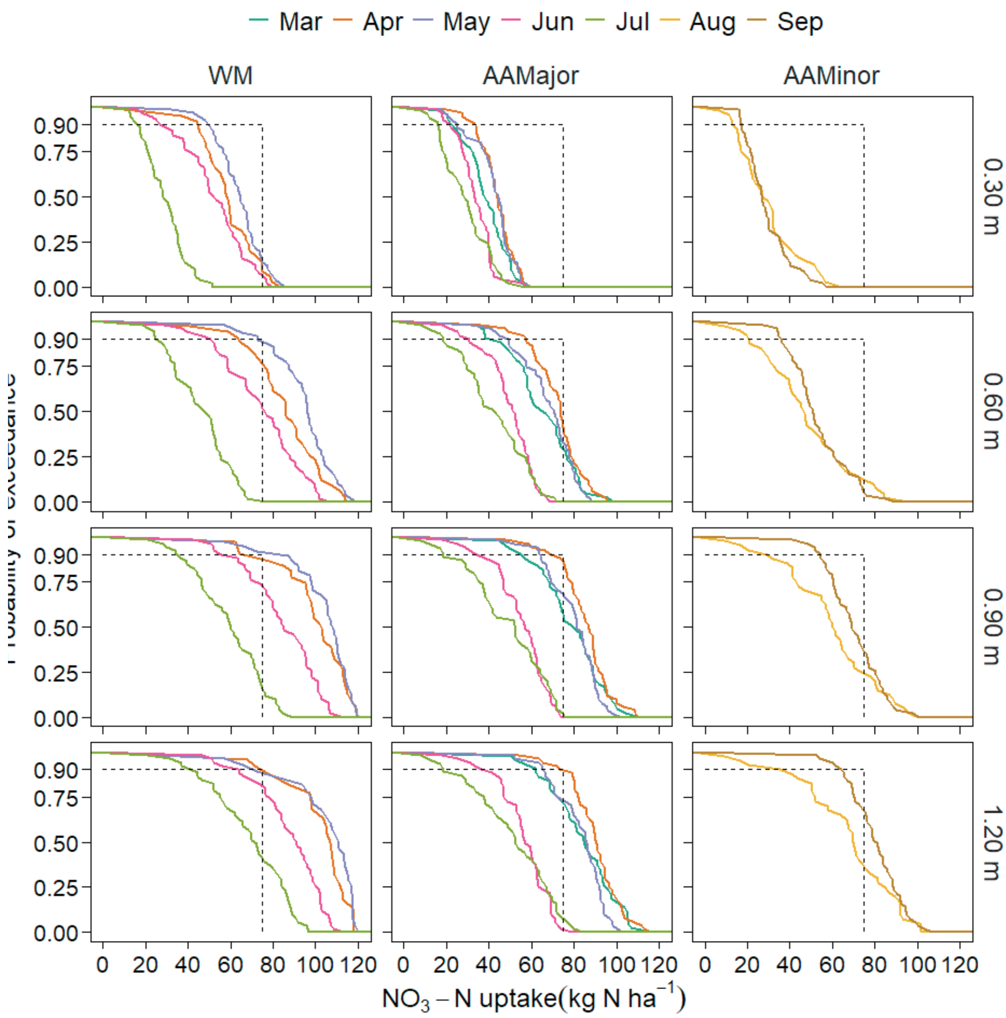

Figure 12. Simulated NO_3-N uptake for different maize rooting depth in treatment receiving 75 kg N ha^{-1} and for various sowing months. The vertical broken line denotes NO_3-N uptake and the horizontal broken line represents the 90% probability that crop uptake will be equaled or exceeded.

The simulated water stress index (swdef_photo) shown in Figure 13 is an index used to modify the rate of photosynthesis in APSIM. Zero indicates maximum water stress, corresponding to a non-transpiring crop (stomata fully closed), whereas the value 1.0 represents non-water-stressed, and is indicative of a fully watered crop. The simulations showed negligible water stress (swdef_photo) for AAMajor and WM. In contrast, in AAMinor, a higher probability of water stress was predicted, and the degree of stress increased with rooting depth and varied between August and September sowing windows (data not shown). The water stress in AAMinor was as a result of low in-crop rainfall and restricted root depth. Overall, the sites, crops with shallow root depth (0.30 m), were more severely affected than deep-rooted ones.

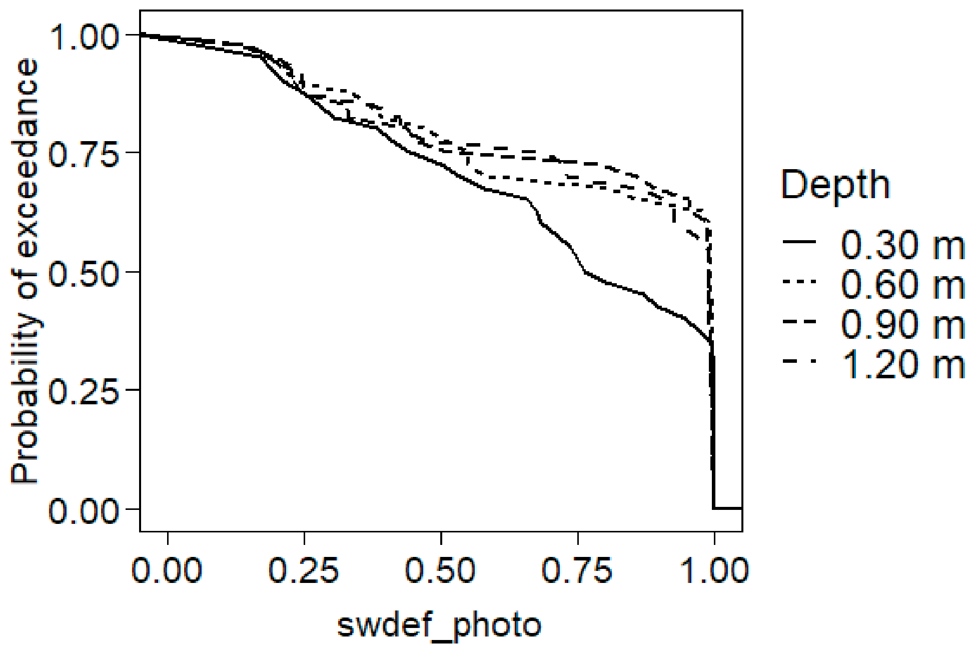

Figure 13. Simulated water stress index (swdef_photo) for AAMinor at different rooting depth, August sowing window and fertilization treatment 75 kg N ha^{-1}.

Leaching loss for different sowing windows with deep rooting maize that received 75 kg N ha^{-1} is indicated in Figure 14. A higher leaching loss is estimated for July sowing window in WM and AAMajor, and September sowing window for AAMinor.

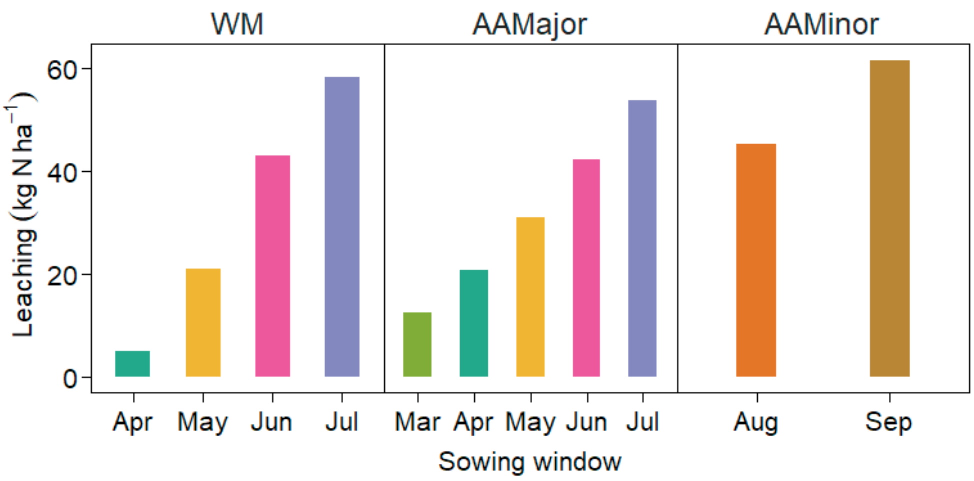

Figure 14. Simulated leaching (kg N ha^{-1}) loss for a 1.20 m rooting depth, different sowing windows (x axis) and fertilization treatment 75 kg N ha^{-1}.

4. Discussion

4.1. Field Observations

Several studies in Ghana showed that maize yield response increases with N application [17,47–50]. Others have also shown that the addition of fertilizer N increases maize radiation interception and radiation use efficiency, and thereby biomass and yield [51–53]. Contrary to expectations, our study shows there was large variation in the response of grain yield to additional N fertilization. The yield of maize with the application of <30 kg N ha^{-1} was equivalent or higher than that of maize grown >60 kg N ha^{-1}. Muchow and Davis [52] indicated that the efficiency of N's utilization by maize (defined as grain yield per unit N uptake) varies under different climatic, soil, and management conditions. It also demonstrated that radiation use efficiency at higher rates of N declines during grain filling and supplying N under water-limited growth decreases nitrogen use efficiency. Thus far, the evidence supports the notion that N rate alone is not adequate for maximum yield at these study sites. Farmers' management decisions need to consider N application options that are adjusted to climatic variables (radiation and rainfall) and return the benefit of enhanced photosynthetic efficiency and solar radiation interception between emergence and grain filling stages.

Root architecture and water uptake are interrelated and thereby determine the potential of the crop to access soil water [54]. The soil moisture data collected at 0.30 m showed the soil dried to −25 to −75 kPa, while the sub-soil (0.60–0.80 m depth) was saturated for most of the growing season (Figure 4a–f), and at the same time the crops experienced terminal drought. The question is why the roots are not proliferating deeper in the soil to take up water and nutrient? A possible explanation for the drier topsoil and wet sub soil could be due to the strong force of the crown roots in water uptake than seminal roots. It was reported that seminal roots of maize supply one fifth of the water used by the plant during its lifetime [55]. In addition, crown roots are thicker, have more and larger xylem vessels (which leads to a higher axial conductivity) than seminal roots and have better ability to transport water [56–58]. Reduced NO_3-N uptake could have also been caused by NO_3-N losses through leaching [59,60].

4.2. Modelling Analysis

4.2.1. Yield, Sowing Windows and Climate Variables

The modelling study investigated the effect of nitrogen fertilizer, sowing windows, in crop rainfall and radiation on crop grain yield. The results show that simulated yield was higher than the measured yield, when maize was fertilized with 75 kg N ha^{-1} and was sown in May for WM, April AAMajor and August for AAMinor (Figures 6 and 8). This suggests there is potential to increase yields when crops are planted early. This finding is consistent with the results of Lopez-Pereira and Morris [61] and MacCarthy et al. [37]. A maize grain yield range of 231 kg ha^{-1} with no mineral N fertilizer and 3831 kg ha^{-1} following the addition of 120 kg N ha^{-1} was observed [62].

Multiple linear regression analysis shows that radiation interception and sowing window-controlled yield and biomass in WM and AAMajor (p-value: <2.2e^{-16}). In both sites, APSIM simulated yield decrease when maize was planted late in the season, i.e., in June and July (Figure 6). For example, in WM, growing season rainfall increases while radiation intercepted decreases from April (700 MJ m^{-2}) to June (400 MJ m^{-2}), and the corresponding yields decreased from 5.0 to 2.0 t ha^{-1}. The reason for the higher yield in AA Major for maize sown in April is due to the high radiation and wet periods occurring at a critical stage (from emergence to grain filling stage (May and June)), which resulted in increased yield potential (Figure 6). Based on these findings, we suggest that the low yields observed among farmers are as a result of late sowing (June–July), where the crop reproductive stages coincide with low rainfall and radiation periods.

In the AAMajor season, in-crop rainfall remains in the range of 480–505 mm from March to June, but in-crop radiation interception decreases from 435 to 248 MJ m^{-2}. The decrease in radiation could be related to the effect on the potential assimilation and further partitioning of biomass to grain. Radiation and temperature have been observed to be the most important limiting factors for simulated maize yield using the LINTUL5 model in central Ghana [63,64]. Additionally, when water and nutrients are not limiting, low yields of maize in West Africa are due to a decline in radiation associated with heavy cloud cover during the peak rainfall months of August and September [38]. Spatial patterns of yield changes due to reduced radiation in central Ghana have been predicted [64].

In both sites, 74% of the farmers planted late in the season between June and August. Thus, low radiation interception that occurs in a critical stage (emergence to flag leaf) of the crop could be one of the reasons for low yield. The simulated results suggest that planting in April and May would give a better yield potential for AAMajor and WM, respectively. In this way, the crops could benefit from relatively higher radiation during the early growth stage and higher rainfall during the flowering stage and would place this month as most favorable for maize planting. However, the probability of yield exceedance of 3.5 t ha^{-1} decreases to 20% as rainfall is variable in amount and distribution, and is also difficult to forecast. Thus, we argue that supplemental irrigation that allows farmers to plant their crops in April (AAMajor) and in May (WM) without needing to wait for the onset of seasonal rain would be of great help to the farmers. However, such an initiative needs to be explored in relation to the socio-economic impact on the region. In AAMinor, the simulated results show that in-crop rainfall significantly affected grain yield for the September planting, and this is due to the low in crop rainfall amount at the flowering stage of the crop (October and November months). Thus, the low yield of farmers in AAMinor is related to low rainfall rather than radiation under 75 kg N ha^{-1} conditions.

4.2.2. Soil Water Stress and NO_3-N Leaching

Soil water stress varied across the three sites and decreased with the increase in root depth (Figure 9). The evidence presented thus far supports the idea that crops adjust their growth strategy according to different environments, and in particular, tend to partition relatively more biomass to root systems under more stressful, low-nutrient, and poor climatic conditions [65].

Higher nitrogen stress was simulated for AAMinor and WM at all depths for July and August planting, respectively. It seems possible that rain could have leached NO_3-N before being used by the crop. The nitrogen stress suggests that synchronization between a rainfall event, crop demand, and nitrogen for a given sowing date would improve yield. From this, it is evident that a predetermined N-application without considering NO_3-N leaching could lead to N-leaching loss [66–68].

N application rate of 75 kg ha^{-1} gave an average NO_3-N leaching value of 22 kg ha^{-1} in AAMajor for April sowing, 45 kg ha^{-1} in the minor season for August sowing, and 20 kg ha^{-1} in West Mamprusi for May sowing. We think that the larger NO_3-N leaching loss could have also caused the low yield in AAMinor. The values estimated for WM and AAMajor are double than the global average estimate [69], which was 15% for maize. Global NO_3-N leaching losses is estimated to be about 20% using process-based modelling [70], which is lower than predicted for the study sites.

5. Conclusions

The field observations highlight the lack of synergy between agronomic decisions (N application) and sowing windows as the principal cause of the low yield. The modelling study shows that early or late sowing causes crop stress, reduces crop establishment, and low radiation interception late in the season limits maximum crop growth. The appropriate management practices (sowing and nitrogen application) that match peak rainfall and radiation are critical for optimal yield.

Author Contributions: E.O.D., collected data, reviewed literature, performed agronomic data analysis, and drafted the paper. Y.B., R.S. and C.S. validated the data, performed the modeling analysis, reviewed literature and reviewed the paper. S.Y., P.O.-D., and F.F. assisted in data collection, reviewed the literature for the write-up, and reviewed the paper. S.A.E. supervised data collection reviewed the paper and played an administrative role for the success of the project. All authors have reviewed and approved the final paper. All authors have read and agreed to the published version of the manuscript.

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