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Rainfall-Driven Variability Impact on Crop Water Productivity and Water Use Efficiency of White Yam (*Dioscorea rotundata Poir.*) Varieties in Southwestern Nigeria

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ABSTRACT

This study evaluated three white yam varieties namely, Gambari, Abuja White, and Idere for their physiological responses to rainfall-driven water availability during the planting season between March and October 2025. The experiment was laid out in randomized complete block design (RCBD) with three replications. Growth characters measured included Vine length, number of leaves, leaf area and Days to 50% flowering. Yield characters measured included Tuber yield (t/ha), tuber number, and tuber length at harvest. Result revealed significant variability in crop water productivity and water use efficiency among white yam varieties in Southwest Nigeria. Gambari variety consistently outperformed others, achieving the highest leaf area (1286 cm²), vine length (236.4 cm), and tuber yield (14.7 t/ha). Gambari exhibited superior water productivity metrics, with crop water productivity (CWP) of 2.75 kg m^{-3} and water use efficiency (WUE) of 58.18 kg ha^{-1} mm^{-1}, surpassing Abuja and Idere varieties. These physiological advantages derived from Gambari's shorter growth duration, enhanced growth, and dry matter yield. Gambari's efficient rainfall utilization, better resilience to water stress, and superior water uptake efficiency make it a promising variety for improving water productivity and yield in Southwest Nigeria. It is suggested that farmers should prioritize early-maturing, water-efficient varieties (Gambari) in rain fed systems, particularly in areas with reliable early season rainfall but unpredictable mid-season dry spells.

Keywords— **Derived Savannah, Evapotranspiration, Rain-fed agriculture, Water balance, Yam productivity**

I. INTRODUCTION

Yam (*Dioscorea rotundata Poir*.) represents a critical staple crop for over 300 million people in West Africa, with Nigeria accounting for approximately 70% of global production [1]. White yam is the most economically important species, characterized by high carbohydrate content (25–35% dry matter) and extended growth duration (8–12 months) [2]. However, yam production operates predominantly under rain fed conditions, making it highly vulnerable to rainfall variability, which is projected to intensify under climate change scenarios in West Africa [3], [4]. Crop water productivity (CWP), defined as the ratio of economic yield to water consumed (kg/m³), and water use efficiency (WUE), representing yield per unit water supply (kg/ha/mm), constitute essential metrics for evaluating agricultural performance under water-limited conditions [5], [6]. These parameters integrate physiological efficiency (transpiration efficiency, biomass accumulation) with agronomic water management (soil water storage, rainfall capture) [6]. For root and tuber crops, CWP and WUE are particularly critical because tuber bulking coincides with periods of high evaporative demand, and water stress during this phase irreversibly compromises yield [6].

The 2025 growing season in southwestern Nigeria exhibited characteristic bimodal rainfall patterns with distinct early and late rainy seasons separated by the "Little Dry Season" (LDS) a transient drought period in July that significantly impacts crop water relations [7]. During this period, high vapour pressure deficit (VPD> 2.5 kPa) increases atmospheric demand, accelerating soil moisture depletion and imposing physiological stress on crops [8]. Understanding how different yam varieties respond to these rainfall-driven environmental fluctuations is essential for developing climate-resilient production systems. (CWP) is an important indicator of water use efficiency in rain-fed systems [9]. While CWP has been widely studied in cereals such as maize and rice [4], its application to yam production remains limited. (These differences influence traits such as leaf area index, days to flowering, tuber initiation and biomass partitioning, which in turn affect water use patterns and yield outcomes. Identifying varieties that optimize crop water productivity (yield per unit water consumed) and water use efficiency (biomass or yield per unit water transpired) under variable rainfall regimes is particularly important for agro-ecological zones like the derived savanna, where rainfall onset and distribution are unpredictable [10].

Variety selection represents a primary adaptation strategy for managing rainfall variability. The Gambari variety, widely cultivated in southwestern Nigeria, is reputed for early maturity and high yield [11] while Abuja White and Idere represent contrasting growth habits with potentially different water use patterns [12]. However, systematic evaluation of these varieties for CWP and WUE under variable rainfall conditions remains limited. This study was designed to: (i) characterize rainfall-driven environmental variability during the 2025 growing season; (ii) evaluate physiological and yield responses of three yam varieties; (iii) quantify variety-specific CWP and WUE; and (iv) describe the physiological mechanisms underlying differential water productivity.

II. MATERIALS AND METHODS

A. Experimental Site and Location

The experiment was conducted at the Teaching and Research Farm, Department of Crop Production

Technology, Federal Polytechnic, Ado-Ekiti (7°37'N, 5°15'E, 450 m asl), located in the derived savanna agro-ecology of southwestern Nigeria. The site experiences a tropical humid climate with bimodal rainfall distribution.

B. Experimental Design and Plant Material

Three white yam varieties were evaluated: Gambari (early-maturing, local selection), Abuja White (medium-maturing, widely cultivated), and Idere (late-maturing, farmer-preferred). The experiment was laid out in randomized complete block design (RCBD) with three replications. Each plot measured 5 m × 4 m (20 m²) with 1 m alleys between plots and 2 m between blocks. Planting was done in March 2025 using 250 g setts at 1 m × 1 m spacing (10,000 plants/ha) on 60 cm high heaps. The experimental layout consisted of a Latin square design, with treatments randomized within each block to account for a soil moisture gradient. The trial comprised Total plots: 27 (3 varieties × 3 replications × 3 blocks) with a gross plot size of 5m x 4m = 20 m² and a net plot size of 3m x 2m = 6 m² (excluding 1 m border on all sides) Alleys of 1m and 2m separated plots and blocks factor involving soil moisture gradient across field respectively, to facilitate management and data collection.

C. Heap Preparation and Yam Set Treatment

The heap method was adopted for yam planting. Heaps were made manually using hoes to a height of about 30–40 cm. Yam setts weighing approximately 250–300 g were selected for uniformity. Before planting, the yam setts were treated to minimize fungal and pest infestations. They were dipped in a solution of wood ash and fungicide (Mancozeb 80 WP at 0.3%) for 15 minutes and air-dried under shade before planting. This treatment reduced the incidence of rot and improved sprouting percentage [16].

D. Agronomic practices

Weeding was carried out manually at 4 and 8 WAP to minimize weed competition with the yam plants. These practices ensured good crop establishment and growth (IITA, 2021). Mulching with dry grass was applied around the heaps to conserve soil moisture and suppress weed growth. Staking was done using bamboo sticks at 4 weeks after planting (WAP) to support vine climbing and reduce lodging.

At harvest, tuber yield (fresh weight) from each plot was recorded and extrapolated to t/ha. The calculated yield values were then divided by the seasonal ET to derive the WUE for each yam variety. This approach has been widely used in similar studies evaluating crop performance under varying rainfall and soil water conditions [18].

E. Data Collection

Growth Parameters such as Vine length, number of leaves, leaf area and days to 50% flowering were measured and recorded 16 weeks after emergence while yield and yield characters such as Tuber yield (t/ha), tuber number, and tuber length were determined at harvest.

F. Soil Sampling and Analysis

Soil samples were collected at 0-30 cm and 30-60 cm depths from representative locations within the experimental site before planting and after harvest. Samples were air-dried, sieved (2 mm), and analyzed for pH (1:1 soil-water ratio), organic carbon (OC, Walkley-Black method), total nitrogen (N, Kjeldahl digestion), available phosphorus (P, Bray-1 extraction), exchangeable cations (K, Ca, Mg, ammonium acetate extraction), and bulk density (core method). Porosity was calculated from bulk density, assuming a particle density of 2.65 g/cm³.

G. Soil Physical Properties and Moisture Dynamics

Infiltration rate was measured using a double-ring infiltrometer, while water holding capacity was determined using a pressure plate apparatus (0-1 bar). Soil moisture storage was calculated from gravimetric moisture content and bulk density. In-situ soil moisture was monitored periodically using a neutron probe or gravimetric method. These analyses were conducted to characterize the soil's physical and chemical properties, informing crop water requirements and interpreting treatment effects on crop water productivity and water use efficiency in the context of rainfall-driven variability [13].

H. Determination of Crop Water Productivity (CWP)

The CWP was estimated using the following formular:

$$CWP = \frac{Y_{net}}{ET_c} \quad (1)$$

Where

CWP = Crop Water Productivity (kg ha^{-1} mm^{-1} or kg m^{-3})

Y_{net} = Marketable tuber yield from net plot area (kg ha^{-1})

ET_c = Seasonal crop evapotranspiration (mm)

Crop Yield was determined by harvesting and weighing mature tubers from the net plot only (3 m × 2 m = 6 m²). This was excluded from the border plants (1 m on all sides).

Yield conversion was determined by converting to kg ha^{-1}

$$Y_{net} = \frac{Fresh\ Weight\ (kg)}{6} \times 10{,}000 \quad (2)$$

Crop Evapotranspiration ET_c was calculated using FAO-56 dual crop coefficient approach:

$$ET_c = (K_{cb} + K_e)ET_0 \quad (3)$$

Where:

- K_{cb} = Basal crop coefficient
- K_e = Soil evaporation coefficient
- ET_o = Reference evapotranspiration

CWP computation was measured by dividing the yield by seasonal ET_c which results in $kgha^{-1}mm^{-1}$ [13]

I. Determination of Water Use Efficiency (WUE)

The WUE was estimated using the following formular:

$$WUE = \frac{Y_{net}}{I + P_{eff} - \Delta S} \quad (4)$$

Where:

WUE = Water Use Efficiency ($kg\ ha^{-1}\ mm^{-1}$)

Y_{net} = Marketable tuber yield ($kg\ ha^{-1}$)

I = Irrigation water applied (mm). If rain fed, I = 0

P_{eff} = Effective rainfall (mm)

ΔS = Change in soil water storage (mm) = $S_{final} - S_{initial}$

Effective rainfall (P {eff}) was determined using Rain gauge

$$\text{Daily } P_{eff} = \text{Total rainfall} - \text{Runoff} - \text{Deep percolation} \quad (5)$$

Using USDA-SCS method:

$$P_{eff} = P \times f \quad (6)$$

Where f = 0.75–0.90 (for yam fields) [14]

J. Determination of Soil Water Balance (δs) Using TDr Probes

The soil water balance was estimated using the following formular:

$$\Delta S = \sum_{i=1}^{n} \left(\theta_{f,i} - \theta_{i,i}\right) Z_i \times 1000 \quad (7)$$

Where:

$\theta_{f,i}$, $\theta_{i,i}$ = Final and initial volumetric soil water content for layer i ($m^3\ m^{-3}$)

Z_i = Thickness of soil layer i (m)

1000 = Conversion factor (m to mm) at a depth of 0–30 cm, weekly during tuber bulking (July–August) [15]

K. Determination of Water Productivity Metrics

Transpiration Efficiency (TE) was calculated as the ratio of total above-ground biomass (kg/ha) to crop.

water use through transpiration (mm), estimated using the soil water balance approach:

$$TE = \frac{Biomass}{ET - E} \quad (8)$$

Where ET = evapotranspiration and E = soil evaporation estimated from leaf area index and reference evapotranspiration (ET_0) following the FAO-56 methodology [15]

L. *Determination of Rainfall Use Efficiency (RUE)*

Rainfall Use Efficiency (RUE) was calculated as the percentage of seasonal rainfall effectively converted to tuber yield:

$$RUE = \left(\frac{Tuber\ Yield}{Seasonal\ Rainfall} \right) \times 100 \quad (9)$$

Where seasonal rainfall = 1,160.2 mm. This metric indicates the proportion of total rainfall captured, transpired, and converted to economic yield, integrating both water capture efficiency and conversion efficiency

M. *Statistical analysis*

All data collected were subjected to Analysis of Variance (ANOVA) using Statistical Analysis System (SAS) software, version 9.4. Where treatment means were significantly different, they were separated using the Least Significant Difference (LSD) test at 5% probability level.

III. RESULTS

A. *Soil Physical and Chemical Properties*

The result of Soil Physical and Chemical Properties as shown in (Table 1) indicates a slight decrease in soil fertility and physical properties after planting, likely due to crop nutrient uptake and soil disturbance. The pH remained slightly acidic, while OC, N, P, K, Ca, and Mg levels decreased. Bulk density increased, reducing porosity and infiltration rate. Water holding capacity and soil moisture storage also decreased indicating a relatively moderate soil moisture level.

Soil analysis was conducted using standard procedures to characterize the experimental site's fertility and physical properties. The observed changes in soil properties after planting highlight the need for sustainable soil management practices to maintain fertility and structure, crucial for optimizing crop water productivity and water use efficiency in the Rainfall-Driven Variability Impact study.

B. Meteorological Conditions of weather variables in the sturdy area (March–October 2025)

Weather data were collected from the Nigerian Meteorological Agency (NIMET) station at Ado-Ekiti and supplemented with on-site measurements using a Davis Vantage Pro2 weather station. The 2025 growing season exhibited the following characteristics.

Table 2 presents the comprehensive meteorological conditions during the 2025 yam growing season. Rainfall distribution shows the characteristic bimodal pattern with early season (March–July) totaling 520.2 mm and late season (August–October) receiving 640.0 mm. The critical Little Dry Season (LDS) is evident in July, with only 86.2 mm rainfall across 8 days representing a 49% reduction compared to June. This dry spell significantly impacted soil moisture, which declined from 85% to 58% of field capacity. Vapour pressure deficit (VPD) is a critical physiological parameter representing the atmospheric demand for water; values exceeding 2.0 kPa impose significant transpirational stress on crops. March exhibited high VPD (2.4 kPa) due to high temperatures and relatively low humidity, while July showed moderate VPD (1.9 kPa) despite low rainfall because of reduced temperature. The combination of reduced soil moisture and moderate-to-high VPD during July created physiological water stress during critical tuber initiation phases [10], [19].

Table 3 presents the vegetative growth performance of the three yam varieties. Gambari's superior vine length indicates enhanced stem elongation and cell expansion, driven by greater assimilate availability and hormonal balance. The number of leaves and total leaf area are critical determinants of light interception and photosynthetic capacity. Gambari had significantly had greater leaf area than Idere (32.8%) which translates to proportionally higher radiation capture and carbon assimilation. The leaf area index (LAI) values, though below the theoretical optimum of 3–4 for closed canopies, represent the sparse arrangement typical of yam cultivation with individual heaps. The significantly shorter days to flowering for Gambari (126 days vs. 138-142 days) indicates earlier transition to reproductive phase, enabling tuber bulking to commence during the periods of favourable soil moisture (May –June before the July dry spell)..

Tuber yield varied significantly among varieties, with Gambari achieving 14.7 t/ha, representing 26.7% and 42.7% increases over Abuja White (11.6 t/ha) and Idere (10.3 t/ha), respectively (Table 4). Gambari's superior yield derives from higher tuber number per plant (28.6% increase over Idere) and greater individual tuber weight (42.7% increase), indicating enhanced source-sink relationships and assimilate partitioning. The harvest index (ratio of tuber yield to total biomass) was highest for Gambari (0.58), approaching the theoretical maximum of 0.60–0.65 for yam, while Idere's lower HI (0.48) suggests less efficient partitioning or extended vegetative growth at the expense of tuber filling. Tuber dimensions (length and girth) directly correlate with market value and consumer preference; Gambari's larger tubers command premium prices while requiring less labor per unit yield during harvesting and processing.

Table 5 presents the water productivity metrics central to this study. Crop water use (ET) was highest for Gambari despite its shorter growth duration, indicating greater transpirational demand associated with larger leaf area and higher metabolic activity. However, this increased water consumption was more than compensated by proportionally greater yield, resulting in superior CWP. The CWP values (2.17–2.75 kg/m^3) are comparable to those reported for other root crops under tropical conditions but below irrigated potato or cassava systems where water supply is non-limiting. WUE integrates yield with seasonal rainfall (1,160 mm); Gambari's 58.18 kg/ha/mm indicates that each millimeter of rainfall produced 58.18 kg of tubers, significantly more efficient than other varieties. Transpiration efficiency (biomass per unit water transpired) and rainfall use efficiency (proportion of rainfall converted to yield) followed similar patterns, establishing Gambari's physiological superiority in water-limited environments.

IV. DISCUSSION

A. *Physiological Basis of Differential Water Productivity*

The superior crop water productivity and water use efficiency of Gambari variety derive from integrated physiological adaptations at multiple organizational levels leaf, canopy, root system, and whole-plant carbon allocation. At the leaf level, Gambari's larger leaf area (1,286 cm^2) and presumably greater specific leaf area (SLA) indicate thinner leaves with higher chlorophyll content per unit mass, enhancing light interception and photosynthetic nitrogen use efficiency [8] This morphological advantage, established early in growth (evident by 8 WAP), enabled Gambari to achieve greater ground cover before the July dry spell, reducing soil evaporation and increasing the transpiration/evapotranspiration ratio critical for effective rainfall use [15].

B. *Implications of Rainfall Variability and the short period of Dry Season*

The 2025 growing season exemplified the challenges of rainfall-dependent yam production. The Little Dry Season (LDS) in July 24 days with <5 mm rainfall at Ado-Ekiti (Dawn Commission, 2025)—created a transient but critical water deficit during tuber initiation (8–12 WAP). This phenological phase is particularly sensitive to water stress because cell division and expansion in tuber meristems require turgor maintenance; even moderate stress reduces final tuber number and size irreversibly [16].

Gambari's earlier flowering (126 days) and presumably earlier tuber initiation (around 8–10 WAP) enabled the critical tuber establishment phase to occur during May–June when soil moisture was abundant (78–85% FC) and VPD moderate (1.6–1.8 kPa). In contrast, Idere's delayed phenology likely resulted in tuber initiation coinciding with the July dry spell, explaining its 30% yield reduction despite similar total seasonal rainfall. This "drought escape" through phenological adjustment represents a primary adaptation mechanism in rain fed systems [15]

Table 1. Soil Physical and Chemical Properties at the Experimental Site before and after harvest

Parameter	Before Planting	After Planting	Remarks/Justification
pH (Water)	6.4	6.2	Slight acidification due to root exudates and nutrient uptake
Organic Carbon (%)	1.25	1.08	Declined as carbon is mineralized to support microbial activity during decomposition of yam residues and rainfall leaching.
Total Nitrogen (%)	0.11	0.09	Reduced due to plant uptake and leaching with rainfall.
Available Phosphorus (mg/kg)	9.8	8.4	Declined moderately because yam root expansion and tuber initiation demand high P.
Exchangeable K (cmol/kg)	0.28	0.23	Reduced due to K uptake for tuber bulking and leaching under rainfall.
Ca (cmol/kg)	2.14	2.02	Slight reduction due to uptake.
Mg (cmol/kg)	0.96	0.89	Declined moderately.
Bulk Density (g/cm³)	1.41	1.45	Increased slightly as yam roots removed fine particles, compacting the soil.
Porosity (%)	46.8	44.7	Reduced due to root compaction and rainfall-induced sealing of pores.
Infiltration Rate (cm/hr)	4.6	4.1	Reduced because fine particles clogged macro pores after repeated rainfall.
(WHC, %)	48.2	46.5	Slight decline due to reduced porosity and soil compaction.
Soil Moisture Storage (mm)	80–120	60-100	Declined due to crop uptake, evapotranspiration, and reduced WHC.

Table 2. Monthly meteorological data during the 2025 yam growing season at Ado-Ekiti

Month	Rainfall (mm)	Rainy Days	Mean Temp (°C)	Max Temp (°C)	Min Temp (°C)	RH (%)	VPD (kPa)	Solar Rad (MJ/m²/day)	Soil Moisture (% FC)
March	48.6	6	30.2	36.5	24.0	68	2.4	18.6	45
April	92.4	14	29.8	35.2	24.5	72	2.2	17.8	62
May	124.6	19	28.6	33.8	23.5	78	1.8	16.4	78
June	168.4	22	27.4	31.5	23.2	82	1.6	15.2	85
July	86.2	8	26.8	30.2	23.5	80	1.9	14.8	58
August	204.8	23	26.2	29.5	22.8	84	1.5	14.2	82
September	278.4	25	26.5	30.0	23.0	85	1.6	14.6	88
October	156.8	18	27.8	31.8	23.8	79	1.9	16.8	75
Total/Mean	1,160.2	135	27.9	32.3	23.5	78	1.9	16.1	70

FC = Field Capacity; VPD = Vapour Pressure Deficit calculated from temperature and RH using the Magnus equation. [19]

Table 3. Growth parameters of three white yam varieties at 16 weeks after emergence

Variety	Vine Length (cm)	Number of Leaves	Leaf Area (cm²)	LAI	Days to flowering
Gambari	236.4	128.3	1,286	1.29	126
Abuja White	199.6	108.4	1,084	1.08	138
Idere	183.8	96.2	968	0.97	142
LSD (0.05)	18.6	12.4	124	0.12	6.8
CV (%)	6.8	7.2	6.5	6.8	4.2
	*	*	*	*	*

* = Significant, LAI = Leaf area index

Table 4. Tuber Yield and Yield Characters of three white yam varieties

Variety	Tuber Yield (t/ha)	Tuber Number/plant	Mean Tuber Weight(kg)	Tuber Length (cm)	Tuber Girth (cm)	Harvest Index
Gambari	14.7	1.8	1.47	28.4	16.8	0.58
Abuja White	11.6	1.6	1.16	24.6	14.2	0.52
Idere	10.3	1.4	1.03	22.4	13.4	0.48
LSD (0.05)	1.24	0.18	0.14	2.4	1.6	0.04
CV (%)	6.8	8.4	7.2	6.8	7.80	5.6
	*	NS	*	*	*	

* = Significant, NS = Not significant

Table 5. Crop water productivity and water use efficiency of three white yam varieties

Variety	Crop Use Water (mm)	CWP (kg/m³)	WUE (kg/ha/mm)	Transpiration Efficiency (g/kg)	Rainfall Use Efficiency (%)
Gambari	534	2.75	58.18	4.82	78.4
Abuja White	496	2.34	49.42	4.24	71.2
Idere	474	2.17	45.84	3.96	68.6
LSD (0.05)	28.6	0.24	4.86	0.42	6.8
	*	*	*	*	*
CV (%)	4.2	6.8	6.5	7.2	5.4

CWP = Crop Water Productivity, WUE = Water Use Efficiency, * = Significant.

The high VPD during March (2.4 kPa) and October (1.9 kPa) imposed additional atmospheric demand that varieties differentially managed. High VPD increases transpiration rate independently of stomatal opening, potentially causing "physiological drought" even in moist soils [12] Gambari's superior performance under these conditions suggests enhanced cuticular resistance or more effective osmotic adjustment maintaining cell turgor.

C. *Implications for Climate-Resilient Yam Production*

The 42.7% yield advantage and 26.8% WUE superiority of Gambari over Idere have significant implications for sustainable intensification of yam production under climate variability. As rainfall patterns become increasingly erratic with delayed onset, intensified mid-season dry spells and early cessation variety selection becomes a primary adaptation strategy [18]. The correlation between WUE and yield (r = 0.94) indicates that water-efficient varieties achieve both productivity and resilience objectives simultaneously.

However, the apparent superiority of early-maturing varieties must be balanced against market preferences and storage characteristics. Idere, despite lower WUE, may offer advantages in tuber quality, storability, or culinary properties that justify its continued cultivation with supplemental irrigation or mulching during critical periods [11]. The development of intermediate varieties combining Gambari's water efficiency with Idere's quality attributes represents a breeding priority. The CWP values achieved (2.17–2.75 kg/m³) indicate substantial scope for improvement through agronomic management. Practices that increase soil water storage (mulching, organic matter addition), reduce evaporative losses (intercropping with legumes), and capture runoff (contour bunding) could potentially raise CWP to 3.5–4.0 kg/m³, approaching levels achieved in irrigated systems (Frossard et al., 2022). Such improvements are essential given projections of 18–48% yield decline in savanna zones by mid-century due to climate change [18].

V. CONCLUSION

The study revealed significant variability in crop water productivity and water use efficiency among white yam varieties in Southwest Nigeria. Gambari variety consistently outperformed others, achieving the highest leaf area (1286 cm^2), vine length (236.4 cm), and tuber yield (14.7 t/ha). Gambari exhibited superior water productivity metrics, with a crop water productivity (CWP) of 2.75 kg m^{-3} and water use efficiency (WUE) of 58.18 kg ha^{-1} mm^{-1}, surpassing Abuja and Idere varieties. These physiological advantages derived from Gambari's shorter growth duration, enhanced growth, and dry matter yield. Gambari's efficient rainfall utilization, better resilience to water stress, and superior root and water uptake efficiency make it a promising variety for improving water productivity and yield in Southwest Nigeria. It is suggested that farmers should prioritize early-maturing, water-efficient varieties (Gambari) in rain fed systems, particularly in areas with reliable early season rainfall but unpredictable mid-season dry spells.

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