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Combating viral mosaic disease of cassava in the Lake Zone of Tanzania by intercropping with legumes

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ABSTRACT

Cassava (*Manihot esculenta Crantz*) production is constrained by many factors, including the viral cassava mosaic disease (CMD). This study was conducted to explore the potential of intercropping cassava with legumes to reduce CMD effects on cassava production. Local (Lyongo Kwimba) and improved (Suma) cassava varieties were intercropped with three types of grain legumes (groundnut, *Arachis hypogea* L. var. Upendo; cowpea, *Vigna unguiculata* (L.) Walp. var. Vuli; and green gram, *Vigna radiata* (L.) R. Wilczek var. Imara). Monocrops of cassava with and without NPK fertilizer were included as controls. The experiment was established using a randomized complete block design with four replications in a split-plot arrangement for three seasons. Cassava varieties intercropped with cowpeas, green gram, and groundnuts and cassava monocrops with and without NPK fertilizer constituted the main plot and sub-plots, respectively. Whitefly population counts and CMD severity and incidence were measured at regular intervals. Cropping system had a significant effect ($P < 0.05$) on whitefly populations and CMD severity. Small whitefly populations (0–7.5 individuals per leaf) and low CMD severity (1–2.4 on a 5-point scale) were recorded in improved and local cassava varieties intercropped with green gram. The local cassava variety intercropped with green gram showed low CMD incidences (0%–40%) in all seasons. Generally, growing cassava with green gram proved effective in reducing whitefly populations and CMD incidence and severity. Intercropping cassava with grain legumes may improve cassava production and food security in CMD-prone areas of the Lake Zone of Tanzania and areas with similar environments.

1. Introduction

In most of the producing regions of the tropics, cassava (*Manihot esculenta Crantz*) plants are infested by a number of yield-reducing agents and pests (Moses et al., 2005; Msikita et al., 2000; Legg and Raya, 1998; Legg et al., 2015), which may lead to marginal or no yields if not controlled. In Tanzania, the prevalent cassava diseases are cassava mosaic disease (CMD), cassava brown streak disease (CBSD), and cassava bacterial blight (CBB) (Msikita et al., 2000). Important pests include whitefly (*Bemisia tabaci*), cassava green mites (CGM), cassava mealy bug (CMB), variegated grasshoppers, and termites (Legg and Raya., 1998; Legg et al., 2015).

Incidence of CMD – caused by *Cassava mosaic virus*-CMV has been reported in all major cassava-growing regions of Africa where it causes a dramatic decline in cassava production (Fondong et al., 2000). In the late 1980s, a mutant of CMV appeared in Uganda, resulting in the East African CMV-Uganda Variant (EACMV-UG), an even more virulent variant that causes complete leaf loss (Olsen et al., 1999). This mutant, which presents a significant threat to cassava cultivation in Africa, has been reported to spread readily at a rate of 50 miles per year from north-central Uganda into Tanzania (Fondong et al., 2000; Sserubombwe et al., 2001). Gibson et al. (1996) reported that infection by a combination of EACMV-UG and African cassava mosaic virus (ACMV) could lead to severe disease symptoms, crop decline, and often complete loss of harvestable roots. Generally, losses from CMD in Africa have been estimated to be 12–23 million tons of harvestable roots annually, equivalent to US$ 1.2–2.3 million (Thresh et al., 1997). In north-

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western regions of Tanzania, the incidence of the disease has increased dramatically, causing severe food shortages, and necessitating emergency food relief. Efficient management of cassava diseases is therefore a critical factor for optimizing yield of this important food crop and ensuring food security in the region.

In the Lake Zone of Tanzania, CMD is a prevalent cassava disease (Kulembeka et al., 1998; Mahungu et al., 1999) due to the abundance of the natural vector and favourable farmers practices. The virus is transmitted either by the tropical whitefly (*B. tabaci*) or by transplanting diseased plants into new fields (Fondong et al., 2000; Sserubombwe et al., 2001; Legg et al., 2015). Its symptoms manifest as chlorotic mosaic of leaves, leaf distortion and stunted growth leading to limited root growth and devastating crop losses (Claude and Denis, 1990). When CMV infects young cassava plants, yields are reduced by up to 80% in the first season and 100% in the following season (Gibson et al., 1996; Sserubombwe et al., 2001; Thresh and Cooter, 2005).

Cassava diseases in the Lake Zone have been managed using various practices (Msikita et al., 2000; Legg and Raya, 1998). The most effective control method for CMD, and indeed most cassava diseases, is using improved, resistant cassava varieties such as Mkombozi, Suma, Meremeta and TMS 4(2)1425. Some local varieties have shown resistance to these diseases. For example, the varieties Kiroba and Kibangameno introduced from the Tanzanian coast are either resistant to CBSD (i.e., they remain uninfected) or develop only very mild symptoms that do not significantly affect yields (Sserubombwe et al., 2001). Also, there is an on-going effort in the Lake Zone to screen and evaluate varieties from the International Institute of Tropical Agriculture (IITA) against CMD, CBSD, and CBB, and the results obtained to date are encouraging (Jeremiah, S.C. personal communication, 2010). Where CMD spreads slowly, the disease can be controlled by removing diseased plants shortly after sprouting (roguing), selecting disease-free stems as planting materials, and isolating new cassava plantations from older diseased plants.

Most farmers in the Lake Zone grow local varieties of cassava, although improved and high-yielding varieties are available. Farmers prefer the local varieties because they have prolonged underground storage capacity and thus increase food security for households. These local varieties are susceptible to CMD (Kapinga et al., 2005) spread by the tropical whitefly (*B. tabaci* Gennadius), which feeds on cassava leaf sap (Fondong et al., 2000; Sserubombwe et al., 2001). Sserubombwe et al. (2001) and Spittel and Van Huis (2000) showed that when cassava is intercropped or rotated with some legumes, fewer whiteflies attack individual crops, thus reducing disease incidence. Furthermore, some results have shown that CMD levels were significantly reduced by the application of green manure (Spittel and Van Huis, 2000). It is conceivable that the reduction in whitefly numbers and consequent reduction in CMD infection when cassava is intercropped with legumes will depend on the type of legume in the intercrop. Therefore, it is necessary to investigate which system of intercropping or rotation is most effective in reducing whitefly numbers and CMD infection. The main objective of this study was to assess the effect of different legume intercrops in reducing CMD infection of cassava crops cultivated in the Lake Zone of Tanzania.

2. Materials and methods

2.1. Experimental site

This study was conducted at the Ukiriguru Agricultural Research Institute, Misungwi District, Mwanza, in the Lake zone of Tanzania (2°42′S, 33°01′E, 1198 m a.s.l.) The site is characterized by transitional, bimodal rainfall pattern with short and long rainy seasons (Ley et al., 2002). The mean annual rainfall (averaged over 1980–2006) is about 846 mm (ranging from 490 to 1378 mm per annum). The short rainy season starts in mid-November and ends in early January, while the long rainy season is from early February to early May. However, the transition between the short and long periods is not discrete. The mean annual temperature from 1986 to 2005 was 28.1 °C (26–31.7 °C). The site is characterized by well-drained sandy arenosols (FAO, 1990; Ley et al., 2002), a predominant soil type in the Misungwi district that is mildly acidic to neutral (pH 6.2–6.8). Such soils are suitable for cassava production when deficient nutrients are supplied at rates recommended for this crop (Mandal, 1993).

2.2. Experimental design

Experimental plots were ploughed and ridged using a hand hoe, as is the standard practice in the region. The gross plot size was 5 m × 5 m, and net plot size was 3 m × 3 m. Plots were separated by 2-m paths and blocks were separated by 4-m spaces.

Experimental treatments consisted of two erect varieties of cassava: Suma (191/0067), which is resistant to CMV, and Lyongo Kwimba, a local susceptible variety. Each variety was intercropped with each of three grain legumes (groundnut, *Arachis hypogea* L. var. Upendo; cowpea, *Vigna unguiculata* (L.) Walp. var. Vuli; and green gram, *Vigna radiata* (L.) R. Wilczek var. Imara). The 'Suma' variety was recently introduced to the Misungwi the Lake Zone. Suma takes 9 months to mature under the local climatic conditions, while Lyongo Kwimba takes 12 months. The three legumes used in the study mature in roughly 55–65 days and are commonly grown in the Lake Zone.

The experiment used a randomized complete block design with four replications in a split plot arrangement, with cassava varieties as main plots and cropping systems (cassava monocrops or cassava–legume intercrops) as subplots. Negative controls were cassava monocrops grown without fertilizer as practiced locally. In the case of positive controls, cassava monocrops were grown with fertilizer at recommended rates (100, 50, and 100 kg ha^{-1} of N, P, and K, respectively) to provide optimal NPK conditions. Each intercropping treatment and the positive control received a dose of 50 kg ha^{-1} P (as $CaH_4P_2O_8$) immediately after planting and 100 kg ha^{-1} K (as KCl) in two split applications of 50 kg ha^{-1} K each at 1 and 2 months after planting; the legume intercrop was assumed to provide the necessary N in these treatments. The 100 kg N ha^{-1} in the positive control was supplied as urea in two applications. All treatments were maintained in the same plots for three consecutive seasons (2007/08, 2008/09, and 2009/10) to monitor cumulative effects.

Cassava cuttings obtained from virus-free plants (i.e., symptomless plants) were planted in December of each year at a spacing of 1 m (10,000 plants ha^{-1}) in all cropping systems. Legumes were planted in late February of the following year to coincide with the peak whitefly population period and distract whiteflies from the cassava. Cowpea and green gram were spaced at 100 cm × 10 cm (two plants per hill; 200,000 plants ha^{-1}) and groundnut at 100 cm × 20 cm (two plants per hill; 100,000 plants ha^{-1}). Legumes were planted in the same ridges as cassava (within-row intercropping). Three seeds per hill were planted and seedlings were thinned to two plants per hill at 7 days after emergence. During legume planting, precautions were taken to avoid injuring the cassava roots.

2.3. Crop management

Weeding was done at 2, 3, and 5 months after planting using a hand hoe. Thiodan was sprayed on the legumes at flowering to control aphids and red beetles (Acland, 1975; Marandu, 2005).

2.4. Whitefly counts and CMD scoring

Whitefly counts were undertaken 14 weeks after planting (WAP) (first week after legume emergence) and continued up to 24 WAP (after legume harvesting) at 2-week intervals. In each treatment plot, 10 plants were selected diagonally (five on each diagonal) and tagged, and then whiteflies beneath five younger leaves of each selected plant were counted (Gibson et al., 1996). Average values were calculated for each treatment plot. Simultaneously, CMD severity was scored on a scale of 1–5, where: 1 = no symptoms; 2 = up to 25% leaf area chlorotic, mild leaf distortion, and no stunting; 3 = 25%–50% leaf area chlorotic, moderate leaf distortion, no stunting; 4 = 50%–75% leaf area chlorotic, severe leaf distortion, and moderate stunting; and 5 = 75%–100% leaf area distortion, small leaflets, almost no lamina, and severe stunting. The incidence of CMD was calculated as the percentage of diseased plants in each treatment plot (Hahn et al., 1980; Fodong et al., 2002).

2.5. Data analyses

Data were subjected to analysis of variance using GENSTAT 2000 (VSNi, Hemel Hempstead, UK). Means were separated using Duncan's New Multiple Range test.

3. Results

3.1. Effect of rainfall and cropping systems on whitefly populations

Significant differences ($P \leq 0.05$) in whitefly populations in the cropping system × cassava variety interactions were observed mainly at 14, 16 and 18 WAP (Appendices 1–3). The average number of whiteflies per plant ranged from 1 to 27 in the first season (2007/08). The highest numbers were observed at 14 WAP and the lowest at 18 WAP (Figs. 1 and 2). However, the average number of whiteflies per plant in cropping system × cassava variety interactions for the 2008/09 ranged from 1.0 to 27 and 1 to 8, respectively (Appendix 2). As in the first season, the highest numbers were at 14 WAP and the lowest at 18 WAP (Fig. 1). In the third season (2009/10), the average number of whiteflies per plant in cropping system × cassava variety interactions ranged from 0 to 3 (Appendix 3). The highest numbers were at 18 and lowest at 14 WAP (Fig. 3). Population density of whitefly corresponded to the rainfall amounts (Fig. 4), in the first and second seasons i.e., as rainfall increased the whitefly population increased.

3.2. CMD severity and incidence

The mean CMD severity scores for cassava in different treatment groups are presented in Figs. 5–7 and Appendices 4–6. Significant ($P \leq 0.05$) differences were observed only in the second season (2008/2009) in the 14 WAP (Appendix 5). The severity scores in the first season (2007/08) ranged from 1.00 in cassava green gram intercrop, to 3 and above in all the remaining cropping systems (Appendix 4 and Fig. 5). Likewise, in 2008/2009, the severity ranged between 1.00 and >2.68 (Appendix 5) with the highest levels recorded in all cropping systems at 24 WAP (Fig. 6). In 2009/2010, the severity ranged between 1.00 and 3 (Appendix 6), with the highest levels recorded in all the cassava monocrops and cassava groundnut intercrops (Fig. 7). Generally, the severity levels ranged between 1.00 and 3.25, with the lowest levels in the second season (2008/09) and the highest in the first (2007/08) and third season (2009/10). The results also showed the highest severity scores in the local cassava variety monocrop without fertilizer, followed by the monocrop with fertilizer and groundnuts intercrop, with lower levels when cassava was intercropped with cowpeas and green gram.

The incidences of diseased plants over the three cropping seasons are presented in Figs. 8–10 and Appendices 7–9. There were significant ($P \leq 0.05$) differences among treatments in CMD incidence levels in all three seasons (Appendices 7–9). The susceptible local cassava variety showed high CMD incidence levels while no plants of the improved variety were infected. Season one (2007/08)

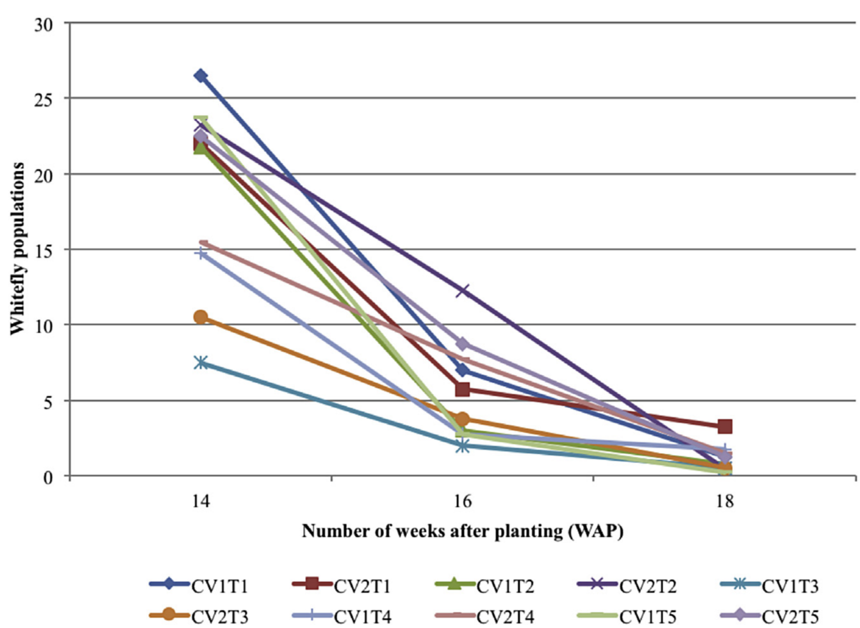

Fig. 1. Effect of cassava variety and cropping system on whitefly populations in 2007/08. Note: In this figure and subsequent figures, WAP = weeks after planting, CV1T1 = Improved Cassava variety + Green gram, CV1T2 = Improved Cassava variety + Groundnuts, CV1T3 = Improved Cassava variety + Cow peas, CV1T4 Improved Cassava variety monocrop + NPK, CV1T5 Improved Cassava variety monocrop − NPK, CV2T1 = Local Cassava variety + Green gram, CV2T2 = Local Cassava variety + Groundnuts, CV2T3 = Local Cassava variety + Cow peas, CV2T4 Local Cassava variety monocrop + NPK and CV2T5 Local Cassava variety monocrop − NPK.

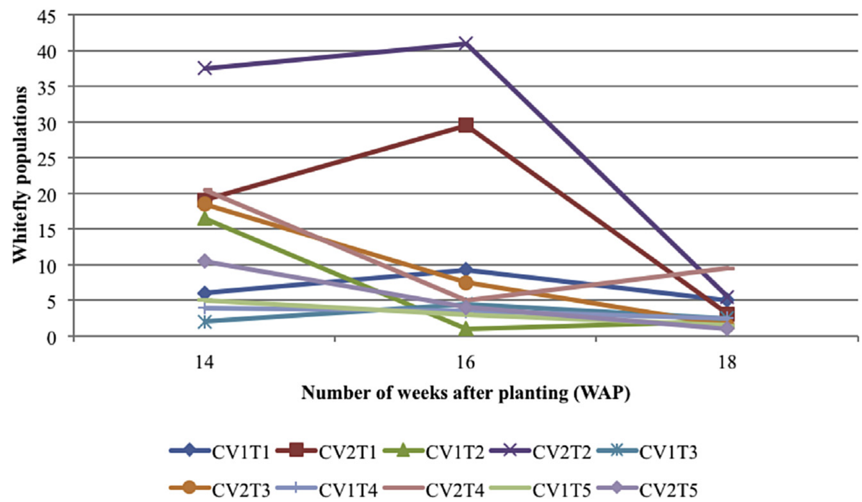

Fig. 2. Effect of cassava variety and cropping system on whitefly populations in 2008/09.

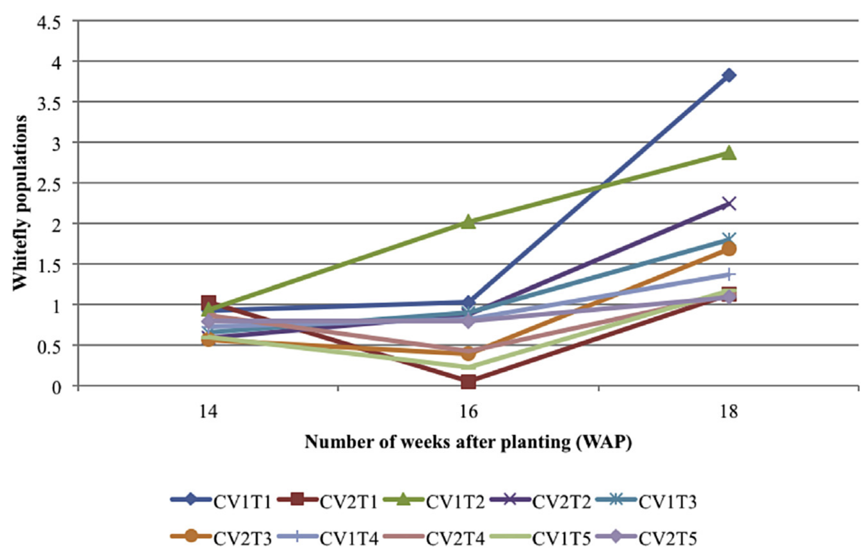

Fig. 3. Effect of cassava variety and cropping system on whitefly populations in 2009/10.

results showed higher incidence levels in the local variety than did other seasons. The highest levels were observed in the local cassava variety intercropped with cowpeas (79%) and in fertilized monocrops (76%), while the lowest levels (40%) were in cassava intercropped with green gram (Fig. 8 and Appendix 7). In the second season (2008/09), the highest levels were in fertilized cassava monocrop (39%) followed by unfertilized monocrops (25%), with lower levels (16%) in the green gram intercrops (Fig. 9 and Appendix 8). The third season (2009/10) showed higher incidences in fertilized cassava monocrops (32%) followed by unfertilized cassava monocrops and cassava–groundnut intercrops (24.5% each) and the lowest in cassava–green gram and cassava–cowpea intercrops (21.5% and 20.0%, respectively) (Fig. 10 and Appendix 9). Generally, higher incidence levels occurred in fertilized local cassava monocrops followed by unfertilized local cassava monocrops, and the lowest were in local cassava–green gram intercrops. The improved (resistant) cassava variety suffered no disease in any cropping season.

4. Discussion

4.1. Effect of rainfall and cropping systems on whitefly populations

The increase in the number of whiteflies with rainfall may be related to rainfall triggering vigorous cassava growth and the emergence of tender new leaves, which consequently provides a good environment for whiteflies that feed on the leaf sap of young leaves. This is in agreement with the observations of Leite et al. (2003), which showed that whitefly populations increased with rainfall. The irregular pattern of whitefly increase in the third season of this study might be due to the irregular rainfall pattern observed in that season. Whitefly populations were generally lower at 18 WAP, indicating that as the cassava leaves mature, whitefly populations decrease. At 18 WAP, most of the existing cassava leaves had matured, and with low/no rainfall, young leaves ceased to form, forcing the whiteflies to look for alternative hosts. An earlier study by Sseruwagi et al. (2003) also showed that whitefly populations decrease as the crop matures.

Generally, in the three seasons of testing the different cropping

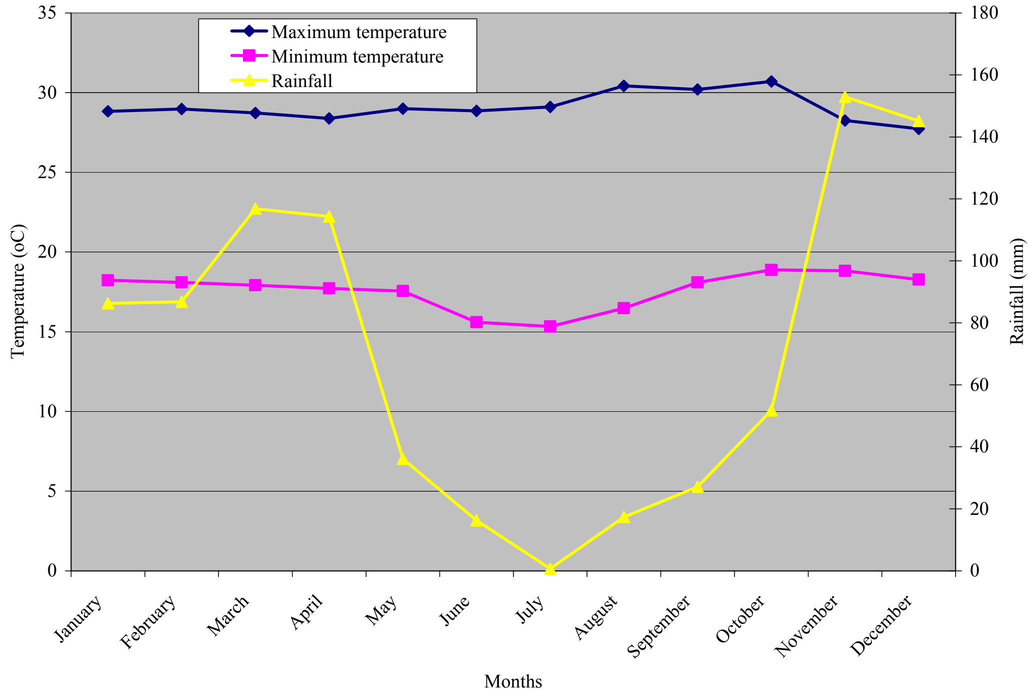

Fig. 4. Average weather pattern during the study period (2007–2010). Source: ARDI Ukiriguru Weather Station.

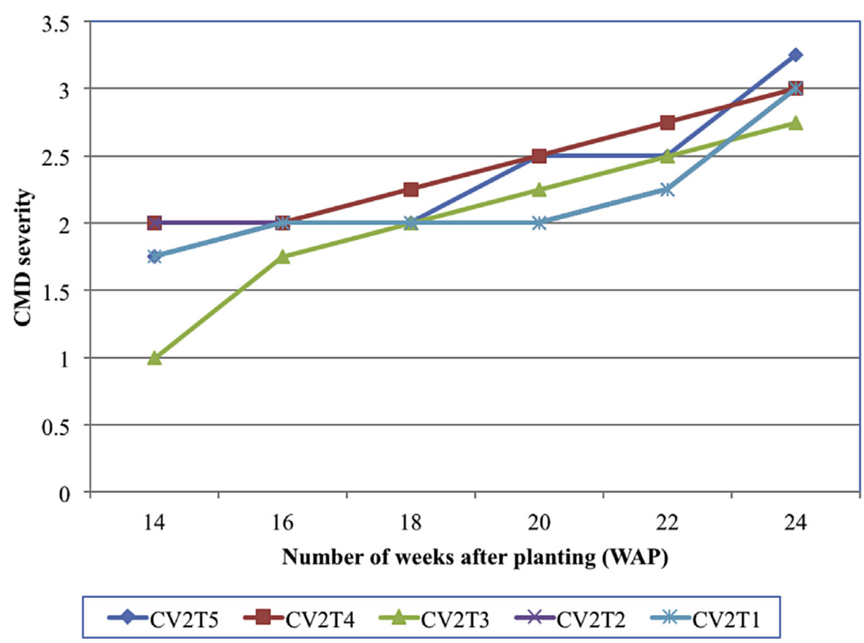

Fig. 5. Effects of cassava variety and cropping system on CMD severity in 2007/08. Note: In this figure and subsequent figures, CV1T1 = Improved Cassava variety + Green gram, CV1T2 = Improved Cassava variety + Groundnuts, CV1T3 = Improved Cassava variety + Cow peas, CV1T4 Improved Cassava variety monocrop + NPK, CV1T5 Improved Cassava variety monocrop − NPK, CV2T1 = Local Cassava variety + Green gram, CV2T2 = Local Cassava variety + Groundnuts, CV2T3 = Local Cassava variety + Cow peas, CV2T4 Local Cassava variety monocrop + NPK and CV2T5 Local Cassava variety monocrop − NPK. In the CMD severity scale, 1–5; where 1 = no symptoms; 2 = up to 25% leaf area chlorotic, mild leaf distortion and no stunting; 3 = 25%–50% leaf area chlorotic, moderate leaf distortion, no stunting; 4 = 50%–75% leaf area chlorotic, severe leaf distortion with moderate stunting; and 5 = 75%–100% leaf area distortion, small leaflets, almost no lamina and severe stunting disease symptoms.

systems, the lowest whitefly populations were observed in cassava–green gram intercrops followed by groundnut intercrops and the highest were in fertilized and unfertilized cassava monocrops. The higher whitefly populations observed in fertilized cassava monocrops might have been attributed to the NPK application. The results conform to the findings by Sseruwagi et al. (2003), who reported significant increases in whiteflies populations due to NPK fertilization. Moreover, Ogbe et al. (1993) suggested using a balanced NPK fertilizer on cassava varieties susceptible to CMD. However, Hilje et al. (2001) reported that the role of N in regulating whitefly populations is equivocal; there is evidence that N fertilization triggers the development of new leaves, which favour

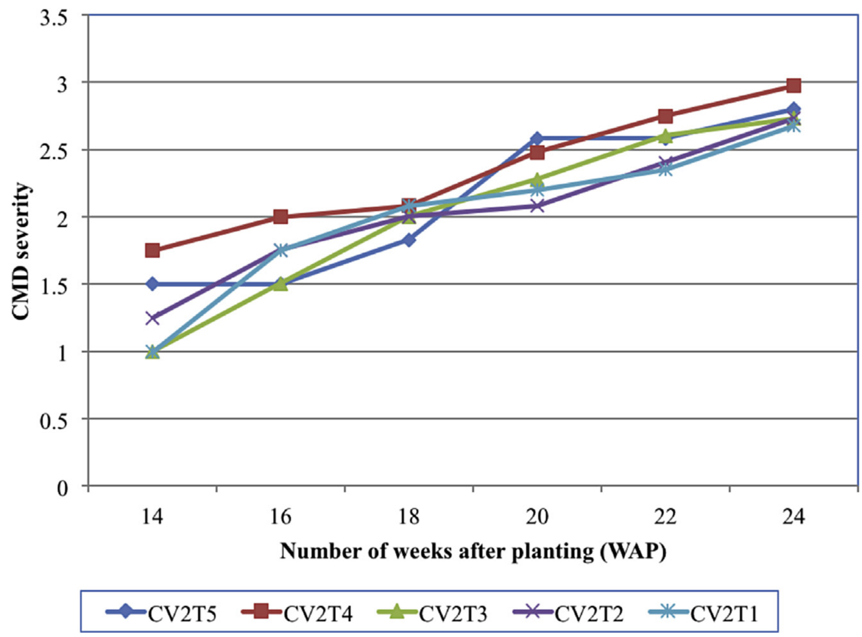

Fig. 6. Effects of cassava variety and cropping system on CMD severity in 2008/09.

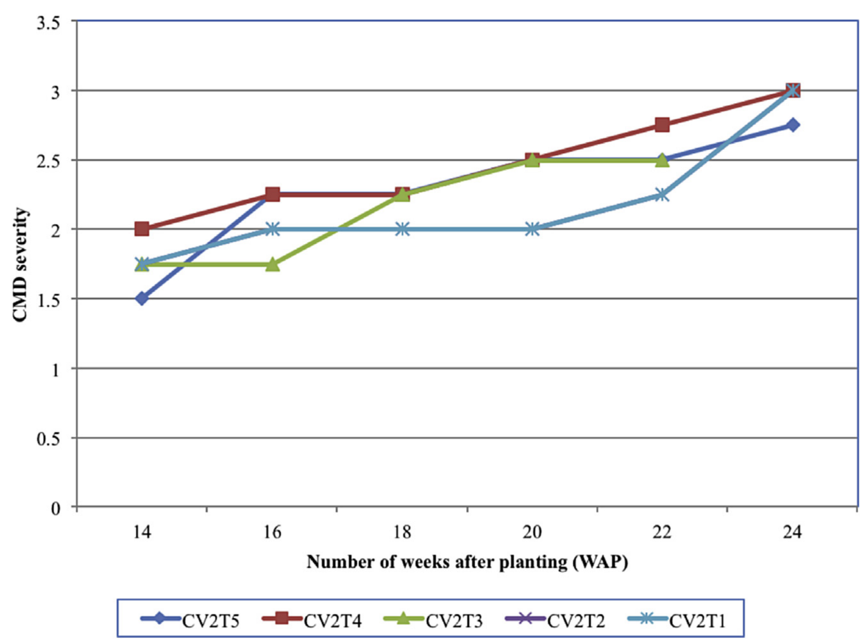

Fig. 7. Effects of cassava variety and cropping system on CMD severity in 2009/10.

whitefly development (Blua et al., 1994; Ellsworth and Carrillo, 2001). To minimize whitefly populations and consequently CMD incidence and severity, farmers have been recommended to supply the N needs of their crop in split applications (Ellsworth and Carrillo, 2001) at of 4–6 WAP (first split) and 14–16 WAP (second split), when tuberization is critical (IITA, 2002).

The relatively low whitefly populations observed on cassava intercropped with legumes when compared with cassava monocrops suggest that the presence of legumes in the intercropped plots triggered unfavourable conditions for whitefly multiplication. Some legumes may be resistant or repellent to some pests/pathogens prevalent in cropped fields, thus keeping their presence low (Burdon, 1978; Ibeawuchi et al., 2007). Generally the trend of whitefly populations in the intercrops was green gram intercrops < groundnuts intercrops < cowpeas intercrops. The observations suggest that intercropping green gram with cassava could reduce the whitefly populations and consequently the diseases associated with viruses that are transmitted by this whitefly vector. This agrees with the observations of Spittel and Van Huis (2000); Sserubombwe et al. (2001) and Ibeawuchi et al. (2007).

4.2. CMD severity and incidence

The higher severity and incidence levels observed in the local

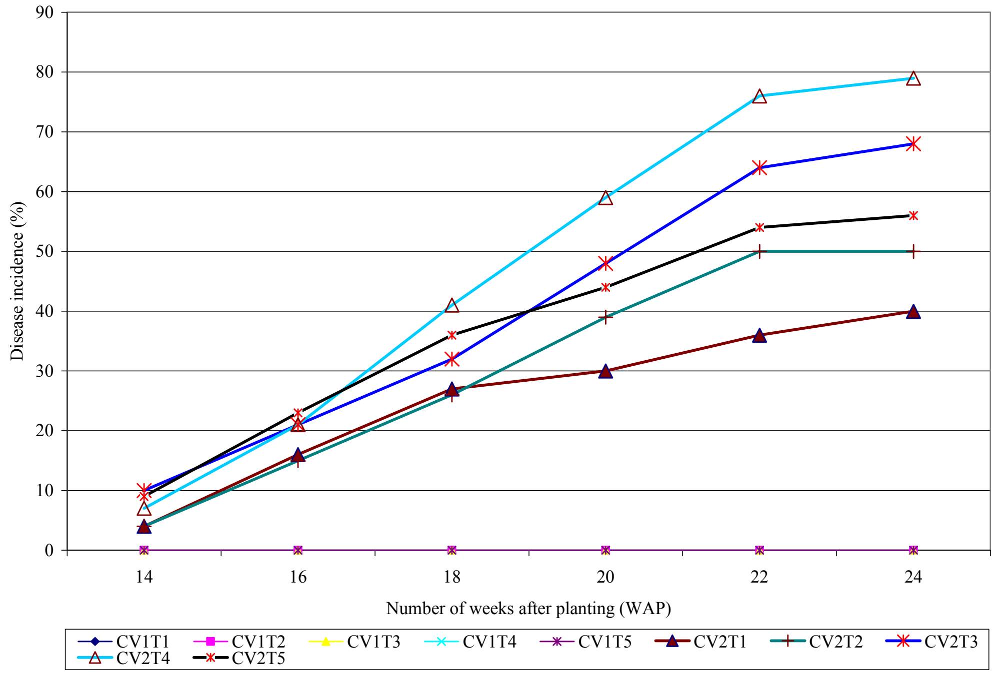

Fig. 8. Effects of cassava variety and cropping system on CMD incidence in 2007/08. Note: In this figure and subsequent figures, CV1T1 = Improved Cassava variety + Green gram, CV1T2 = Improved Cassava variety + Groundnuts, CV1T3 = Improved Cassava variety + Cow peas, CV1T4 Improved Cassava variety monocrop + NPK, CV1T5 Improved Cassava variety monocrop– NPK, CV2T1 = Local Cassava variety + Green gram, CV2T2 = Local Cassava variety + Groundnuts, CV2T3 = Local Cassava variety + Cow peas, CV2T4 Local Cassava variety monocrop + NPK and CV2T5 Local Cassava variety monocrop − NPK.

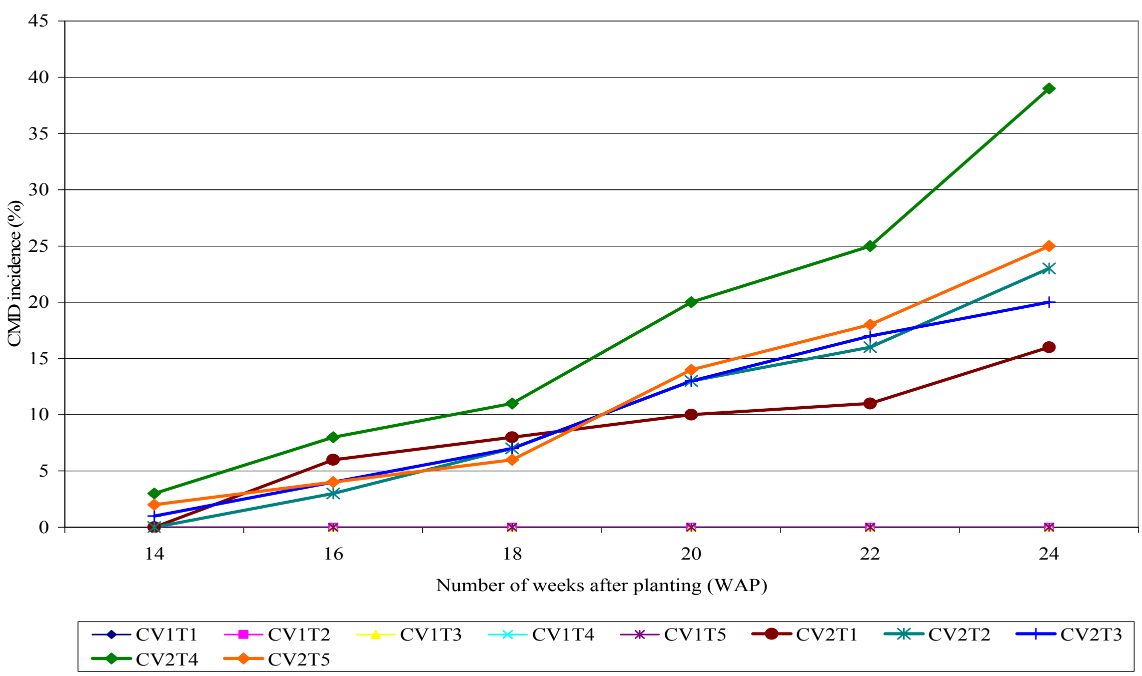

Fig. 9. Effects of cassava variety and cropping system on CMD incidence in 2008/09.

cassava monocrops (fertilized and unfertilized) in this study, might have been attributed to the larger whitefly populations observed in these cropping systems. Conversely, higher severity and incidence levels in the local cassava monocrops might have been caused by the cropping systems. In the monocropping system, cassava was the sole crop, perhaps increasing the chances that the susceptible local variety was attacked by whiteflies migrating from infested fields compared with the same cassava variety intercropped with a second (legume) host.

Furthermore, higher severity and incidence levels in the fertilized local cassava monocrops might have been influenced by NPK fertilization and cropping systems. Mollard (1987) concluded that NPK fertilization increased CMD incidence and severity levels. The vigorous growth induced by NPK fertilization may lead to earlier

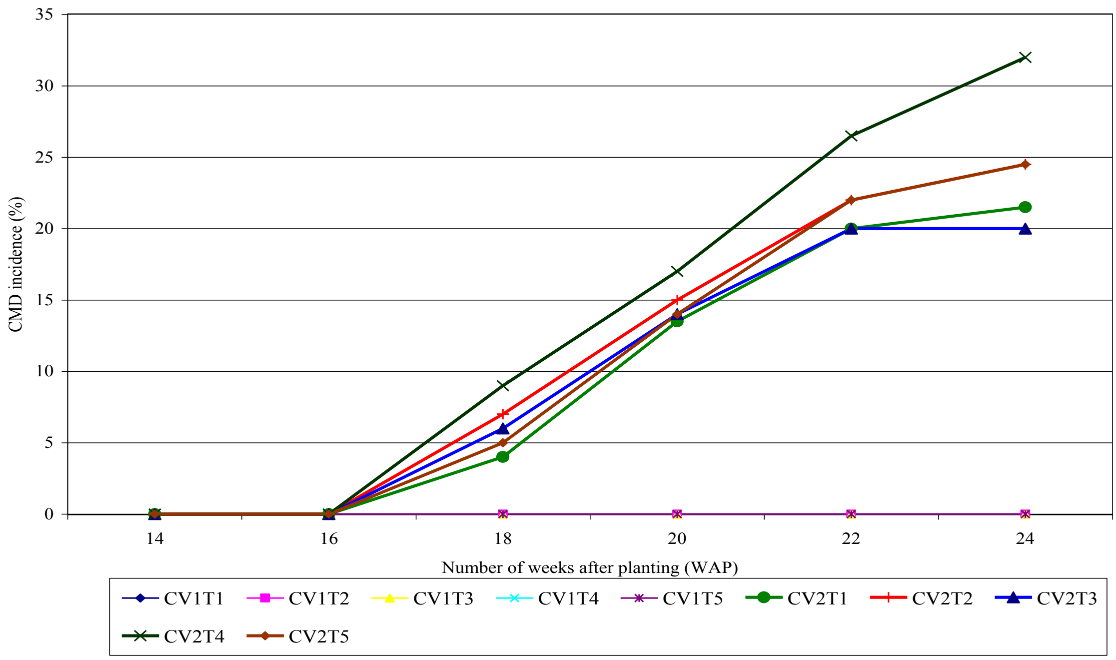

Fig. 10. Effects of cassava variety and cropping system on CMD incidence in 2009/10.

infection and spread of the disease onto susceptible varieties (Sseruwagi et al., 2003). In their recent study, Fermont et al. (2009) found that NPK fertilization resulted in decreased green-mite attack, but increased CMD severity and incidence in CMD-susceptible varieties. However, the influence of NPK fertilizer on CMD severity and incidence is uncertain; Sseruwagi et al. (2003) suggested that a lack of NPK positively influences the CMD severity and incidence levels because of the vigorous growth caused by the fertilizer. However, the way in which each nutrient affects the spread and expression of the disease is unknown (Mollard, 1987; Sseruwagi et al., 2003). The high incidences observed in fertilized cassava monocrops suggest that NPK may affect CMD incidence only. Conversely, the high severity levels observed in unfertilized cassava monocrops in the 2009/10 conform to the results of Otim-Nape (1987), who reported higher CMD incidence levels in cassava monocrops located in areas with low soil fertility in Uganda. Therefore, cropping system might be the main cause of the higher CMD severity and incidence levels observed in the local variety in this study. However, more research to verify the influence of NPK fertilizer on CMD is a priority, and future studies should explore the roles of individual nutrients, i.e., nitrogen, phosphorus, potassium, and/or their combinations.

The low CMD severity and incidence levels observed in the green gram and groundnut intercrops in cropping system × cassava variety interactions might have been caused by the relatively low whitefly populations observed in these cropping systems. Sserubombwe et al. (2001) and Spittel and Van Huis (2000) suggested that when cassava was intercropped with some legumes, whitefly numbers attacking an individual crop were often reduced, hence lowering disease incidences. The ability of a legume to reduce whitefly populations depends on the type and genetic makeup of the legume (Spittel and Van Huis, 2000). There is evidence that whiteflies prefer to eat common beans (*Phaseolus vulgaris*) and cowpeas, and their fecundity increased significantly when feeding on these legumes (Bethke et al., 2006). Therefore, the decrease in CMD severity and incidence in cassava–legume intercropping observed during the study period might have been caused by the presence of two hosts rather than one. Although a few whiteflies were observed feeding on the legumes, no resulting disease occurred in the legumes. Mau and Kessing (2007) found that whiteflies had the least preference for green gram and failed to complete their life cycle when this was the only host available. This observation might explain the lower CMD severity and incidence levels observed in cassava–green gram intercrops in cropping system × cassava variety interactions. Fodong et al. (2002) suggested that the changes in the microclimate under cassava intercrops may have an influence on the vector, movement, vector behaviour and the efficiency with which virus is being transmitted leading into lower disease incidences. Similar results of disease reduction in intercrops have been reported by Fauquet and Fargette (1990) when cassava was intercropped with maize. However, more studies are needed on the effects of green gram and groundnuts on whitefly abundance. Based on the observations in this study, cassava should be intercropped first with green gram to improve cassava yield, while intercropping with groundnut or cowpea may be adopted as second and third priorities, respectively.

4.3. Summary and conclusions

The aim of this study was to explore the effectiveness of different intercropping systems in reducing the size of the whitefly population and the incidence and severity of CMD in cassava crops. We drew two main conclusions from our results.

(i) Cassava–legume intercropping significantly ($P \leq 0.05$) reduced whitefly population size and CMD severity and incidence. Overall, the cassava–green gram intercrop was most effective, followed by the cassava–cowpea intercrop, and then the cassava–groundnut intercrop. The improved cassava variety had relatively high whitefly populations, although this variety was resistant to CMD. The local variety had comparatively low whitefly populations, but was susceptible to CMD.

(ii) Rainfall was related to whitefly population size but temperature was not. The size of whitefly populations increased with higher rainfall. Whitefly population size varied irregularly during the season, with low levels at 18 WAP and higher levels at 14 and 16 WAP. Conversely, CMD severity and incidence increased over the season, because it took time for the symptoms to become visible after the initial infection.

4.4. Recommendations

Based on the results of this study, we propose three recommendations to improve the management of whitefly and CMD in cassava crops:

(i) Intercropping cassava with grain legumes, especially those shown to reduce whitefly populations, is strongly recommended. Intercropping will increase the household food security of small-scale farmers by increasing cassava yields through reduced CMD incidence and severity and extra gains from legume yields.

(ii) The best system to reduce whitefly populations is cassava–green gram intercropping, followed by cassava–cowpea intercropping.

(iii) Farmers should be encouraged to grow improved cassava varieties that are resistant to CMV.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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Appendices

Appendix 1. Effects of cropping system and cassava variety on whitefly populations (season one, 2007/2008)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	26.50a	7.00ab	1.25b	1.75a	0.00a	0.00a
	Local	22.00ab	5.75ab	3.25a	1.25a	0.25a	0.50a
Cassava monocrop + NPK	Improved	21.75ab	3.00b	0.75b	1.00a	0.00a	0.00a
	Local	23.25ab	12.25a	0.50b	1.25a	0.00a	0.25a
Cassava + Green gram	Improved	7.50c	2.00b	0.50b	2.00a	0.00a	0.00a
	Local	10.50bc	3.75b	0.50b	0.75a	0.00a	0.25a
Cassava + Groundnut	Improved	14.75abc	2.75b	1.75ab	1.00a	0.00a	0.00a
	Local	15.50abc	7.75ab	1.50ab	2.25a	0.75a	0.25a
Cassava + Cow pea	Improved	23.75a	2.75b	0.25b	1.25a	0.00a	0.00a
	Local	22.50ab	8.75ab	1.25b	2.00a	0.75a	0.25a
F test		***	*	*	Ns	Ns	Ns
Cv (%)		33.85	89.82	103.35	73.82	363.28	235.70

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting.

Appendix 2. Effects of cropping system and cassava variety on whitefly populations (season two, 2008/2009)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	6.0b	9.3b	5.0ab	2.0a	7.5a	5.0a
	Local	19.0ab	29.5a	3.0ab	0.5a	6.5ab	7.0a
Cassava monocrop + NPK	Improved	16.5ab	1.0b	2.0b	0.0a	2.0abc	6.0a
	Local	37.5a	41.0a	5.5ab	0.5a	0.0c	2.5a
Cassava + Green gram	Improved	2.0b	4.5b	2.5b	0.5a	3.5abc	2.5a
	Local	18.5ab	7.5b	1.5b	1.5a	3.0bc	1.5a
Cassava + Groundnuts	Improved	4.0b	3.5b	2.5b	1.0a	1.5abc	5.0a
	Local	20.5ab	5.0b	9.5a	1.5a	5.5abc	6.0a
Cassava + Cow peas	Improved	5.0b	3.0b	1.5b	0.0a	2.5abc	4.5a
	Local	10.5a	4.0b	1.0b	0.0a	1.0bc	3.0a
F test		*	**	*	Ns	*	Ns
Cv (%)		108.90	104.01	124.03	210.82	112.98	103.61

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting.

Appendix 3. Effects of cropping system and cassava variety on whitefly populations (season three, 2009/2010)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	0.93a	1.03b	3.83a	4.05a	0.33a	0.00
	Local	1.03a	0.05b	1.13b	2.85ab	0.45a	0.00
Cassava monocrop + NPK	Improved	0.95a	2.03a	2.88ab	2.53ab	0.28a	0.00
	Local	0.60a	0.88b	2.25ab	1.75b	0.53a	0.00
Cassava + Green gram	Improved	0.65a	0.90b	1.80b	2.45ab	0.00a	0.00
	Local	0.57a	0.40b	1.69b	1.68b	0.08a	0.00
Cassava + Groundnuts	Improved	0.73a	0.83b	1.38b	2.63ab	0.05a	0.00
	Local	0.87a	0.43b	1.13b	1.48b	0.04a	0.00
Cassava + Cow peas	Improved	0.60a	0.23b	1.18b	2.25ab	0.08a	0.00
	Local	0.80a	0.80b	1.10b	1.80b	0.08a	0.00
F test		Ns	*	*	*	Ns	N/A
Cv (%)		48.76	85.76	61.05	44.14	181.85	N/A

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting.

Appendix 4. Effects of cropping system on cassava mosaic disease severity (season one, 2007/08)

Cropping systems	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	1.75a	2.00a	2.00a	2.50a	2.50a	3.25a
Cassava monocrop + NPK	2.00a	2.00a	2.25a	2.50a	2.75a	3.00a
Cassava + Green gram	1.00a	1.75a	2.00a	2.25a	2.50a	2.75a
Cassava + Groundnuts	2.00a	2.00a	2.00a	2.00a	2.25a	3.00a
Cassava + Cow peas	1.75a	2.00a	2.00a	2.00a	2.25a	3.00a
F test	Ns	Ns	Ns	Ns	Ns	Ns
Cv (%)	23.00	15.14	19.44	13.66	27.05	27.00

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. CMD severity scale of 1 = no symptoms; 2 = up to 25% leaf area chlorotic, mild leaf distortion and no stunting; 3 = 25%–50% leaf area chlorotic, moderate leaf distortion, no stunting; 4 = 50%–75% leaf area chlorotic, severe leaf distortion with moderate stunting; and 5 = 75%–100% leaf area distortion, small leaflets, almost no lamina and severe stunting disease symptoms. WAP = weeks after planting.

Appendix 5. Effects of cropping system on cassava mosaic disease severity (season two, 2008/2009)

Cropping systems	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	1.50ab	1.50a	1.83a	2.58a	2.58a	2.80a
Cassava monocrop + NPK	1.75a	2.00a	2.08a	2.48a	2.75a	2.975a
Cassava + Green gram	1.00b	1.500a	2.00a	2.28a	2.60a	2.73a
Cassava + Groundnuts	1.25ab	1.75a	2.00a	2.08a	2.40a	2.73a
Cassava + Cow peas	1.00b	1.75a	2.08a	2.20a	2.35a	2.68a
F test	*	Ns	Ns	Ns	Ns	Ns
Cv (%)	33.6	28.92	13.05	11.55	14.03	9.86

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. CMD severity scale of 1 = no symptoms; 2 = up to 25% leaf area chlorotic, mild leaf distortion and no stunting; 3 = 25%–50% leaf area chlorotic, moderate leaf distortion, no stunting; 4 = 50%–75% leaf area chlorotic, severe leaf distortion with moderate stunting; and 5 = 75%–100% leaf area distortion, small leaflets, almost no lamina and severe stunting disease symptoms. WAP = weeks after planting.

Appendix 6. Effects of cropping system on cassava mosaic disease severity (season three, 2009/2010)

Cropping systems	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	1.75a	2.25a	2.25a	2.50a	2.50a	3.00a
Cassava monocrop + NPK	2.00a	2.25a	2.25a	2.5a	2.75a	3.00a
Cassava + Green gram	1.50a	1.75a	2.25a	2.50a	2.50a	2.75a
Cassava + Groundnuts	1.75a	2.00a	2.00a	2.00a	2.25a	3.00a
Cassava + Cow peas	1.75a	2.00a	2.00a	2.00a	2.25a	2.75a
F test	Ns	Ns	Ns	Ns	Ns	Ns
Cv (%)	27.11	16.06	12.77	17.75	13.66	26.17

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. CMD severity scale of 1 = no symptoms; 2 = up to 25% leaf area chlorotic, mild leaf distortion and no stunting; 3 = 25%–50% leaf area chlorotic, moderate leaf distortion, no stunting; 4 = 50%–75% leaf area chlorotic, severe leaf distortion with moderate stunting; and 5 = 75%–100% leaf area distortion, small leaflets, almost no lamina and severe stunting disease symptoms. WAP, weeks after planting.

Appendix 7. Effects of cropping system and cassava variety on cassava mosaic disease incidence (%) (season one, 2007/2008)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	0.0c	0.0b	0.0b	0.0c	0.0d	0.0d
	Local	9.0ab	23.0a	36.0a	44.0ab	54.0bc	56.0bc
Cassava monocrop + NPK	Improved	0.0c	0.0b	0.0b	0.0c	0.0d	0.0d
	Local	10.0a	21.0a	30.0a	48.0ab	64.0ab	76.0a
Cassava + Green gram	Improved	0.0c	0.0b	0.0b	0.0c	0.0d	0.0d
	Local	4.0bc	16.0a	27.0a	30.0b	36.0c	40.0c
Cassava + Groundnuts	Improved	0.0c	0.0b	0.0b	0.0c	0.0d	0.0d
	Local	4.0bc	15.0a	26.0a	39.0b	49.0bc	50.0bc
Cassava + Cow peas	Improved	0.0c	0.0b	0.0b	0.0c	0.0d	0.0d
	Local	7.0ab	21.0a	41.0a	59.0a	68.0a	79.0a
F test		*	*	*	*	**	**
Cv (%)		103.85	83.42	64.2	52.50	46.90	44.26

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting.

Appendix 8. Effects of cropping system and cassava variety on cassava mosaic disease incidence (%) (season two, 2008/2009)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	0.0c	0.0c	0.0c	0.0c	0.0c	0.0e
	Local	2.0ab	4.0abc	6.0b	14.0b	18.0b	25.0b
Cassava monocrop + NPK	Improved	0.0c	0.0c	0.0c	0.0c	0.0c	0.0e
	Local	3.0a	8.0a	11.0a	20.0a	25.0a	39.0a
Cassava + Green gram	Improved	0.0c	0.0c	0.0c	0.0c	0.0c	0.0e
	Local	0.0c	6.0ab	8.0ab	10.0b	11.0c	16.0d
Cassava + Groundnut	Improved	0.0c	0.0c	0.0c	0.0c	0.0c	0.0e
	Local	0.0c	3.0bc	7.0b	13.0b	16.0b	23.0bc
Cassava + Cow peas	Improved	0.0c	0.0c	0.0c	0.0c	0.0c	0.0e
	Local	1.0bc	4.0abc	7.0b	13.0b	17.0b	20.0c
F test		**	**	**	**	**	***
Cv (%)		206.38	129.00	73.42	50.71	42.28	10.20

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting.

Appendix 9. Effects of cropping system and cassava variety on cassava mosaic disease incidence (%) (season three, 2009/2010)

Cropping systems	Cassava variety	14 WAP	16 WAP	18 WAP	20 WAP	22 WAP	24 WAP
Cassava monocrop without NPK fertilizer	Improved	0.00	0.00	0.00b	0.00b	0.00b	0.00c
	Local	0.00	0.00	5.00ab	14.00a	22.00a	24.50b
Cassava monocrop + NPK	Improved	0.00	0.00	0.00b	0.00b	0.00b	0.00c
	Local	0.00	0.00	9.00a	17.00a	26.50a	32.00a
Cassava + Green gram	Improved	0.00	0.00	0.00b	0.00b	0.00b	0.00c
	Local	0.00	0.00	4.00ab	13.50a	20.00a	21.50b
Cassava + Groundnuts	Improved	0.00	0.00	0.00b	0.00b	0.00b	0.00c
	Local	0.00	0.00	7.00a	15.00a	22.00a	24.50b
Cassava + Cow peas	Improved	0.00	0.00	0.00b	0.00b	0.00b	0.00c
	Local	0.00	0.00	6.00ab	14.00a	20.00a	20.00b
F test		NAS	NAS	*	*	*	*
Cv (%)		NAS	NAS	110.70	68.16	67.52	33.54

Means within a column followed by the same letter are not significantly different ($P \leq 0.05$) according to Duncan's new multiple range test. WAP, weeks after planting; NAS, not analysed statistically.

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