European Journal of Agronomy 133 (2022) 126448

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Understanding changes in cassava root dry matter yield by different planting dates, crop ages at harvest, fertilizer application and varieties

Rebecca Oiza Enesi [a,b,*], Stefan Hauser [b], Pieter Pypers [c], Christine Kreye [b], Meklit Tariku [c], Johan Six [a]

[a] Department of Environmental Systems Science, Group of Sustainable Agroecosystems, Swiss Federal Institute of Technology, ETH Zurich, CH-8092 Zurich, Switzerland
[b] International Institute of Tropical Agriculture, IITA, Ibadan PMB 5320, Oyo State, Nigeria
[c] International Institute of Tropical Agriculture, ICIPE Campus, P.O. Box 30772-00100, Nairobi, Kenya

ARTICLE INFO

Keywords:
Cassava
Fertilizer
Root yield and field experiments

ABSTRACT

Cassava is a perennial crop that can adapt to periods of drought at different times in a growing season, which permits scheduling planting and harvest to develop production systems supplying roots continuously. However, farmers plant and harvest cassava at the onset of rains which creates glut and results in unattractive root prices. Thus, farmers need to understand how cassava varieties respond to different planting dates and crop ages at harvest to be able to use opportunities in income generation that may arise from flexible planting and harvest dates resulting from price and dry matter (DM) variabilities. Thus, this study was conducted to identify the best time to plant and harvest cassava for different varieties (TME419 and TMS581) and to determine the effect of fertilizer on root DM yields in three locations (Idi-Ose, Moniya and Ido) in Nigeria, over two years. The overall objective was to provide information to guide farmers on how to schedule planting and harvesting in Nigeria. The trials were conducted using a factorial split-split plot design. Effects of early, mid and late planting dates combined with harvest at 9, 11 and 13 months after planting (MAP) were tested. Fertilizer treatments included a control (F0) and applications of 75 kg N ha^{-1}, 20 kg P ha^{-1} combined with 90 (F1), 135 (F2) and 180 (F3) kg K ha^{-1}. A root DM yield increase of 44.8% was observed when crop age increased from 9 to 11 MAP, and an increase of 13.1% when crop age increased from 11 to 13 MAP, indicating that delaying harvests does increase root DM yield across all planting dates. In contrast, root DM yield differences between planting dates were marginal, an increase of 8.1% was observed from early to mid-planting date and of 9.5% from early to late planting dates. Fertilizer treatments significantly interacted with location and the largest responses were observed at Ido. Fertilizer increased cassava root DM yields when compared with control at Ido by 15.38%, 23.1% and 16.7% in F1, F2 and F3, respectively. Responses were inconsistent at Moniya and Idi-Ose. With information on the effect of crop age and fertilizer, farmers could benefit from targeting seasons with shortage of cassava roots and high cassava prices, which would benefit processing industries securing year-round root supply.

1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important source of carbohydrates to millions of people in Sub-Saharan Africa. In Nigeria, the largest cassava producer globally, it is a subsistence and cash crop for smallholder farmers (Visses et al., 2018; Wang et al., 2018). Recent increases in cassava production were achieved through expansion of the cultivated area, from 3.87 million hectares in 2007–6.79 million hectares in 2017, rather than through higher productivity (FAO, 2019). The average root dry matter (DM) yield obtained on farmers' fields in Africa is 2.51 t ha^{-1} which is lower than the global average of 3.35 t ha^{-1} (De Souza et al., 2017). The yield gap between farmer- and researcher-managed fields remains large. For example, Adiele et al. (2020) reported root DM yields of 35 t ha^{-1} in Nigeria.

Cassava can withstand long periods of drought and erratic rainfall (El-Sharkawy, 2005; Okogbenin et al., 2013). The storage roots remain

* Corresponding author at: Department of Environmental Systems Science, Group of Sustainable Agroecosystems, Swiss Federal Institute of Technology, ETH Zurich, CH-8092 Zurich, Switzerland.
E-mail address: rebecca.enesi@usys.ethz.ch (R.O. Enesi).

https://doi.org/10.1016/j.eja.2021.126448
Received 5 December 2020; Received in revised form 9 December 2021; Accepted 16 December 2021
Available online 23 December 2021
1161-0301/© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

viable in the soil for a long time and the crop has no specific maturity phase, because starch deposition and reallocation continues (Jolayemi and Opabode, 2018) throughout the growth of the crop. This provides flexibility in planting and harvesting times, which allows improved crop management and labour schedules with less pronounced peak labour periods for planting, crop management and harvesting. In 2002, Nigeria launched a presidential initiative to use cassava as a source of foreign revenue through organizing and promoting the export of cassava products (Donkor et al., 2017). Cassava storage roots have a high starch content, of about 80% of the root dry matter (Ceballos et al., 2007; El-sharkawy and De Tafur, 2010). Cassava is suitable for industrial utilization and can be processed into starch, ethanol, flour, chips and a number of non-food products (Balagopalan, 2009). Over the last decades, cassava has transitioned from a subsistence to a more commercial crop (Onyenwoke and Simonyan, 2014). Although 60–70% of cassava produced serves as food, the cassava processing industry keeps expanding (Tonukari, 2004).

In the future, the growing industrial and food consumption demand for cassava will need to be covered (Spencer and Ezedinma, 2017). The industry requires constant supply throughout the year to avoid under-utilization of processing capacities or downtimes, while households require quality food at affordable prices (Abass et al., 2013). To serve these two purposes a greater portion of the Nigerian cassava production needs to be tailored towards commercialization and at the same time, it is imperative to develop systems that are more productive to ensure a sufficient supply. Current planting and harvest schedules are based on seasonal rainfall (Moreno and Gourdji, 2015). Farmers prefer to plant and harvest at the onset of the rainy season (April – May) when there is adequate soil moisture (Sriroth et al., 2001). This leads to peaks in planting and harvest, causing gluts in supply around the harvest time and root supply shortages to the cassava processing industries over relative long periods (Moreno and Gourdji, 2015). Thus, attaining year-round root supply to the processors requires an expansion of planting and harvesting periods to flatten the current harvest peaks.

However, to take advantage of the flexibility of cassava, the specific growth and starch accumulation and translocation patterns of the crop through the rainy and dry seasons need to be considered. Adjebeng-Danquah et al. (2016) reported that cassava could be left in the field for more than a year to avoid starch losses after the dry season, yet bulking in the second year could be less than in the first year, thus productivity may decline. Studies conducted in cassava-producing regions of Asia (Howeler, 2007) and West Africa (Bakayoko et al., 2009) have shown that cassava root yields increase when cassava is planted at the start of the first and second rainy season and delaying the harvest beyond 12 months after planting (MAP). Therefore, by scheduling planting and harvesting outside commonly used phases there is a possibility for farmers to increase income and improve the supply over time to processors. Many processors adjust their root prices to the starch content of the roots and offer higher prices during periods of scarcity (Howeler et al., 2007). For farmers this opens a second avenue to increase income by focusing on planting and harvesting dates that would produce roots with high dry matter content and/or when cassava roots are in low supply. Various factors affect changes in planting and harvest dates such as differences in bulking rates of varieties, cultural or management practices and environmental conditions (Wholeya and Booth, 1979).

Currently, cassava is commonly cultivated without the use of fertilizers, because it is considered well-adapted to low-fertility soils, thereby creating the false impression that cassava does neither require nor respond to fertilizer (Agbaje and Akinlosotu, 2004; Pypers et al., 2012). Insufficient nutrient supply is one of the factors contributing to the large gap between actual yields on farmers' fields and the potential yield of cassava (Ezui et al., 2016). Trials in Brazil, India and Africa showed significant increases in root yields by fertilizer application (FAO, 2013). Research in Nigeria has shown cassava yield can be increased and even maintained for many years with adequate fertilizer application (Odedina, 2012). The current fertilizer recommendation for cassava in Nigeria is a blanket application of 400 kg ha^{-1} NPK 15:15:15 (Fondufe et al., 2001), without considering variety, environmental differences, the season in which the crop is planted, the crop duration and the target yield, although these factors certainly affect nutrient demand and response to fertilizer.

If farmers expand the planting window and intensify cassava production, they need appropriate fertilizer recommendations suited to their respective conditions, planting dates and length of growing period. With delayed planting (closer to the dry season), the fertilizer application window shortens considerably, yet the crop needs to be well-supplied to grow fast and survive the 4 months of dry season. Potassium plays a key role in the crop's water regulation and assimilation (Umeh et al., 2015), yet only limited research on effects of variable K rates to improve cassava canopy maintenance during the dry season and related yield effects has been conducted. There is a lack of information on the ability of cassava to recover after the dry season and continue to grow and accumulate starch until different crop ages at different K supply levels. Several studies have investigated the effect of crop age and fertilizer use on cassava yield (Trajano De Oliveira et al., 2017), but little information exists on the effect of different K supply levels on root yields of cassava with different planting dates and crop ages at harvest.

Cassava varieties differ in their response to drought and differ in their ability to recover after the dry season. So-called 'stay-green' varieties are more drought-tolerant than others and maintain some canopy throughout the dry season. Thus, recovery may have a lower impact on root yield losses caused by starch mobilization from roots to the shoots to promote leaf growth at the onset of rains (El-Sharkawy, 2007). However, little is known about the magnitude of such losses and varietal differences in responses to changing environmental conditions and agronomic measures.

The objectives of this study were to: 1) understand the effect of different planting dates in relation to rainfall on cassava root DM yield, 2) determine the effect of crop age at harvest on cassava root DM yield and, 3) determine the effect of fertilizer application on cassava root DM of two different varieties in relation to rainfall, and 4) to develop planting and harvest schedules to ensure year-round supply of cassava roots.

2. Materials and methods

2.1. Study area, trial site history and land clearing

Field experiments were conducted at Moniya (7.525°N, 3.915°E), Ido (7.402°N, 3.917°E) and Idi-Ose (7.501°N, 3.910°E) in Oyo State, South-west Nigeria, in 2017–2018 and 2018–2019. Fields were selected in collaboration with lead farmers and were representative for cassava production in the area.

In both years, trials were repeated in different fields with the same land use history, using the same design in each location. The trial location in Idi-Ose was cleared in 2014 from about 12 years old abandoned *Leucaena leucocephala* fallow by manual slashing of understory growth, felling the trees and removing all tree stumps to allow tillage. Boles and branches > 5 cm diameter were removed from the site and the remaining biomass was burned. In 2015, yam was cultivated, followed in 2016 by one year of cassava before the establishment of trials. The Moniya trial location had been under 5 years of bush fallow dominated by broad leaves but infested with *Imperata cylindrica*. The clearing was conducted in early 2014, using a tractor-mounted slasher, followed by herbicide (4 litres ha^{-1} of Round up, a.i. 370 g l^{-1} glyphosate) application after 2 weeks of regrowth. All plant residues were manually removed from the field and cassava was cropped for two years before the establishment of trials. The Ido trial location had been under grass fallow dominated by *Panicum maximum* for 10 years before the installation of trials. Clearing was done using a tractor-mounted slasher, followed by herbicide (4 litres ha^{-1} of Round up, a.i. 370 g l^{-1} glyphosate) application after 2 weeks of regrowth. All plant residues were manually removed from the field before the establishment of trials.

All sites have a bimodal rainfall pattern: the first rainy season starts in April and lasts until the end of July followed by a dry period in August. The second raining season lasts from early September to mid-November, followed by a dry season from December to March. The mean annual rainfall is 1400 mm per year and mean annual temperature is 30 °C. The meteorological data for the years 2017, 2018 and 2019 were obtained from Climate Hazards Group Infrared Precipitation (CHIRPS, 2020).

2.2. Trial design

The design was a 4-factorial split-split plot with planting date as main plot at 3 levels: early planting, mid planting and late planting. The exact planting dates (Table 1) depended on the start of rains. The second factor was cassava variety (sub plot) at 2 levels: IITA-TMS-IBA980581 (further called TMS581) and TMEB 419 (further called TME419). The third factor was crop age at harvest at 3 levels (sub-subplots): 9, 11 and 13 MAP, Fourth factor was fertilizer at 4 levels: a control without fertilizer application (F0) and NPK at 75:20:90 (F1), 75:20:135 (F2) and 75:20:180 (F3) kg N:P:K ha^{-1} resulting in 24 treatments for each planting date. Fertilizer treatments were randomly allocated within sub-subplots. Treatments were replicated four times in all sites.

The two cassava varieties differ in their growth habit and drought tolerance. TME419 is erect, branches very late and has a very limited tendency to flower. It is considered not drought-tolerant. TMS581 is branching, produces flowers late, retains canopy during the dry season, and is therefore considered more drought-tolerant. Disease-free planting stakes of TME419 were sourced from the International Institute of Tropical Agriculture (IITA) and stakes of TMS581 were sourced from NIJI farms, Ilero, Kayola, Oyo State. The third factor, fertilizer split-application was done with NPK 15:15:15 compound fertilizer, urea and MoP (potassium chloride). At the first and second dressing 153.5 kg ha^{-1} compound NPK (15:15:15) fertilizer were applied containing 23:10:19 kg ha^{-1} N:P:K. The 3rd dressing was 63 kg ha^{-1} of urea providing 29 kg ha^{-1} N. The 4th and 5th dressings were equal rates of 52 kg ha^{-1} MoP, providing 26 kg ha^{-1} K for F1, 97 kg ha^{-1} MoP, providing 48.5 kg ha^{-1} K for F2 and 142 kg ha^{-1} MoP, providing 71 kg ha^{-1} K for F3. Fertilizer was applied by using a small weeding hoe to scrape a half moon shaped furrow 20 cm from the base of the cassava plant and apply the fertilizer into the furrow and cover the applied fertilizer with soil.

MAP = months after planting. *Note: Year 2017 and 2018 refer to the planting dates only, harvests were in 2018 and 2019 for planting in 2017 and 2018, respectively.

2.3. Trial establishment and crop husbandry

Before planting, the cleared land was disc-ploughed, disc-harrowed and ridged by tractor. Cassava was planted from 25 cm long planting stakes, inserted to 2/3 of their length into the soil at an angle of 45–60°. Planting pattern was rectangular with 0.8 m distance along the ridges and 1 m distance between ridges, resulting in a plant density of 12,500 ha^{-1}. Plot size was 7 m by 5.6 m, with 49 plants of which the inner 25 plants (5 m by 4 m) were used for the measurements and yield assessment. Non-sprouted stakes were replaced 4 week after planting (WAP) to ensure a complete and homogeneous plant stand. Weed control was done by pre-emergence herbicide application (4 litres ha^{-1} Primextra Gold, a.i. 290 g/L S-Metolachlor plus 370 g/L Atrazine) at planting, followed by three to four post-emergence manual weedings by hand hoe, as needed.

2.4. Cassava root harvest

At each harvest, cassava storage roots were sorted into those suitable for consumption or marketing (good roots) versus those not suitable (bad roots), counted and their fresh mass was determined. From each plot, three good roots were sampled, sliced into about 1 cm thick discs and 300–500 g of cassava root tissue were selected from the top, middle and tip end of these sliced roots. All plant samples were weighed fresh, oven-dried to constant mass at 80 °C and weighed again to determine DM content.

2.5. Soil sampling and analysis

Prior to trial installation, soil samples were collected with an auger at 0–20 cm and 20–50 cm depth, air-dried, passed through a 2 mm sieve and analyzed for texture and chemical properties. Soil particle size analysis was done by the hydrometer method (Bouyoucos, 1951), organic C by chromic acid digestion (Heanes, 1984), total nitrogen by Kjeldahl digestion and colorimetric determination on a Technicon AAII autoanalyzer (Bremmer, 1982), soil pH was determined in water at 1:2.5 soil/water ratio (Okalebo, 2002), available P using the Olsen method (Olsen et al., 1954), and exchangeable cations were determined by Mehlich-3 extraction. All analyses were conducted at the analytical service laboratory of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Table 1
The planting and harvest dates at three locations over two years.

Location		Planting date	Harvest*		
			9 MAP	11 MAP	13 MAP
Ido	Early	19/07/2017	19/04/2018	08/06/2018	11/09/2018
	Mid	19/09/2017	11/06/2018	13/09/2018	25/10/2018
	Late	11/10/2017	28/07/2018	26/10/2018	23/11/2018
Idi-Ose	Early	24/06/2017	22/03/2018	23/05/2018	25/07/2018
	Mid	22/08/2017	16/05/2018	23/07/2018	08/10/2018
	Late	12/10/2017	17/07/2018	13/09/2018	13/11/2018
Moniya	Early	05/05/2017	15/01/2018	06/04/2018	01/06/2018
	Mid	30/06/2017	28/03/2018	20/06/2018	01/08/2018
	Late	25/08/2017	31/05/2018	08/08/2018	04/10/2018
Ido	Early	04/05/2018	06/02/2019	15/04/2019	20/06/2019
	Mid	16/07/2018	13/04/2019	13/06/2019	22/08/2019
	Late	24/09/2018	18/06/2019	23/08/2019	28/10/2019
Idi-Ose	Early	28/04/2018	28/01/2019	04/03/2019	20/06/2019
	Mid	09/07/2018	23/03/2019	31/05/2019	05/08/2019
	Late	18/09/2018	03/06/2019	15/08/2019	09/10/2019
Moniya	Early	11/05/2018	18/02/2019	06/04/2019	24/06/2019
	Mid	23/07/2018	29/04/2019	01/07/2019	21/10/2019
	Late	02/10/2018	08/07/2019	29/09/2019	21/10/2019

2.6. Statistical analysis

The R software version 3.6.0 was used for all statistical analysis (R Core Team, 2020) . Data were checked for normal distribution using the hist function. Data were subjected to analysis of variance (ANOVA) using the linear mixed-effect model (lme4) package in R to determine the effect of treatments. Significance of differences was evaluated at $P \leq 0.05$ and $P \leq 0.01$. A combined analysis of the two years was done. In the model, planting date, crop age, fertilizer application, variety, year and location were fixed factors while replications within location, planting date within replication and variety within planting date were random factors. ANOVA and mean separation were done with lmer and lsmeans functions respectively.

3. Results

3.1. Rainfall and soil properties

Cassava planted at different planting dates received very different total amounts of rainfall, which were differently distributed over the growth period of the cassava (Fig. 1). The soil physico-chemical properties at the trial locations were also different, especially texture, soil organic carbon and soil exchangeable K (Table 2). The soil at Ido had a higher sand content than soils at Idi-Ose and Moniya. Clay content was higher at Idi-Ose and Moniya than at Ido. The lowest soil organic carbon and potassium contents were found at Idi-Ose.

3.2. Analyses of Variance for cassava root DM yield and main factor effects

The statistical analyses revealed that planting date, crop age at harvest, fertilizer application and location had significant effects on the cassava root DM yield (Table 3). There were two-way, three-way and four-way interactions of factors: The interaction between planting date, crop age and variety was significant ($P < 0.05$) so were the interactions between planting date, crop age, location and year ($P < 0.01$) and the interaction between crop age, variety, location and year ($P < 0.01$). There was a highly significant location x fertilizer x year interaction effect ($P < 0.001$) on root DM yield. The single factor effects on cassava root DM yields are shown in Table 4. Crop age at harvest had the strongest effect, with 3.7 t ha^{-1} higher root DM yields at 13 MAP than at 9 MAP. Location affected yields with a 1.2 t ha^{-1} difference between Idi Ose and Ido. Fertilizer application increased root DM yield by 0.8 t ha^{-1} from F0 to F3. Late planting increased yields by 0.7 t ha^{-1} over early planting (Table 4).

Root yields within the same factor, followed by different superscript letter differs significantly.

3.3. Interactions between planting date, crop age and variety on cassava root DM yield

There was a significant interaction between planting date x crop age x variety $P < 0.05$ (Table 3). Root DM yields increased when the growth period of cassava was prolonged for TME419 and TMS581 (Fig. 2). The highest yields were mostly obtained at 13 MAP for both varieties, except for TME419 which, when planted late, produced less at 13 MAP than at 11 MAP. At 9 MAP, mean root DM yield for both varieties were 5.8, 5.5 and 6.2 t ha $^{-1}$ for early, mid and late planting dates, respectively and TME419 had the highest root DM yields (6.6 t ha^{-1}) at late planting dates. TME419 also had the highest root DM yields (9.8 t ha^{-1}) at 11 MAP when cassava was planted late and mean root DM yields for both varieties were 7.2, 8.6 and 9.3 t ha $^{-1}$ for early, mid and late planting dates respectively. At 13 MAP, TMS581 had the highest root DM yields (10.7 t ha^{-1}) at mid planting dates and mean root DM yields for both varieties were 9.3, 10.1 and 9.0 t ha^{-1}. The yield gain due to increased length of the growing period from 11 to 13 MAP was larger in TMS581 (+2.8, +2.1, and +0.9 t ha^{-1}) than in TME419 (+1.4,+ 0.7, −1.68 t ha^{-1}) at early, mid and late planting dates, respectively.

3.4. Interactions between planting date and crop age at different locations and in years on cassava root DM yield

There was a significant planting date x crop age x location x year interaction $P < 0.01$ (Table 3). In all locations, root DM yields increased when the growth period for cassava was prolonged for all planting dates in both years and for late planting date, yield differences between 11 MAP and 13 MAP were mostly marginal (Fig. 3). The effects observed differ between planting dates, crop ages and locations. Increasing the

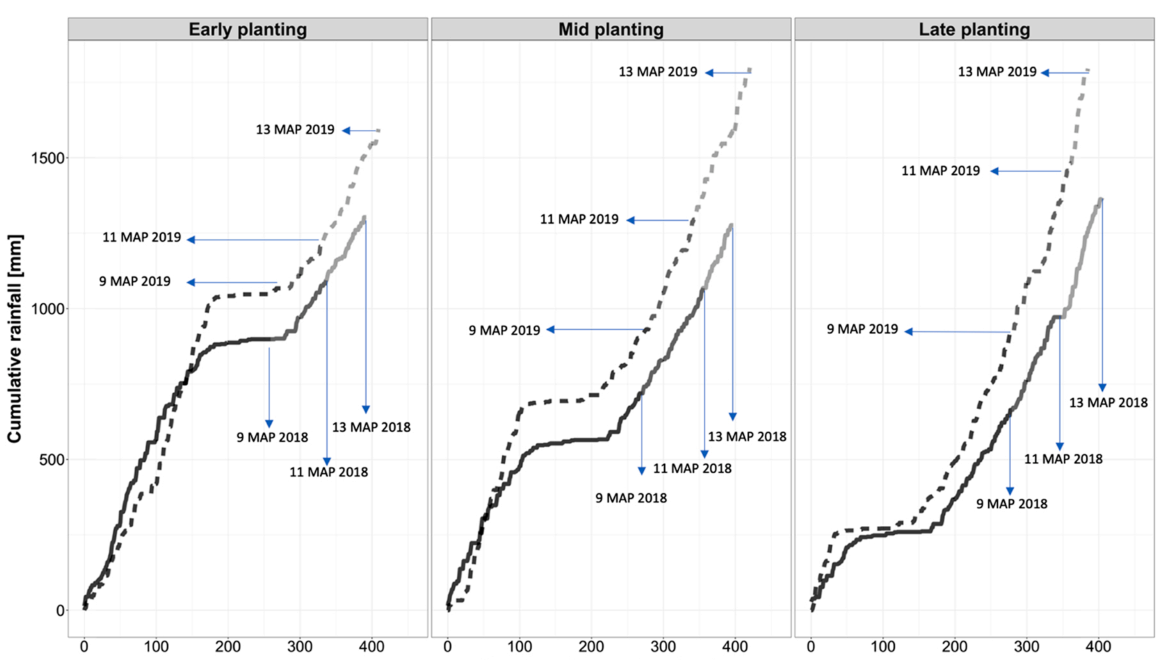

Fig. 1. Cummulative rainfall (mm) from planting to harvest for all trials planted in 2017 and 2018.

Table 2
Soil texture and chemical properties at two depths for experimental fields in Ido, Idi-Ose and Moniya in 2017 and 2018.

Location	Year	Depth	Sand	Silt	Clay	pH	Org. C	Total N	P Olsen	Calcium	Magnesium	Potassium	Cation exchange capacity
			%				g kg^{-1}		mg kg^{-1}	cmol[+] kg^{-1}			
Ido	2017	0–20	78.2	12.4	14.2	7.24	7.93	0.87	7.74	5.40	1.17	0.18	6.87
Ido	2017	20–50	80.2	10.6	13.4	7.35	7.87	0.77	9.55	4.86	1.10	0.18	6.24
Ido	2018	0–20	78.4	8.0	13.6	6.90	9.03	0.80	3.21	3.44	0.99	0.17	4.67
Ido	2018	20–50	80.6	5.9	13.5	7.09	7.53	0.70	2.50	3.96	1.00	0.15	5.17
Idi-Ose	2017	0–20	77.4	7.6	15.0	6.69	6.73	0.68	4.61	2.13	0.49	0.10	2.84
Idi-Ose	2017	20–50	77.2	8.1	14.7	6.72	6.07	0.71	5.84	2.20	0.54	0.11	2.93
Idi-Ose	2018	0–20	74.3	8.4	17.3	6.45	8.40	0.83	10.29	2.30	0.71	0.23	3.29
Idi-Ose	2018	20–50	74.7	8.0	17.3	6.56	7.90	0.81	11.18	2.34	0.72	0.23	3.34
Moniya	2017	0–20	78.7	7.9	13.4	7.11	7.42	0.74	7.11	3.13	0.97	0.19	4.40
Moniya	2017	20–50	77.7	6.7	15.6	7.06	7.66	0.75	6.23	2.51	0.89	0.18	3.68
Moniya	2018	0–20	74.9	8.6	16.5	6.85	8.80	0.83	8.60	3.08	0.80	0.17	4.13
Moniya	2018	20–50	74.3	9.4	16.4	6.93	7.48	0.77	5.36	2.92	0.78	0.17	3.94

Table 3
Levels of significance of planting date, variety, crop age at harvest, fertilizer, and their interactions on root dry matter yield.

Factors	Root DM yield t ha^{-1}
Planting date	0.00**(0.3)
Crop age	0.00***(0.1)
Variety	ns
Fertilizer	0.00***(0.1)
Location	0.00**(0.5)
Year	ns
Planting date x Crop age	0.00***(0.3)
Crop age x Variety	0.00***(0.2)
Planting date x Location	0.00***(0.6)
Crop age x Location	0.00***(0.4)
Fertilizer x Location	0.00***(0.4)
Variety x Location	0.00***(0.5)
Planting date x Year	0.00***(0.5)
Crop age x Year	0.00***(0.3)
Planting date x Crop age x Variety	0.03*(0.4)
Crop age x Variety x Location	0.00***(0.5)
Planting date x Variety x Year	0.03*(0.6)
Crop age x Variety x Year	0.04*(0.4)
Planting date x Location x Year	0.00***(0.8)
Crop age x Location x Year	0.00***(0.7)
Variety x Location x Year	0.00***(0.7)
Fertilizer x Location x Year	0.00***(0.7)
Planting date x Crop age x Location x Year	0.00**(0.9)
Crop age x Variety x Location x Year	0.00**(0.8)

Note: Interactions above three-way that were not significant was not reported in the table.
* Significant at $P < 0.05$,
** Significant at $P < 0.01$,
*** Significant at $P < 0.001$. Standard errors (SE) in parentheses. ns=not significant

Table 4
Mean effect of fixed factors planting date, crop age, variety, fertilizer, location and year on cassava root DM yield (t ha^{-1}).

Fixed factors	Factor level	Root DM yield (t ha^{-1})
Planting date	Early	7.4^{b}
	Mid	8.0^{a}
	Late	8.1^{a}
Crop age	9 MAP	5.8^{c}
	11 MAP	8.4^{b}
	13 MAP	9.5^{a}
Variety	TME419	7.9^{a}
	TMS581	7.8^{a}
Fertilizer	F0	7.4^{c}
	F1	7.9^{b}
	F2	8.1^{ab}
	F3	8.2^{a}
Location	Idi-Ose	7.2^{b}
	Moniya	7.6^{b}
	Ido	8.4^{a}
Year	2017	7.5^{a}
	2018	8.3^{a}

crop age from 9 to 11 MAP increased yields by 51.6% and when crop age was prolonged from 11 to 13 MAP yields increased by 10.9% at Ido. At Idi-Ose increasing crop age from 9 to 11 MAP increased yields by 46.2% and 11–13 MAP increased yields by 14.4%. At Moniya, an increase of 38.9% was observed between 9 and 11 MAP and a decrease of 0.6% was observed from 11–13 MAP. Averaged across crop age, cassava root DM yields were higher in 2018 than 2017 for all planting dates expect at Moniya 2018, where yields were lower at the late planting date in 2018 (5.8 t ha^{-1}) than in 2017 (8.1 t ha^{-1}). Averaged across crop age and year, the highest root yields were observed at Ido at the late and early planting dates (9.9 and 8.8 t ha^{-1}), while at Idi-Ose the highest root DM yields were attained at mid planting date (8.1 t ha^{-1}).

3.5. Interactions of crop age, variety and location and year on cassava root DM yield

Crop age x variety x location x year interacted significantly $P < 0.01$ (Table 3). Root DM yields of both varieties increased with prolonged growing periods in all locations in both years (Fig. 4). The varieties performed differently in all locations. Averaged across years, TME419 outperformed TMS581 at Ido at 9,11and 13 MAP. At Idi-Ose, TME419 yielded better than TMS581 at 9 and 11 MAP only. For Moniya, TMS581 outperformed TME419 at 11 and 13 MAP. The highest yields (11.6 t ha^{-1} and 11.3 t ha^{-1}) were recorded at 13 MAP from at Ido for TME419 and TMS581, respectively.

3.6. Effect of fertilizer on cassava root DM yield

Root DM yield responses to fertilizer were most pronounced and consistent at Ido (Fig. 5). Averaged across years, root DM yields increased with fertilizer application at Ido. The control plots produced the lowest yields (7.8 t ha^{-1}) followed by F1 (9.0 t ha^{-1}), F2 (9.6 t ha^{-1}) and F3 (9.1 t ha^{-1}). At this location, the differences between F1, F2 and F3 were insignificant. At Moniya and Idi-Ose fertilizer responses were mostly insignificant.

4. Discussion

Currently, decisions on planting and harvest schedules in cassava production systems in Nigeria are in sync with the rainy seasons, such that farmers plant and harvest cassava with the onset of rains, usually in April and May. At that time, planting material is easily available, soil moisture is adequate, and harvesting from moist soils is easy. Although cassava planting material (i.e. stems) is inexpensive, its bulkiness and the fact that cassava stems become less viable if not planted shortly after harvesting, deters farmers from harvesting in phases when it is not

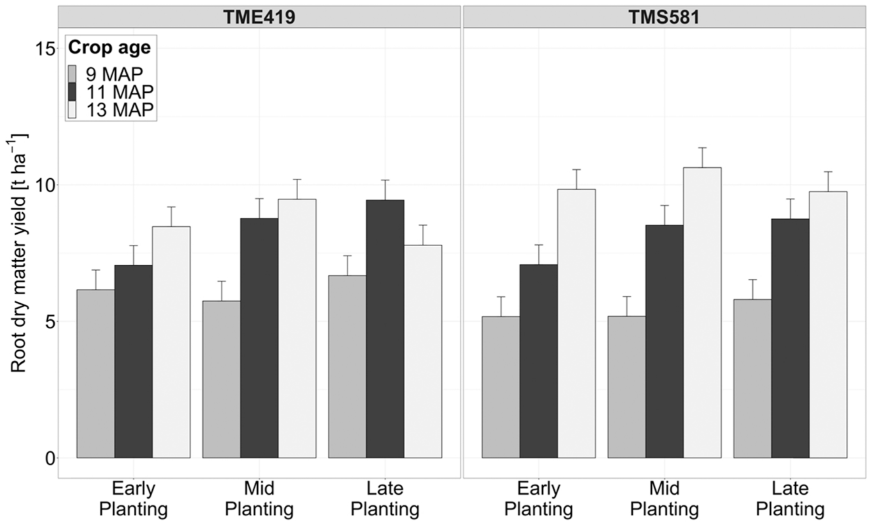

Fig. 2. Root dry matter yields (t ha^{-1}) as affected by planting date (early, mid and late planting dates) and crop age at harvest (9, 11 and 13 MAP) of cassava varieties TME419 and TMS581 averaged across three locations and two years. Error bars represent SEs for the different crop ages at harvest.

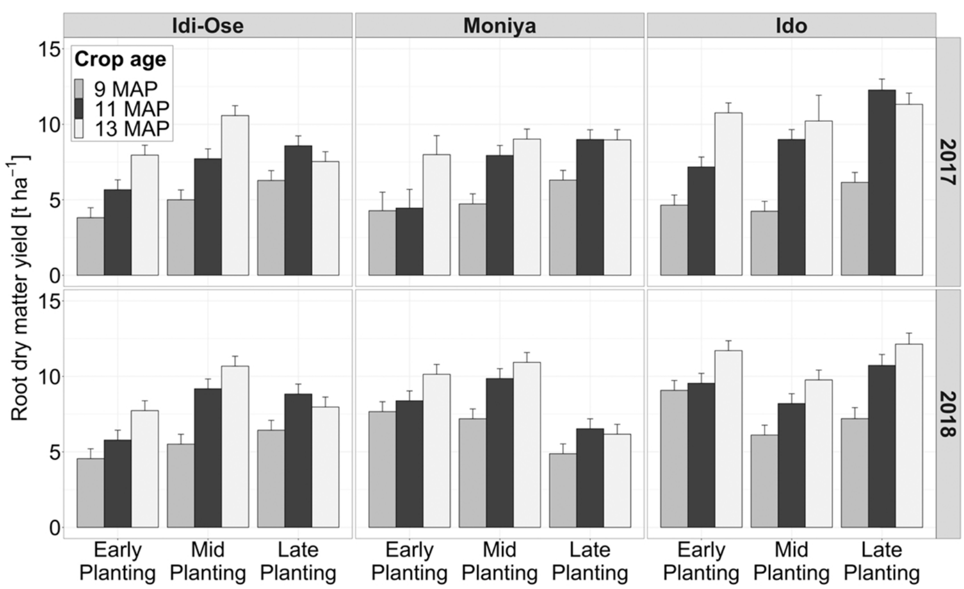

Fig. 3. Root dry matter yields (t ha^{-1}) at Idi-Ose, Moniya and Ido as affected by planting date (early, mid and late planting dates) and crop age at harvest (9, 11 and 13 MAP) averaged across varieties and fertilizer levels for 2017 and 2018. Error bars represent SEs for the different crop ages at harvest.

possible to replant. Planting late, i.e., just before the long dry season is uncommon due the risk of losing the crop if it does not establish before rains cease.

Our results show that cassava root DM yields can be increased by expanding planting dates beyond the conventional, usually early planting window used by farmers (Fig. 2 and 3). Even though early planted cassava received larger amounts of rainfall during its early growth, the final yields were not different from those of late planted cassava and sometimes lower (Table 4). When planted late, the amounts of rainfall received during the early growth phases in these trials were sufficient to establish the crop and to produce competitive final root DM yields. This is in accordance with Howeler et al. (2007) who found that attaining maximum yields when planting late, required cassava being planted during the last months of the rainy season to allow good crop establishment before the dry phase. Furthermore, Ezedinma et al. (1981) reported a consistent increase in root DM yield with delayed planting dates from June to October in trials conducted in south eastern Nigeria and showed that although early season planting may promote more vegetative growth, the final root yields of the early planted crops are likely to be lower than root yields of cassava planted late in the season. Similar fresh root yield increases between April and September were observed by Ambe (1993) in Cameroon. However, results by Kayode (1983) contradict the findings of this study, reporting a consistent decrease in root DM content, starch and fresh root yields with delayed planting dates in south west Nigeria, and highest cassava yields with early planting date. This was attributed to high soil moisture and N availability during the early planting phases. We would recommend based on our results to not solely focus on planting early after the start of rains but to stretch planting dates over a longer period. While for farmers high root DM yields are important, they need to also consider the price volatility caused by temporary periods of glut and scarcity. Farmers attempting to harvest during high price phases, usually in the dry season will need to consider opportunity costs for not being able to use the land for other purposes when the cassava is allowed to grow longer, as well as potential problems with harvesting during the dry season such as increased labour requirements for uprooting, yield losses

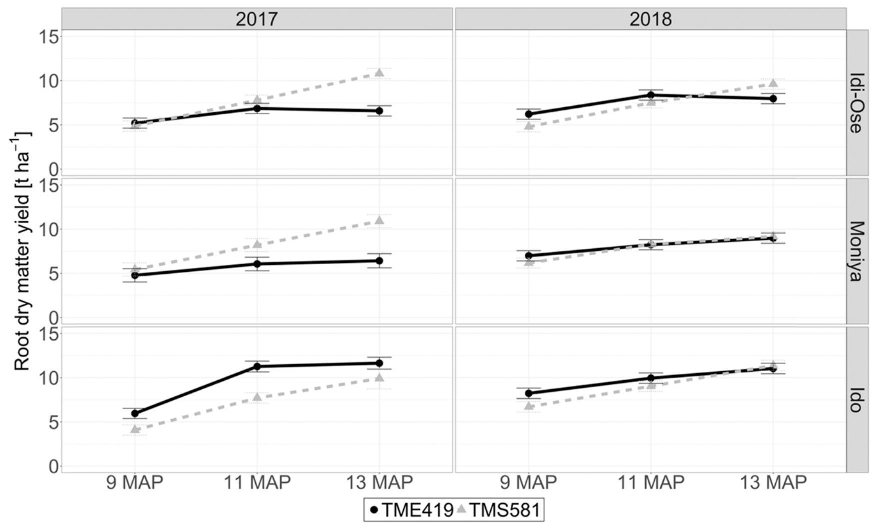

Fig. 4. Effects of crop age at harvest and variety on root dry matter yield (t ha^{-1}) at 3 locations (Idi-Ose, Moniya and Ido), averaged across planting dates and fertilizer levels. Error bars represent SEs for the different varieties.

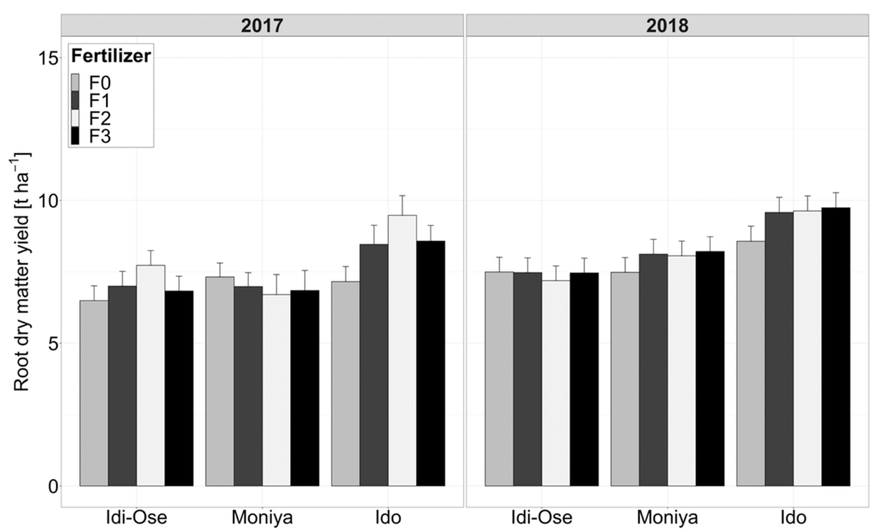

Fig. 5. Effects of fertilizer on root dry matter yield (t ha^{-1}).Fertilizer treatments were control without fertilizer application (F0) and NPK at 75:20:90 (F1), 75:20:135 (F2) and 75:20:180 (F3) kg N:P:K kg ha^{-1}. Error bars represent SEs for the different fertilizer treatments.

due to storage root breakage and the loss of potential planting material.

Cassava root DM yield was influenced by crop age at harvest for all planting dates across the different locations (Fig. 3). A general increase in yield was observed with longer growth periods despite differences between locations and planting dates. This study also shows that the optimum crop age to attain the highest yields is dependent on the variety; cassava root DM yield differed between varieties and among crop ages in different locations (Fig. 4). This significant interaction showed that there is a potential for recommending specific varieties best suited for a chosen crop age at harvest. Farmers could use such information to select specific varieties to be harvested at different crop ages and thereby stretching the root supply phase even when planting at the same time. Being able to supply roots over long phases would stabilize income and likely reduce the risk of suffering income losses during low price phases. Harvesting varieties at their peak of bulking and starch accumulation would thus maximize root DM yields and potentially income. The higher yields attained by TME419 at 9 and 11 MAP on some experimental fields suggest that TME419 bulks earlier and faster than TMS581, yet does not continue at the high rate in the dry season. Okogbenin et al. (2013) and Suja et al. (2010) reported that bulking rate in early-bulking varieties declines as the crop age increases, while in late-bulking varieties the bulking rate increases with crop age. The lower yields of TMS581 at 9 and 11 MAP indicate the variety is late and slow bulking, yet has higher bulking rates than TME419 at later stages as shown by the yield increases from 11 M to 13 MAP. Farmers will also need to consider that beyond a certain crop age at harvest, roots become fibrous or might rot and thus productivity may decline. Recommending a variety best suited for a specific planting date is not possible because of the inconsistent root yield trends of the varieties across the different locations. Multi-locational testing with a larger number of varieties is required to select varieties suited to specific locations, planting phases and crop age at harvest as well as other conditions (Benesi et al., 2007; Ssemakula and Dixon, 2007; Tan and Mak, 1995).

Storage root DM yield differences observed between planting dates and crop age in different locations were probably due to differences in the amount of rainfall received over the growing phases and varying soil properties. Higher yields at Ido may be due to the fact that soils are sandy. Cassava produces best on loose soils, allowing easy soil penetration by roots, preventing root rot (Fasinmirin and Reichert, 2011) and low losses as roots would not break when pulled from the sand soil.

Similar yields at Idi-Ose and Moniya might be due to their proximity with climatic conditions were not being different between both locations.

In our trials, the effect of fertilizer on root DM yields was significant but yield increments compared to the control were marginal and location specific (Fig. 5). Adiele et al. (2020) reported that different responses to fertilizer application in different sites and location may be due to variability in soil and water availability. Ido had higher sand content and CEC than other sites, which could have promoted better responses to fertilizer application. The most limiting nutrient at Ido was P, while Mg was most limiting at Idi-Ose and Moniya. The supply of adequate amounts of K to cassava is essential for maximum root DM yield (Howeler and Cadavid, 1983). Kang and Okeke (1984) showed yield response to K was dependent on soil type. Uwah et al. (2013) reported that cassava root yields increased with increased K rates and that yield increases of 20.0% and 27.0% were observed at 40 kg ha^{-1} and 80 kg ha^{-1} K. However, yield declined by 23.0% when 120 kg ha^{-1} K were applied. Mazetti Fernandes et al. (2017) also reported an increase of 36.0% in fresh storage root yield at 45 kg ha^{-1} K but no further increase when 90, 135 or 180 kg ha^{-1} K were applied. Thus, despite a high K demand, increased K rates did not increase root yields greatly, indicating that other factors limited root yields when the K supply was increased. For farmers, investing in fertilizer would be risky as shown by the relatively small root yield responses. As such, fertilizer use remains a high-risk investment, and recommendations for on fertilizer use in cassava systems must consider the planting and harvest schedule and should be site specific to ensure a profitable root yield response.

5. Conclusions

Cassava can be harvested nearly all year round by expanding planting and harvesting windows to meet the growing demand for year-round supply by processors. To ensure year-round availability of cassava roots, varieties that suit farmers' intended harvest date and crop age at harvest should be considered. Farmers generally should avoid harvesting at 9 MAP unless root prices are very attractive and can compensate for lower yields. Irrespective of location, the crop age at harvest and variety are key factors farmers must consider to increase profits. Future studies should be conducted on different planting and harvest schedules with a wider range of varieties in more contrasting multiple locations to understand how these factors interact and affect root dry matter yields.

CRediT authorship contribution statement

Rebecca Enesi: Investigation, Data curation, Writing – original draft. **Stefan Hauser**: Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition. **Christine Kreye**: Methodology, Investigation, Writing – review & editing, Project administration, Funding acquisition. **Meklit Tariku:** Data curation, Methodology, Writing – review & editing. **Johan Six:** Conceptualization, Supervision, Methodology, Writing – review & editing, Funding acquisition. **Pieter Pypers**: Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the Engineering for Development (E4D) of ETH Zurich and the African Cassava Agronomy Initiative (ACAI) of IITA for funding.

References

Abass, A., Mlingi, N., Ranaivoson, R., Zulu, M., Mukuka, I., Abele, S., Bachwenkizi, B., Cromme, N., 2013. Potential for Commercial Production and Marketing of Cassava: Experiences From the Small-scale Cassava Processing Project in East and Southern Africa. IITA, Ibadan, Nigeria, pp. 13–88.

Adiele, J.G., Schut, A.G.T., van den Beuken, R.P.M., Ezui, K.S., Pypers, P., Ano, A.O., Egesi, C.N., Giller, K.E., 2020. Towards closing cassava yield gap in West Africa: agronomic efficiency and storage root yield responses to NPK fertilizers. F. Crop. Res 253. https://doi.org/10.1016/j.fcr.2020.107820.

Adjebeng-Danquah, J., Gracen, V.E., Offei, S.K., Asante, I.K., Manu-Aduening, J., 2016. Genetic variability in storage root bulking of cassava genotypes under irrigation and no irrigation. Agric. Food Secur. 59. https://doi.org/10.1186/s40066-016-0055-7.

Agbaje, G.O., Akinlosotu, T.A., 2004. Influence of NPK fertilizer on tuber yield of early and late-planted cassava in a forest alfisol of south-western Nigeria. African. J. Biotechnol. 3, 547–551.

Ambe, J.T., 1993. The effect of planting dates on three cassava diseases in Cameroon. Int. J. Pest Manag. 39, 309–311. https://doi.org/10.1080/09670879309371811.

Bakayoko, S., Tschannen, A., Nindjin, C., Dao, D., Girardin, O., Assa, A., 2009. Impact of water stress on fresh tuber yield and dry matter content of cassava (Manihot esculenta Crantz) in Côte d'Ivoire. Afr. J. Agric. Res. 4, 21–27.

Balagopalan, C., 2009. Cassava biology and physiology. In: Hillocks, R.J., Thresh, J.M., Bellotti, A.C. (Eds.), Cassava Utilization in Food, Feed and Industry. Wallingford CAB Int, pp. 67–89. https://doi.org/10.1079/9780851995243.0067 https://doi.org/10.1079/9780851995243.0301.

Benesi, I.R.M., Labuschagne, A.M.T., Herselman, A.L., Mahungu, A.N.M., Saka, A.J.K., 2007. The effect of genotype, location and season on cassava starch extraction. Euphytica 160, 59–74. https://doi.org/10.1007/s10681-007-9589-x.

Bouyoucos, G.J., 1951. A recalibration of the hydrometer method for making mechanical analysis of soils1. Agron. J. 43, 434. https://doi.org/10.2134/agronj1951.00021962004300090005x.

Bremmer, J.M., Mulvaney, C.S., 1982. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Nitrogen-total. In Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties, 2nd edn.,. American Society of Agronomy, Madison, WI, pp. 595–624.

Ceballos, H., Sánchez, T., Morante, N., Fregene, M., Dufour, D., Smith, A.M., Denyer, K., Pérez, J.C., Calle, F., Mestres, C., 2007. Discovery of an Amylose-free Starch Mutant in Cassava (Manihot esculenta Crantz). J. Agric. Food Chem. 55, 7469–7476. https://doi.org/10.1021/jf070633y.

CHIRPS, 2020. Climate Harzards Group Infrared Preciputation with Station data SERVIR ClimateSERV [WWW Document]. URL https://climateserv.servirglobal.net/ (Accessed 28 July 2020).

De Souza, A.P., Massenburg, L.N., Jaiswal, D., Cheng, S., Shekar, R., Long, S.P., 2017. Rooting for cassava: insights into photosynthesis and associated physiology as a route to improve yield potential. New Phytol. https://doi.org/10.1111/nph.14250.

Donkor, E., Onakuse, S., Bogue, J., de Los Rios Carmenado, I., 2017. The impact of the presidential cassava initiative on cassava productivity in Nigeria: implication for sustainable food supply and food security. Cogent Food Agric. 3. https://doi.org/10.1080/23311932.2017.1368857.

El-sharkawy, M., De Tafur, S., 2010. Comparative photosynthesis, growth, productivity, and nutrient use efficiency among tall- and short-stemmed rain-fed cassava cultivars. Photosynthetica Vol. 48, 173–188. https://doi.org/10.1007/s11099-010-0023-6.

El-Sharkawy, M.A., 2007. Physiological characteristics of cassava tolerance to prolonged drought in the tropics: Implications for breeding cultivars adapted to seasonally dry and semiarid environments, Braz. J. Plant Physiol.

El-Sharkawy, M.A., 2005. How can calibrated research-based models be improved for use as a tool in identifying genes controlling crop tolerance to environmental stresses in the era of genomics - From an experimentalist's perspective. Photosynthetica 43, 620. https://doi.org/10.1007/s11099-005-0097-8.

Ezedinma, F.O.C., Ibe, D.G. and Onwuchuruba, A.I., 1981. Tropical Root Crops. Perform. cassava Relat. to time Plant. Harvest. Trop. Root Crop. Strateg. 1980s (Terry, E.R., Oduro, K.A. Caveness, F., Eds) Proc. first Trienn. Root Crop. Symp. Int. Soc. 30, 63–64. https://doi.org/10.1093/besa/30.4.63a.

Ezui, K.S., Franke, A.C., Mando, A., Ahiabor, B.D.K., Tetteh, F.M., Sogbedji, J., Janssen, B.H., Giller, K.E., 2016. Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. Field Crop. Res. 185, 69–78. https://doi.org/10.1016/j.fcr.2015.10.005.

FAO, 2013. Save and grow: Cassava-A guide to sustainable production intensification. Rome: FAO.

Fasinmirin, J.T., Reichert, J.M., 2011. Conservation tillage for cassava (Manihot esculenta crantz) production in the tropics. Soil Tillage Res. 113, 1–10. https://doi.org/10.1016/j.still.2011.01.008.

Fondufe, E., Eneji, A., Agboola, A., Yamamoto, S., Honna, T., 2001. An assessment of some fertilizer recommendations under different cropping systems in a humid tropical environment. Tropicultura 19, 21–27.

Heanes, D.L., 1984. Communications in Soil Science and Plant Analysis Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. Commun. Soil Sci. Plant Anal. 15, 1191–1213. https://doi.org/10.1080/00103628409367551.

Howeler, R., Internacional, C., Tropical, A., 2007. Agronomic practices for sustainable cassava production in Asia. In: Centro Internacional de Agricultura Tropical (CIAT). Cassava research and development in Asia: Exploring new opportunities for an ancient crop. Proceedings of the 7th Regional Workshop.

Howeler, R.H., Cadavid, L.F., 1983. Accumulation and distribution of dry matter and nutrients during a 12-month growth cycle of cassava. Field Crops Res. 7, 123–139.

Jolayemi, O.L., Opabode, J.T., 2018. Responses of cassava (Manihot esculenta Crantz) varieties to in vitro mannitol-induced drought stress. J. Crop Improv. 32, 566–578. https://doi.org/10.1080/15427528.2018.1471431.

Kang, B.T., Okeke, J.E., 1984. Nitrogen and potassium responses of two cassava varieties grown on an alfisol in Southern Nigeria. Ferr. Res.

Kayode, G.O., 1983. Effects of various planting and harvesting times on the yield, HCN, dry-matter accumulation and starch content of four cassava varieties in a tropical rainforest region. J. Agric. Sci. 101, 633–636. https://doi.org/10.1017/S0021859600038661.

Mazetti Fernandes, A., Gazola, B., Geibel da Silva Nunes, J., Loli Garcia, E., Leonel, M., 2017. Yield and nutritional requirements of cassava in response to potassium fertilizer in the second cycle. J. Plant Nutr. 4020, 2785–2796. https://doi.org/10.1080/01904167.2017.1382520.

Moreno, L.P., Gourdji, S., 2015. Cassava starch content and its relationship with rainfall. CCAFS Info Brief. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhague (Dinamarca). Available online at: www.ccafs.cgiar.org. Tech. Rep.

Odedina, J., Ojeniyi, S., Odedina, S., 2012. Integrated nutrient management for sustainable cassava production in South Western Nigeria. Arch. Agron. Soil Sci. S132–S140. https://doi.org/10.1080/03650340.2012.695865.

Okalebo, G.W., 2002. Laboratory methods of soil and plant analysis: a working manual. Res. Net. 128. https://doi.org/10.1109/ISIT.2012.6284704.

Okogbenin, E., Setter, T.L., Ferguson, M., Mutegi, R., Ceballos, H., Olasanmi, B., Fregene, M., 2013. Phenotypic approaches to drought in cassava: review. Front. Physiol. 4 MAY 1–15. https://doi.org/10.3389/fphys.2013.00093.

Olsen, S., Cole, C., Watanabe, F., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Physiol. Plant. 3, 152–164.

Onyenwoke, C.A., Simonyan, K.J., 2014. Cassava post-harvest processing and storage in Nigeria: a review. Afr. J. Agric. Res. 9, 3853–3863. https://doi.org/10.5897/AJAR2013.8261.

Pypers, P., Bimponda, W., Lodi-Lama, J.P., Lele, B., Mulumba, R., Kachaka, C., Boeckx, P., Merckx, R., Vanlauwe, B., 2012. Combining mineral fertilizer and green manure for increased, profitable cassava production. Agron. J. 104, 178–187. https://doi.org/10.2134/agronj2011.0219.

R Core Team, 2020. The R Project for Statistical Computing (3.4.4)[software]. Retrieved from. https://www.r-project.org/.

Spencer, D.S.C., Ezedinma, C., 2017. Cassava cultivation in sub-Saharan. Africa 123–148. https://doi.org/10.19103/as.2016.0014.06.

Sriroth, K., Piyachomkwan, K., Santisopasri, V., Oates, C.G., 2001. Environmental conditions during root development: Drought constraint on cassava starch quality. Euphytica 120, 95–101.

Ssemakula, G., Dixon, A., 2007. Genotype X environment interaction, stability and agronomic performance of carotenoid-rich cassava clones. Sci. Res. Essay 2, 390–399.

Suja, G., John, K.S., Sreekumar, J., Srinivas, T., 2010. Short-duration cassava genotypes for crop diversification in the humid tropics: growth dynamics, biomass, yield and quality. J. Sci. Food Agric. 90, 188–198. https://doi.org/10.1002/jsfa.3781.

Tan, S.L., Mak, C., 1995. Genotype × environment influence on cassava performance. Field Crop. Res. 42, 111–123. https://doi.org/10.1016/0378-4290(95)00016-J.

Tonukari, N.J., 2004. Biotechnology issues for developing countries Cassava and the future of starch. Electron. J. Biotechnol. 717–3458.

Trajano De Oliveira, N., Catia, S., Uchôa, P., Maria, J., Alves, A., De, J., Alves De Albuquerque, A., Rodrigues, G.S., 2017. Effect of harvest time and nitrogen doses on cassava root yield and quality. Artic. Rev. Bras. Cienc. Solo 41, 150204. https://doi.org/10.1590/18069657rbcs20150204.

Umeh, S.I., Onyeonagu, C.C., Umeh, B.U., 2015. Potassium nutrition and translocation in cassava (Manihot esculenta Crantz). Inter. Soybean 5, 281–286. https://doi.org/10.9734/AJEA/2015/7868.

Uwah, D.F., Effa, E.B., Ekpenyong, L.E., Akpan, I.E., 2013. Cassava (Manihot esculenta Crantz) performance as influenced by nitrogen and potassium fertilizers in Uyo, Nigeria. J. Anim. Plant Sci. 23, 550–555.

Visses, F., de, A., Sentelhas, P.C., Pereira, A.B., 2018. Yield gap of cassava crop as a measure of food security - an example for the main Brazilian producing regions. Food Secur 10, 1191–1202. https://doi.org/10.1007/s12571-018-0831-2.

Wang, W., Hostettler, C.E., Damberger, F.F., Kossmann, J., Lloyd, J.R., Zeeman, S.C., 2018. Modification of cassava root starch phosphorylation enhances starch functional properties. Front. Plant Sci. 9, 1–16. https://doi.org/10.3389/fpls.2018.01562.

Wholeya, D.W., Booth, R.H., 1979. Influence of variety and planting density on starch accumulation in cassava roots. J. Sci. Food Agric. 30, 165–170.