

# Canopy Structure Influence the Critical Period for Weed Removal of Three Cassava (*Manihot esculenta* Crantz) Varieties in Zambia

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## Abstract

Cassava (*Manihot esculenta* Crantz) is an important crop for food, feed and income security. Cassava productivity is limited by poor weed management. Field trials were conducted in Zambia to determine the Critical Period for Weed Removal (CPWR) on 3 cassava varieties (Chila, Mweru and Nalumino), with contrasting canopy structure, using a split-plot design in randomized blocks. Nine weeding treatments, *i.e.*, control, 21, 42, 63, 84, 105, 126, 147, 168 days after planting (DAP), were applied on two sets of weeding regimes. In one set, weeds were allowed to grow followed by a weed free period while in the second, plots were kept weed-free followed by a period of natural weed infestation at Kabangwe and Kaoma. Cassava varietal means were in the order Chila (10,199 kg ha<sup>-1</sup>) > Nalumino (9,047.6 kg ha<sup>-1</sup>) > Mweru (8,429 kg ha<sup>-1</sup>). Chila, a branching cassava variety, significantly out-yielded ( $P < 0.05$ ) other varieties. Fresh cassava root yields were higher at Kabangwe (23,270 kg ha<sup>-1</sup>) compared to Kaoma (21,347 kg ha<sup>-1</sup>). The CPWR was determined to be 60 DAP (48-73 DAP), at both sites. Yield differences among weeding treatment ranged between 18% and 75%. The determined CPWR is a determinant of weed management strategy for branching cassava varieties. The branching canopy architecture smothered weeds and hence is considered an important cassava varietal attribute. The yields in the current study are doubled the regional yield average of 8000 kg ha<sup>-1</sup> and four times the Zambian average of 5000 kg ha<sup>-1</sup>.

**Keywords:** field management practices, weed interference, biotic stress factors, root and tuber crops, Southern Africa

## 1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important food, feed, energy and income security crop grown mainly for its starchy roots that can be processed into various products (Balagopalan, 2002; Scott, 2021). It is an important source of food calories for > 800 million people. Cassava provides double the amount of energy (250 kcal) compared to sorghum (114) or wheat (110) per capita per day (El-Sharkawy, 2012). It is a perennial crop belonging to the Euphorbiaceae family that has been cultivated for 50 years (Altieri et al., 2012; Godfray et al., 2010; Hirschmann & Vaughan, 1983). The crop is highly adapted for growth in the tropics between latitudes 30° north and south of the equator, at elevations between 0-2,000 m above sea level (asl). Cassava can be grown under semi-arid or humid eco-zones with annual precipitation ranging from 500 mm to > 2,000 mm, because of its wide adaptation (El-Sharkawy, 2012). Cassava production and utilization has been projected to increase by between 50-80% in Sub-Saharan Africa (SSA) due to its resilience to climate impacts (El-Sharkawy, 2006; FAO, 2013; Jarvis et al., 2012; Scott et al., 2000). However, the practice of growing cassava on marginal lands with minimal external inputs by smallholder farmers threatens future production in SSA. Production per unit area across most regions in SSA has remained extremely low, *i.e.*, 8.3 t ha<sup>-1</sup> (FAOSTAT, 2022) while the realist potential to produce yields exceeding 30 t ha<sup>-1</sup> exist (Biratu et al., 2018).

In Zambia, cassava is important for food security, it ranks second after maize in daily consumption, is grown by over half a million smallholder rural households and is served in a range of dishes (Chitundu et al., 2006; ITC, 2010). The crop is mostly grown in the five provinces of Luapula, Northern, Western, Copperbelt, and Western provinces, where it is regarded as a staple food (Alene et al., 2013). The production of cassava has been growing and now exceed one million metric tonnes (MT) annually (Kabwe, 2014). Due to the increasing prominence, its production has expanded in recent years most of which (92%) is consumed locally (Haggblade et al., 2007) and contributes to social and economic development opportunities (Chipeta & Bokosi, 2013). However, cassava production faces various biotic challenges that constrain production on smallholder farms. Weed infestation is one of the major biotic stresses affecting yield, drudgery, and cost of production (Gianessi, 2013).

Weed infestation in cassava production systems, which often receives less attention from researcher, is likely to cause large yield losses if not managed (Ekeleme et al., 2016). Weeds have been estimated to cost more than US\$ 420 million and cause yield losses greater than 0.65 million tonnes in Sub-Saharan countries annually (Rodenburg & Johnson, 2009). Relying on manual weeding was found to increase drudgery among farmers and took between 173 and 376 labour hours per hectare (Ogwuikwe et al., 2014) hence the need for better weed management strategies. Appropriate weed management has been found to lead to high yield gains compared to other crop management practices, *i.e.*, as high as 91.6% on crop yields (Nhamo et al., 2014) and reduce the total time spent on by at least 31% (Johnson et al., 2019). Valadatilde et al. (2013) reported that weed emergence, weed population density and abundance are the important weed factors influencing crops while crop factors such as time of planting, canopy, stage of crop development and competitive ability can increase chances of higher crop yields. Weed management practices have been found to influence the seed weed bank in the soil over time (Ekeleme et al., 2016). Therefore, management of both weed and crop factors is important in designing integrated weed management practices for crops such as cassava.

In cassava, weed pressure results in intensive competition and when left to cover substantial portions of the growth cycle can cause root, stem and leaf yield losses, *e.g.*, Khanthavong et al. (2016) reported a range of between 46-95% of produce losses. Reducing weed residence on cassava fields has been used as a practical method of minimizing the impact of weeds on the crop yields. Therefore, determination of the specific timing of applying weeding operations is important for successful cassava production.

In Zambia, weed control methods commonly used by smallholder farmers are hand slashing, hand pulling and hoeing. These manual methods are inefficient because of drudgery, time consuming, expensive, and high labour demands during peak production periods (Islami et al., 2017; Maniyam et al., 2013). Alternative weed management practices such as chemical control (herbicides), cultural methods and integrated weed management practice have been tried elsewhere with variable results in cassava production systems (Ola et al., 2021a; Quee et al., 2016). Similarly, mechanical weed control tools that are gender neutral and labour saving have not attained the desired impact due to high initial cash outlay and hence low uptake by smallholder farmers (Johnson et al., 2019; Rodenburg et al., 2015). Access and knowledge of use of technologies remains a barrier for many smallholder farmers as evidenced by the number of accidents from chemical and mechanical weed control methods (Malambo et al., 2019). Nevertheless, appropriately timed weeding can contribute to drudgery reduction. To establish the specific time for weed removal, the peak period of weed competition must be determined (Shukor et al., 2009; Silva et al., 2013).

Research on the determination of the appropriate timing of control, management and effective removal of weeds, dates back to around 6000BC and peaked post herbicide discovery in the 1940 and became intensive in the 1960s before the green revolution of the 1970s (Timmons, 1970). This work is the genesis of the integrated weed management (IPM) paradigm which became popular in the late 20<sup>th</sup> century (Young, 2012). The “critical period of weed control” is a more commonly used phrase in literature and has been aligned with the ground-breaking work on refining weed management timing in many crops. Critical period of weed control has several definitions including (a) the period during which weed control is necessary to avoid yield penalty (Nazarko et al., 2005), (b) the period of time between the minimum time point weed-free (MTPWF) and the maximum time point under weed-infestation (MTPWI). Where MTPWF, refers to the time after which the crop must be kept weed-free to prevent crop yield loss from the competition while MTPWI is the time up to which the crop must be kept weed-free from the beginning to avoid crop yield loss from emerging weeds thereafter (Singh et al., 1996). Further definitions of the critical period of weed control include (c) an interval in the life cycle of the crop when it must be kept weed-free to prevent yield loss (Van Acker et al., 1993), and (d) the shortest time spent in the crop growth cycle when weeding will result in highest economic returns (Hasanuzzaman, 2015). Based on the current understanding of integrated weed management, we define the critical period of weed removal in cassava based on the time of equal interference determined from weed-free and the weed-infested best fit polynomial

equations from cassava root, stem and leaf yields measured at equal time intervals during the growth cycle from planting through to harvesting. Thus, CPWR is the threshold time interval within which the application of weeding will effectively reduce crop-weed competition to a level that supports viable crop production at no yield penalty. We use the terms critical period of weed removal (CPWR) in place of the critical period of weed control (CPCR) in this publication. The knowledge of the CPWR is critical in the determination of appropriate timing of manual, mechanical or chemical weed management for economic and environmental sustainability.

Cassava is susceptible to weed interference during the early growth stages, *i.e.*, before full canopy development and this time period, depending on the variety and climatic conditions, ranges between 8 to 16 weeks after planting. Slow canopy development entails that the crop requires a prolonged period for the crop aerial parts to effectively shade the area under the crop thereby making early smothering of weed and hence weed suppression a challenge (Gianessi, 2013). Weed proliferation during early growth stages of cassava that encompass canopy development and early tuberization impact both yield and yield components (Onochie, 1975). Cassava variety, canopy architecture and branching behavior, and phenology are important determinants of the CPWR. Thus, determination of CPWR is a key component of integrated weed management for cassava production and it is useful for making decisions on the need and timing of weed control (Silva et al., 2013). The CPWR helps to make decisions on the necessity and selection of best time for weed control (Knezevic et al., 2002).

The main objective of this study was to determine the critical period for weed removal (CPWR) in three improved cassava varieties, namely Mweru, Nalumino and Chila that are commonly grown in cassava growing areas of Kabangwe and Kaoma districts in Zambia. The research tested the hypotheses that; CPWR is longer in branching varieties than non-branching varieties due to early canopy development and more weed smothering from shading effects, and fresh root yield and yield components respond positively to appropriately timed weed removal.

## 2. Materials and Methods

### 2.1 Description of the Study Sites

#### 3.1.1 Location

The study was conducted between 2016 and 2018 at two locations: (1) at IITA-Zambia research farm at Kabangwe (S15°3', E 28°3') in Chongwe district and (2) at ZARI-Longe experimental farm (S14°8', E 24°9') in Kaoma district in Western Province, Zambia. The altitude for the two site was not significantly different (about 16.6 m) with Kabangwe at 1188.6 m.a.s.l and Longe at 1163.3 m.a.s.l.

#### 2.1.2 Soils

To characterise the sites, soil samples were collected at the onset of the experiment and analysed in the Zambia Agricultural Research Institute (ZARI) central laboratories at Chilanga in Lusaka. Results of the chemical analysis showed that soils from the sites at Kaoma were sandy clay, with pH 5.4 (CaCl<sub>2</sub>), organic carbon 0.4% (Walkley Black, Anderson & Ingram, 1993), while those at Kabangwe were sandy loam with pH 5.6 and organic carbon 0.4%. These soils were classified as medium to slightly acidic. Sandy soils are dominant in Zambia and constitute about 70% of agricultural land (Yerokun, 2008).

#### 2.1.3 Rainfall

The total rainfall amounts received during the 2016/2017 cropping season at Kabangwe research station and Kaoma experimental site were 906.2 mm and 1221.9 mm respectively. Both sites (Kabangwe and Kaoma) received most rainfall in January compared to other months (316.6 mm and 366.2 mm) respectively. Both sites, Kaoma and Kabangwe, had adequate rainfall for growth of Cassava. The long-term mean monthly rainfall, maximum and minimum temperature for the study sites is presented in Figure 1.

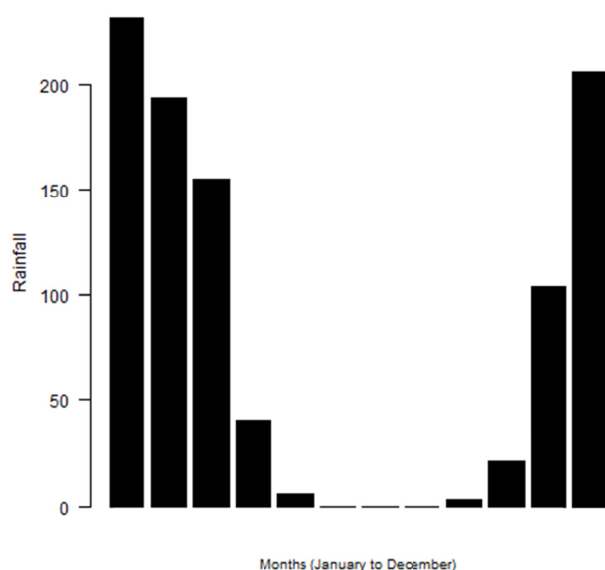


Figure 1. Mean monthly rainfall (mm), for the period between 2001 and 2020 for the two research sites at Kabangwe and Kaoma in Zambia

Both Kabangwe and Kaoma sites experience a unimodal tropical rainfall pattern which starts invariably around November and finishes around April. The timing and intensity of the tropical rains are influenced by the Congo moisture rich airmasses and closely related to the movement of the intertropical convergence zone (ITCZ) that shifts in the north-south direction. Easterly winds that are influenced by the warm Indian Ocean current flow through the Mozambique channel also influence rainfall events. An El Niño Southern Oscillation (ENSO) is a recurring phenomenon and is often associated with extreme events such as droughts and floods in this country located in Southern Africa (Davis-Reddy & Vincent, 2017). The topography of the specific sites also contributes to the amount of rainfall receipts and temperature variations (Libanda et al., 2020).

The rainfall distribution during the cassava growth period, soils and temperatures were favourable for cassava production. Earlier reports have shown successful cassava production under sandy loamy or loamy sands and minimum annual rainfall of about 500 mm distributed across the crop growing period to support both tuber development and above ground biomass growth (El-Sharkawy et al., 1992).

#### 2.1.4 Temperatures

The minimum and maximum temperature recorded in Kabangwe ranged between 19.7 °C and 27.4 °C and between 18.7 °C and 26.4 °C at Kaoma with the lowest averages recorded in May and June while the highest was recorded in October. The mean maximum temperature (35 °C) in Kabangwe was observed in October while the minimum temperature (10 °C) was observed in May. Both sites experience suitable average temperatures for cassava growing except during the May, June and July period where night temperatures drop to below 12 °C. Optimal photosynthetic rates and cassava storage roots bulking occur when temperatures average between 25 °C and 35 °C for cool climate and between 30-40 °C for hot climatic regions, while overall growth is reduced to minimal at temperatures below 15 °C (DPP, 2010; El-Sharkawy et al., 1992). Work of Alves (2002) has summarized the effect of temperature on cassava growth as follows: < 15 °C plant growth is inhibited, > 17 °C the crop can grow, 25-29 °C optimal cassava growth, and 30-40 °C highest photosynthesis rates are attainable in the field.

#### 2.2 Experimental Design

The experiment was laid out using a Split-plot design in randomized complete blocks with the varieties as the main plot factor and the weeding management as the subplot factor. Three cassava varieties were used while a total of nine (9) weeding treatments were studied. The varieties and weeding treatments were studied under a weed free and weed infested management systems. The experimental units were replicated three times.

Land was ploughed and harrowed using a tractor in November 2016. Fresh cassava cuttings 30 cm long were used for planting the trials. Planting was conducted by burrowing a minimum of three nodes on cassava cuttings into the soil at a slanted position while keeping the rest of the cutting above the ground.

### 3.2.1 Main Plot Factor

Three (3) varieties, Chila, Mweru and Nalumino, constituted the main plot factor in this experiment. Plant stature varies among the varieties and the branching characteristic affects the impact of cassava canopy on weeds and weed development in the field. The varieties also have different adaptation with some varieties having a wide adaptation to environmental growth conditions. Table 1 summarizes the characteristics considered in selecting the varieties for use in the study.

Table 1. Characteristics of three cassava varieties used in the critical period of weed removal experiment at Kabangwe and Kaoma from 2016 to 2018

Variety	Taste	Architecture	Year released
Mweru	Sweet	Upright architecture	2000
Nalumino	Bitter	Branching architecture	1993
Chila	Bitter	Semi-branching architecture	2000

Source : Chitundu et al. (2006); Chiona et al. (2016).

### 2.2.2 Sub-plot Factor

A total of nine (9) treatments constituted the sub-plot factor in this study. The weeding treatments were executed at 21, 42, 63, 84, 105, 126, 147, 168 days after planting (DAP) and a control treatment was made up of weed free or weed infested plots that were kept throughout a period of 168 days. Growth parameters were measured at the same time intervals and at crop harvest. Weeds were allowed to interact (compete) with the crop for a period of about 6 months and this period constituted the study period when weed management treatments were applied. Earlier studies had shown that weed management during the initial vegetative and tuberization periods largely impacts the total marketable fresh root yield of cassava and its yield components. Table 2 shows the two sets of nine (9) weeding treatments used in the study under the weed free and weed infested regimes.

Table 2. Treatment description for the weed free plots and weed infested plots in a study to determine the critical period of weed removal at Kabangwe and Kaoma in Zambia

#	<b>Set one (1) Weed Free Plots (WF)</b>	
	Treatment	The plots were kept free from weeds for the first:
1	21 DAP	21 Days After Planting and then left with weeds (weed infested) until harvest
2	42 DAP	42 Days After Planting and then left with weeds (weed infested) until harvest
3	63 DAP	63 Days After Planting and then left with weeds (weed infested) until harvest
4	84 DAP	84 Days After Planting and then left with weeds (weed infested) until harvest
5	105 DAP	105 Days After Planting and then left with weeds (weed infested) until harvest
6	126 DAP	126 Days After Planting and then left with weeds (weed infested) until harvest
7	147 DAP	147 Days After Planting and then left with weeds (weed infested) until harvest
8	168 DAP	168 Days After Planting and then left with weeds (weed infested) until harvest
9	Control WF	Control Free from weeds all the time (Weed Free) until 168 DAP
#	<b>Set two (2) Weedy Infested plots (WI)</b>	
	Treatment	Plots were infested with weeds for the first:
1	21 DAP	21 Days after planting and then weed free until 168 DAP
2	42 DAP	42 Days after planting and then weed free until 168 DAP
3	63 DAP	63 Days after planting and then weed free until 168 DAP
4	84 DAP	84 Days after planting and then weed free until 168 DAP
5	105 DAP	105 Days after planting and then weed free until 168 DAP
6	126 DAP	126 Days after planting and then weed free until 168 DAP
7	147 DAP	147 Days after planting and then weed free until 168 DAP
8	168 DAP	168 Days after planting and then with weeds until the time of harvesting
9	Control WI	Control (Weedy Infested) infested with weeds until harvest

Note. T = Treatment. WF = Weed free plots, WI = Weed infested plots.

### 2.2.3 Plot Management

Cultural plot management practices were applied from planting through to harvesting to ensure uniformity and minimal effects of pests and diseases. A uniform plant establishment was maintained by replacing the non-sprouting cassava cutting with in the first 21 days and eliminating varietal mixtures. Diseased plants were rouged out to avoid the spread.

The positive control treatment which constituted weed-free plots throughout the 168 days while the negative control had weeds for the same period were carefully managed as they were important in the determination of the CPWR.

### 3.3 Variables and Data Collection

Cassava yield and yield parameters were recorded at 3, 6 and 24 months during the experiment at Kabangwe and Kaoma. Cassava yield variables collected from aerial plant portions were leaf weight and stem weight; variables for soil part were root girth, root length and fresh root weight. The cassava storage root weights were the main factor which were used to determine critical period for weed removal. Prior to sampling, the plant stands were counted for each plot.

During the final crop harvest at 24 months, yield data was collected from net plots sizes of 16 m<sup>2</sup> (4 × 4 rows). Sampling proceeded by removing the whole plant and separate measurements taken for leaves, stems, and cassava roots. The roots were cleaned of soil before weighing them on a digital portable scale. Fresh subsamples were then collected for further analysis in the laboratory.

#### 2.3.1 Root Weight

Cassava root tubers were harvested by removing the edible below-ground structure from rest of the plant root systems. To maintain consistency, tubers were separated from the roots at the point where the edible part start to bulge and form the starch containing edible structure. Fresh cassava root yield was measured in the field to avoid moisture losses during storage or transportation. Thereafter cassava storage roots samples were chopped into small pieces (about 2 cm) to enhance drying at temperature of 100 °C for 36 hours (Ekanayake, 1996; Chikoye et al., 2008).

#### 2.3.2 Stem Weight

Cassava stems were cut from within a height of 5 cm from the ground. The weight of the stems was measured after removing all leaves and roots of the plant. The measured biomass constituted the above-ground cassava plant parts except for the leaves. In cassava, mature stems are used for vegetative propagation in their fresh form. Farmers use traditional methods to store harvested stems for longer periods running into several months after harvesting but creating special storage conditions to prevent loss of moisture or drying is necessary. Samples were taken from each weeding treatments.

#### 2.3.3 Leaf Weight

Leaves were harvested by detaching them from the nodes where the petioles form the stem nodes. The measured weight of leaves included both the lamina and the petioles. In cassava, leaves develop from the meristems located at nodes along the stem. Fresh leaf weight was determined in the field while samples were taken for drying and further processing in the laboratory.

### 2.4 Data Analysis

The Analysis of Variance (ANOVA) based on statistical model for split plot was used:

$$Y_{ijk} = \mu + \beta_i + A_j + \delta_{ij} + B_k + AB_{ij} + \varepsilon_{ijk} \quad (1)$$

where,  $Y_{ijk}$  = Output;  $\mu$  = General mean;  $\beta_i$  = Block effect;  $A_j$  and  $B_k$  = Main plot and sub-plot Factors;  $\delta_{ij}$  = Error main plot;  $AB_{ij}$  = Interaction effect and  $\varepsilon_{ijk}$  = Error sub-plot (Bradley and Nachtsheim, 2009). GenStat statistical software was used to analyse data (GenStat, 2012). Tukey HSD ( $P < 0.05$ ) was used to separate treatment means of the main-plot and sub-plot factors.

### 2.5 Determination of CPWR

The CPWR determination using fresh root, stem and leaf weight data from the weed free and the weed infested treatment schemes (Table 2). Means from the weed infested scheme were plotted and a best fit function fitted [ $f(WI) = 1$ ] and a similar iteration was conducted on the weed free data to generate a second function [ $f(WF) = 2$ ]. by taking the period within weed free days that had low yield below the mean and the period within weed infested days that had the yield above the mean. Basing on the combination of the analysed data and the graph of yield, the range was obtained, that range was the CPWR. Using the quadratic functions from the treatment

effects of the weed free and weed infested data, the critical period was defined as the point of intersection of the weed free and weed infested best fit functions. At this point the two functions are equal. The best fit was determined by minimizing the sum of squares between the response function and the fitted function.

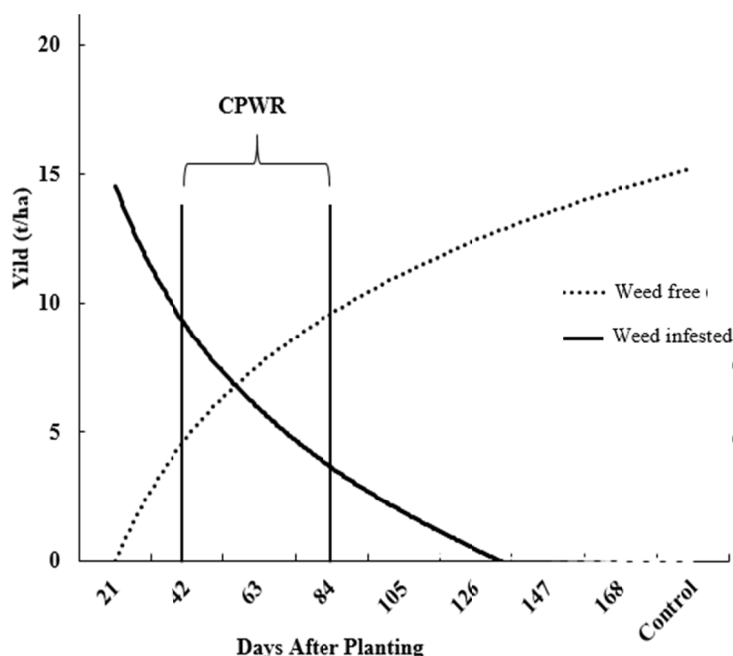


Figure 2. Critical period for weed removal (CPWR) determination using the weed free and weed infested best fit regression lines and the range around the average value for fresh root, stem and leaf yields harvested from three cassava varieties at Kabangwe and Kaoma

### 3. Results

#### 3.1 Varietal Responses at Kabangwe and Kaoma

The plant architecture characteristic presented in Table 1 suggest that at full canopy, Nalumina will have a more smothering effect on weeds compared to the other varieties. Current results from Kabangwe, showed that there were no significant cassava root yield differences between Chila and Mweru. Nalumino had significantly lower yield ( $P < 0.05$ ) than Chila and Mweru (Table 2). At Kaoma, Mweru yielded least ( $P < 0.05$ ) compared to the other varieties. No significant differences were observed between Chila and Nalumino. The overall varietal comparisons showed the following order Chila ( $10199 \text{ kg ha}^{-1}$ ) > Nalumino ( $9047.6 \text{ kg ha}^{-1}$ ) > Mweru ( $8429 \text{ kg ha}^{-1}$ ). The mean root yields of Chila were significantly higher ( $P < 0.05$ ) compared to the other two varieties (Table 3). There were however no significant differences between the yields of Mweru and Nalumino.

Table 3. Root mean yield ( $\text{kg ha}^{-1}$ ) of three varieties (Chila, Mweru and Nalumino) used in the experiment harvested at 24 months after planting at Kabangwe and Kaoma in Zambia

Variety	Kabangwe	Kaoma
Chila	11241.7 a	9240.3 a
Mweru	9703.3 ab	6579.2 b
Nalumino	8496.6 b	10121.0 a

Note. Overall means: Chila = 10198.7; Nalumino = 9047.6; Mweru = 8429.2  $\text{kg ha}^{-1}$ .

#### 3.2 Critical Period for Weed Removal

The overall critical period of weed removal calculated using the weed free and weed infested function (Figure 2) across two study sites in Zambia ranged from 57 DAP to 68 DAP for measurements conducted at over a period of 3, 6 and 24 months after planting (MAP). A similar range of between 51 DAP and 61 DAP was observed

when the calculations were done using different plant components, *i.e.*, fresh root, stem and leaf weight harvested across the three sampling times (Table 4). Calculation across fresh cassava yield components and across three sampling dates resulted in an average critical period of weed removal of 60.4 DAP. The confidence interval was calculated as 12.3 days suggesting that the range of critical period of weed removal for the three varieties was between 48 DAP and 73 DAP.

Table 4. The critical periods determined from solving the quadratic equations generated from data from root yields, stem weight and leave weight at 3, 6 and 24 months after planting (MAP) at Kabangwe and Kaoma

Time	Root weight	Stem weight	Leave weight	Mean
3 MAP	53	63	55	57
6 MAP	51	55	63	56
24 MAP	50	70	84	68
Mean	51.3	62.7	67.3	60.4
95% Confidence interval (n = 9; t = 3.35539)				+/- 12.3

*Note.* NB: The critical period of weed removal calculated from resolving the WF and WI functions +/- the confidence interval. MAP: months after planting.

### 3.3 Fresh Cassava Root, Stem and Leaf Yields at Kabangwe and Kaoma Study Sites

At Kabangwe, there was significant difference ( $P < 0.05$ ) among weeding treatments under the weed infested scheme. Treatments 63 DAP, 42 DAP and 21 DAP yielded 8.8 t ha<sup>-1</sup>, 11.3 t ha<sup>-1</sup> and 17.1 t ha<sup>-1</sup>, respectively (Table 5). The control, 168 DAP, and 147 DAP treatments, yielded least with 0.9, 2.4 and 2.8 t ha<sup>-1</sup> respectively. In the weed free scheme, treatments 105 DAP, 126 DAP, 147 DAP, 168 DAP, and the control attained significantly higher cassava root yields with means of 10.6, 13.2, 16.6, 18.7 and 23.3 t ha<sup>-1</sup> respectively. The lowest yielding treatments 21 DAP, 42 DAP, and 63 DAP had mean yields of 2.3, 3.8 and 5.6 t ha<sup>-1</sup> respectively.

At Kaoma research site's weed infested scheme, the highest root yields were obtained from treatments 84 DAP, 63 DAP, 42 DAP, and 21 DAP from which means of 9.5, 14.2, 15.6 and 20.1 t ha<sup>-1</sup> were recorded, respectively. The control treatment, 168 DAP, 147 DAP yielded 1.1, 1.9 and 3.4 t ha<sup>-1</sup> respectively. In the weed free scheme, the highest yield emanated from treatments 105, 126, 147, 168, and control (9.9, 11.4, 14.0, 18.1 and 21.4 t ha<sup>-1</sup>) while the lowest yields were obtained from treatments 21 DAP, 42 DAP and 63 DAP (2.8, 3.6 and 5.5 t ha<sup>-1</sup>), as presented in Table 4.

The comparison of cassava root yield performance across sites for the WI scheme showed that treatment 105 DAP, 84 DAP, 63 DAP, 42 DAP and 21 DAP significantly attained higher yield at Kaoma translating to a 74.8, 48.2, 61.2, 37.8 and 17.7% respectively compared to the same treatments at Kabangwe. Weeding treatment 126 DAP to 168 DAP had similar yields ( $P < 0.05$ ) across the two sites. There were no difference in yield for the weed free scheme at the two location and best treatments yielded 23270.8 kg ha<sup>-1</sup> at Kabangwe and 21347.8 kg ha<sup>-1</sup> at Kaoma.

Table 5. Mean cassava root yield ( $\text{kg ha}^{-1}$ ) measured from weed free (WF) and weed infested (WI) plots at twenty-four (24) months after planting at Kabangwe and Kaoma

(a) Site		Kabangwe		Kaoma	
(b) Scheme		WI (kg/ha)	WF (kg/ha)	WI (kg/ha)	WF (kg/ha)
(c) Weeding Treatments	21 DAP	17125.0 a	2348.6g	20154.2a	2826.9g
	42 DAP	11327.8b	3808.9fg	15605.8b	3630.8fg
	63 DAP	8824.7bc	5548.3fg	14223.6b	5530.8efg
	84 DAP	6400.0cd	7306.7ef	9487.5c	7904.2def
	105 DAP	4307.2de	10595.3de	7527.8cd	9868.9cde
	126 DAP	3241.9de	13211.1cd	5677.8cde	11399.2cd
	147 DAP	2760.8de	16320.0bc	3411.1def	14004.2bc
	168 DAP	2443.1de	18740.8b	1861.1ef	18055.0ab
	Control	926.4e	23270.8a	1081.9f	21347.8a
	<i>Treatment Mean</i>	6373.0	11239.0	8781.20	10507.5
<i>CV (%)</i>		27.0	52.81	24.1	26.31
<i>P &lt; 0.05</i>		0.000	0.000	0.000	0.000

Note. WF = Weed free treatments set, WI = Weed infested treatments set, DAP = Days after planting, RW = Root weight, CV = Coefficient of variation. Yield followed by same letter were not significantly different at  $P < 0.05$  while different letters show significant statistical differences; Tukey HSD was used for mean separation.

The overall treatment means of weed schemes at the two study sites showed that the WF scheme at Kabangwe and Kaoma yielded higher than the weed infested schemes (Table 6). At Kabangwe, the best treatment 21 DAP significantly yielded higher fresh stems (difference of  $11.4 \text{ t ha}^{-1}$ ) of compared to the un-weeded control. Under the weed free scheme however, there were no significant difference in stem weights between the treatments. A similar trend was observed at Kaoma where the 21 DAP treatment significantly out-yielded the control by about  $12.8 \text{ t ha}^{-1}$  and no statistical differences were observed under the weed free treatments.

Table 6. Cassava stem weight (kg/ha) measured from three (3) varieties and nine (9) weeding treatments after twenty-four (24) months from transplanting at Kabangwe and Kaoma sites in Zambia

(a) Site		Kabangwe		Kaoma	
(b) Scheme		WI (kg/ha)	WF (kg/ha)	WI (kg/ha)	WF (kg/ha)
(c) Weeding Treatments	21 DAP	14183.3a	10016.4	13853.9a	5979.4
	42 DAP	12959.4a	11037.5	11655.6abc	6988.6
	63 DAP	9680.0ab	9040.0	12265.3ab	7822.5
	84 DAP	6955.6ab	12411.1	9575.0abc	8030.6
	105 DAP	10618.3ab	12735.8	6836.1bcd	11093.1
	126 DAP	6544.4ab	11077.2	5891.1cd	10712.5
	147 DAP	4669.7b	12086.4	5950.8cd	10580.3
	168 DAP	4093.6b	13167.0	1980.0d	12081.4
	Control	2810.0b	12563.6	1099.4d	13247.5
	<i>Treatment Mean</i>	8057.16	11570.56	7678.58	9615.09
<i>CV (%)</i>		57.57	66.03	55.27	51.47
<i>P &lt; 0.05</i>		0.000	0.923	0.000	0.06

Note. WF = Weed free treatments set, WI = Weed infested treatments set, DAP = Days after planting cassava, SW = Stem weight, CV = Coefficient of variation, CONTROL = weed infested or weed free all the time. Yield followed by same letter were not significantly different at  $P < 0.05$  while different letters show significant statistical differences; Tukey HSD was used for mean separation.

Significant difference among weeding treatments were observed in the WI scheme at both Kabangwe and Kaoma (Table 7). However, mean cassava fresh leaf weights were higher from the WF scheme compared to the WI scheme

at both study sites. Significantly higher leaf weight was observed at Kabangwe under the WF scheme. At Kabangwe the WF scheme yielded 77% more leaves than the WI.

Table 7. Cassava leaf weight (kg/ha) measured from three (3) varieties and nine (9) weeding treatments after twenty-four (24) months from transplanting at Kabangwe and Kaoma sites in Zambia

(a) Site		Kabangwe		Kaoma	
(b) Scheme		WI (kg/ha)	WF (kg/ha)	WI (kg/ha)	WF (kg/ha)
(c) Weeding Treatments	21 DAP	407.5a	193.6	225.3a	152.8
	42 DAP	270.3ab	233.3	191.7ab	98.6
	63 DAP	202.8ab	317.5	137.2abc	126.7
	84 DAP	193.3ab	381.1	157.8abc	164.7
	105 DAP	190.8ab	344.7	131.7abc	149.2
	126 DAP	176.7ab	380.0	84.3bc	66.4
	147 DAP	138.1ab	383.3	98.1abc	156.4
	168 DAP	131.9ab	558.9	81.1bc	216.9
	Control	112.2ab	593.6	55.0c	211.9
	<i>Treatment Mean</i>	212.62	376.23	129.10	160.34
<i>CV (%)</i>		95.17	85.40	55.40	66.61
<i>P &lt; 0.05</i>		0.002	0.307	0.002	0.155

Note. WF = Weed free treatments set, WI = Weed infested treatments set, DAP = Days after planting cassava, CV = Coefficient of variation, CONTROL = weed infested or weed free all the time, Yield followed by same letter were not significantly different at  $P < 0.05$  while different letters show significant statistical differences; Tukey HSD was used for mean separation.

## 4. Discussion

### 4.1 Cassava Canopy Smothering Effect on Weeds

The three varieties used in the study, *i.e.*, Chila, Mweru and Nalumino responded differently to the weeding treatment at Kabangwe and Kaoma with Chila significantly outyielding the other two varieties. Highest yields were obtained from Chila, a semi-branching cassava variety at Kabangwe and a branching variety Nalumino has highest yields at Kaoma. At both sites the non-branching variety Mweru yielded least. The current results (Table 3) support our hypothesis that canopy cover reduces weed-competitiveness as observed in the branching (Chila) and semi-branching (Nalumino) varieties. The current results are corroborated by the work of Ola et al. (2021a) who reported higher cassava root yields emanating from 20% weed suppression from a variety with a broad canopy structure. A similar weed smothering effect from branching cassava varieties on weeds was also reported by Temitope (2012) from studies conducted in Nigeria.

Cassava canopy structure has been widely reported to affect both the weed population and the diversity annual weed species which grow in cassava plots. Therefore, the branching and broad canopy structure is an important attribute that determines weed competitiveness in sole and intercropping systems (Ola et al., 2021a; Weeraratne et al., 2017). In experiments where weeds were left to freely infest cassava fields, there is evidence that reduced yield losses were observed in plots where branching plant type was grown (40%) compared to root yield losses of non-branching cassava varieties (Akobundu, 1980). The current result contributes to the knowledge required by cassava producers in making decision on the need and timing of weed control (Silva et al., 2013).

The mechanisms through which cassava canopy smothers weeds which include shading effect on weeds, light restriction through the canopy, allelopathy, and were put forward by several authors (Ibeawuchi et al., 2007; Mobasser et al., 2014; Sims et al., 2018; Tesio & Ferrero, 2010). However, few studies have been published on cassava cropping systems that take advantage of the morphological plant structure, physiological impact of canopy on weed development and subsequent support of higher root yield from such mechanisms (Ibeawuchi et al., 2007; Onochie, 1975). Work of Onochie (1975), highlighted a characteristic weak competitiveness against weeds during early canopy development for cassava. The current results suggest the importance of weed management during the early canopy development stages and canopy structure as an attribute worth considering in breeding programmes aimed at the reduction of biotic stress factors such as weed competition. Modifications

in canopy architecture seem to be the key factor contributing to weed-smothering capacity in different cassava production systems (Weerarathne et al., 2017).

#### 4.2 Critical Period of Weed Removal

The critical period of weed removal (CPWR) determined at Kabangwe and Kaoma from three cassava varieties, *i.e.*, Chila, Mweru, Nalumino, ranged between 48 DAP and 73 DAP (at 95% Confidence interval), with an overall mean of 60.4 DAP (Table 4). The current result confirmed our hypothesis that weed control during the early growth stages of cassava (within three (3) months of crop establishment), significantly reduces weed competition and support high fresh root, stem and leaf yields. The current result is in line with findings of Costa et al. (2013) who observed the effectiveness of weed control treatments applied during the third month (60-90 DAP), on increasing root yields and reducing weed pressure. Similar results were observed by several authors such as Onochie (1975) who found 28-84 DAP; Akobundu (1980) found 40-84 DAP, Melifonwu (1994) reported 42-84 DAP in studies conducted in Nigeria and Ambe et al. (1992) determined 20-60 DAP as the critical period of weed removal in Cameroon. Studies conducted in Brazil found similar ranges of CPWR, *i.e.*, 28-70 DAP (Albuquerque et al., 2008) and 88-91 DAP (Costa et al., 2013). Except for the work of P. M. Olorunmaiye and K. S. Olorunmaiye (2009), the methods of determining the critical period of weeding in cassava were invariably different. Furthermore, the actual range of the critical period of weed removal as measured in days after planting (DAP), were not the same though they ranged between 20 DAP to 90 DAP. Regardless, the current result provides an important piece of information on the timing of weeding operations on cassava fields in Zambia and beyond.

In Zambia, weed control practices used are manual pulling, hand-hoe weeding and slashing at the methods of weed control in cassava fields. In total, weeding three (3) times were reported to be optimal for cassava and significantly increased yield. The first weeding significantly produced higher yield gains with the subsequent weeding events causing incremental gains (Barratt et al., 2006). Chiona et al. (2016) recommended weed control at 45 DAP and two more operations separated by 45 days. Similar recommendations have been reported by Abass (2014) for Eastern and Western Africa. However, farmers apply late weeding to cassava fields due to a range of reasons. These include labour demand that exceeds supply during pick periods of agricultural operations, priority and focus directed to annual food crops whereas perennial cassava landraces which spend multiple seasons on the fields do not receive adequate attention and limited knowledge on optimizing cassava inputs in relation to the crop phenology (Akobundu, 1980; Kaluba et al., 2021). The recommendation of three (3) weeding operation and the observation of the critical period of weeding is in line with the work of (Ambe et al., 1992). The findings of work conducted in Cameroon confirmed that a single weeding though important was not enough to support high yields rather Ambe et al. (1992) recommended a minimum of two (2) weeding rounds during the early growth stages of cassava at 4 and 12 weeks after planting (WAP). The study in Cameroon showed that yield greater than the content average of about 8 t ha<sup>-1</sup> were highly possible at weed management resulted in yields of between 11 t ha<sup>-1</sup> and 17 t ha<sup>-1</sup> from red and white-skinned cassava varieties.

#### 4.3 Approach to Determination of the Critical Period of Weed Removal

Several studies focusing on the determination of the critical period of weed removal in cassava and other crops have used the application of three or more predetermined weeding operations, *e.g.*, Melifonwu (1994) in west Africa and Costa et al. (2013) in Brazil. The current method of CPWR period determination used a range of treatments applied at 21-day intervals for the WI and WF schemes (Figure 2). Onochie (1975) was one of the early researchers to use two schemes of WI and WF with monthly intervals for eight (8) months. A similar approach was used by Albuquerque et al. (2008) in which a yearlong intensive analysis of weed dynamic was conducted at 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325 and 350 DAP. The study concluded that the critical period of weed interference in Brazil ranged between 25 and 75 DAP, a result similar to our current observation. Melifonwu (1994) reviewed the history of this approach and concluded that the results were replicable. The current study answered the fundamental question about the critical period for weed removal (CPWR) in cassava varieties grown in Kaoma and Kabangwe, Zambia.

#### 4.4 Harvested Fresh Cassava Root and Stem Yields at Maturity

Weed removal resulted in statistically significant higher cassava fresh root yield for the treatments executed within the 60 DAP critical period of weed removal for both WI and WF schemes (Table 5). The current results confirm our hypotheses that weeds are a significant biotic stress factor with a huge impact of cassava yields and control practices lead to yield gains, *e.g.*, 11.4 t and 12.8 t from the WI treatments at Kabangwe and Kaoma respectively. At Kaoma, yields increased by between, 17.7% and 75% from the WI scheme. Current findings are

in line with the results from the work of Doll and Piedrahita Castaneda (1976) who reported 75% cassava root yield increase from two well-spaced weeding operations.

Several researchers have reported yield penalty from un-weeded cassava plots. Table 4 shows that all treatments where weeding was delayed yielded lower compared to treatments when weeding was conducted early. Similarly, more frequent weeding under the WF scheme had higher yield compared to the delayed weeding plots. While 100% yield losses have been reported on un-weeded plots, Ambe et al. (1992) reported 90% losses. Losses ranged from 40% to 68% were observed in an experiment with cassava varieties with different branching patterns in Nigeria (Akobundu, 1980).

The best performing treatments yielded 23270.8 kg ha<sup>-1</sup> and 21347.8 kg ha<sup>-1</sup> while the worst were 1082 and 926.4 kg ha<sup>-1</sup> at Kabangwe and Kaoma respectively (Table 5). While the average cassava yield in Zambia is below 5000 kg ha<sup>-1</sup> and the southern Africa regional average is 8 000 kg ha<sup>-1</sup>, the current yields emanating from improved management practices are far higher than average yields. The work of Ekeleme et al. (2021) who reported root yields higher than 20 t ha<sup>-1</sup> and a doubling of the national average of 8-12 t ha<sup>-1</sup> in studies conducted in Nigeria, support the current results obtained at Kabangwe and Kaoma in Zambia.

#### 4.5 Towards Timely Weed Management Practices in Cassava Systems

Timing is critical in weed control and the same rule of thumb applies to other agronomic practices on cassava. In cassava, timing of weeding in relation to canopy development and tuberization are critical to the overall root yield performance (Onochie, 1975; Melifonwu, 1994).

The wide spacing, both inter- and intra-row spacing, recommended for use to smallholder producers cause weed infection to increase at the beginning of the cropping season compared to other crops which are planted closely together. Both wide spacing and poor land preparation have been reported to increase weed pressure on cassava fields (Ekeleme et al., 2016). Furthermore, poor competitive ability of cassava relative to weeds have explained the high root yield penalty suffered on cassava fields (A'ihl et al., 2021). Recent evidence suggest that productivity increases when cassava and maize are grown at high population and adequately fertilizer (Nwokoro et al., 2021).

However, exceptional cases have been reported where site response to weed management yielded no yield benefit or lower yield compared to the control (Onasanya et al., 2021).

Recognizing the need for weed management during early growth stage of cassava Weerathne et al. (2017) recommended intercropping as a good alternative to the labour intensive non-chemical weed control methods. By intercropping widely spaced cassava benefits from the interference of the companion crop to the early weeds and reducing open spaces between cassava crop which is often exploited by both broadleaf weeds and grasses to exert pressure on the cassava crop. Using this method yield benefit of between 30 and 60% have been recorded (Weerathne et al., 2017).

The study has highlighted the importance of observing the critical period for weed removal on cassava field and the impact it can have on food production, potential incomes, and farmer welfare in Zambia. It also showed the importance of selecting a variety with a plant canopy architecture that is pro-weed smothering. More research is required on the economics of weed technologies accessible to farmers and how these can be used to apply the critical period of weeding to reduce infield crop-weed competition.

### 5. Conclusion

Cassava canopy structure has significant impact on weed smothering and can be used in the reduction of the negative impacts of early season crop-weed competition. Cassava varieties Chila, with a semi-branching architecture, and Nalumino with a branching architecture, yielded significantly higher fresh roots than an upright Mweru. Therefore, the result confirmed the hypothesis that a branching canopy significantly smothers weeds and reduces competition much to the advantage of cassava. The plant architecture of improved varieties in Zambia can be used to inform weed management timing under subhumid tropical conditions in Zambia.

The critical period for weed removal in three cassava varieties commonly grown in Zambia was found to be between 48-73 DAP, with an overall mean of 60.4 DAP. The determined mean CPWR was in line with studies conducted on other tropical regions of sub-Saharan Africa. In Zambia, the CPWR of 60.4 DAP is an important input to the development of weed management recommendations for improved varieties with different architecture. The approach used in the current study produced comparable CPWR results.

Weed management treatment applied on Chila, Mweru and Nalumino significantly controlled crop-weed competition at Kabangwe and Kaoma leading to increased fresh root, stem and leaf yields. Well managed

treatments resulted in fresh root yields of 23270.8 kg ha<sup>-1</sup> and 21347.8 kg ha<sup>-1</sup> while the worst were 1082 and 926.4 kg ha<sup>-1</sup> at Kabangwe and Kaoma respectively. The best yields obtained in the current study doubled the regional yield average of 8000 kg ha<sup>-1</sup> and quadrupled the Zambian average yield of 5000 kg ha<sup>-1</sup>. Yield differences among weeding treatment ranged between 18% and 75%. It can be concluded that weeding on time can significantly increase yields gains on farmers' fields in Kabangwe and Kaoma.

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**Authors Contributions**

JN designed the study, installed the trials, collected data for 3 and 6 months, analysed data developed drafts; NN designed the study, collected yield data at harvest (24 months), analysed data, developed the drafts and is corresponding author; DC shaped the analysis and guided the discussion; KS designed the study and shaped the manuscript; PN designed the study and reviewed the manuscript structure.

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