

# Estimation of Cassava Crop Loss as Influenced by Grasshoppers (*Zonocerus variegatus* L) Infestation under Protected and Unprotected Field Conditions

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## Abstract

An experiment was conducted at three sites (Serabu, Gbassia and Foya) in Sierra Leone during the 2020/2021 and 2021/2022 cropping seasons to assess the cassava crop loss as influenced by grasshopper incidence and severity damage in the upland of Sierra Leone. The experiment utilized three cassava genotypes (Cocoa, SLICASS 4 and SLICASS 6) and two crop pest management practices (protected and unprotected) laid out in a Randomized Complete Block Design (RCBD) with three replications. Findings revealed significant ( $p < 0.05$ ) treatment  $\times$  location  $\times$  year interactions for fresh storage root yield (FSRY) loss, storage root number (SRN) loss and root dry matter content (RDMC) loss. Variety cocoa had the highest percent fresh storage yield loss (20.0%), number of storage roots per plant loss (42.9%) and root dry matter content loss (17.4%), whereas SLICASS 4 had the lowest of 13.3%, 37.7% and 9.5%, respectively. These findings are useful for determination of cassava crop loss using genotypes from diverse genetic backgrounds and cultivation technologies for identification of genotypes with minimal crop loss potential, selection and production of elite cassava genotype with desired end user traits.

## Keywords

Cassava, Genotypic Variability, *Zonocerus variegatus*, Crop Loss, Management

## 1. Introduction

Cassava (*Manihot esculenta* Crantz) is an important staple food crop consumed by over 800 million people worldwide [1]. The crop is grouped with rice, maize and wheat as among the most important food crops in developing countries [2] [3]. The crop's edible tuberous roots feed over 1 billion people in 105 countries [4]. About 40 countries in Sub-Saharan Africa (SSA) produce cassava, contributing approximately 61% of global production [5]-[7]. The SSA region has the highest per capita consumption of cassava (estimated at 800 g per person per day), where the crop supplies a majority of the population's energy needs [8].

Smallholder farmers dominate cassava production in SSA [9]. This may be attributable to the cassava's innate tolerance to drought stress [10], ability to sustainably yield in soils with low fertility or nutrient content [11], ease of propagation with little to no external inputs [12] and ability to be harvested flexibly or piecemeal, thereby providing food security insurance in periods of climatic or agricultural instability [13]. The high resilience of cassava to climatic changes limiting the cultivation of other important food crops, could offer SSA options for adaptation strategies [7] [14]. In the context of ongoing climatic changes, cassava has the potential to contribute to attaining food security [15] [16]. For smallholder farmers in tropical regions where its production is limited by the weather and soil factors as well as socio-economic constraints, the crop has a particularly significant role as a food security crop [17].

Cassava has varying food, feed and industrial applications that support many livelihoods around the world. Farmers in the tropics frequently cultivate cassava for subsistence. Cassava fresh root yields have exceeded 70 t·ha<sup>-1</sup> in experiments at the Centro Internacional de Agricultura Tropical (CIAT), whereas commercial production in regions of Colombia reaches 40 t·ha<sup>-1</sup> and the average global yield is 10 to 15 t·ha<sup>-1</sup> [18]. In Sierra Leone, cassava is the most consumed root crop. Cassava fresh storage roots are rich in starch and possess small amounts of calcium (16 mg/100 g), phosphorus (27 mg/100 g), vitamin C (20.6 mg/100 g), minute quantities of protein and other nutrients [19]. Moreover, the leaves of cassava are consumed in the country as vegetables since they contain protein such as lysine, but lack the amino acid methionine and possibly tryptophan [20].

Despite its enormous significance, low productivity of cassava in SSA is due to several factors generally grouped into agronomic or crop management, abiotic and biotic stresses [21]. Of the three factors, biotic constraints constituting of pests and disease infestations, are the most devastating causing significant yield loss or total crop failure [21] [22]. Biotic constraints such as cassava green mite can cause about 15% and 73% yield losses in resistant and susceptible genotypes of cassava, respectively [23]. African variegated grasshopper (*Zonocerus variegatus* L.) is another major pest of many crops in West and Central Africa occupying the extensive forest and savanna areas [24]. This pest accelerates grassland degradation and desertification, and causes a huge loss of foliage posing a serious threat to the production and livelihood of indigenous farmers and herdsmen [25]. Due to the sig-

nificant yield loss caused by the outbreaks of locusts and grasshoppers, the ability to predict and prevent their occurrence and spread has become an urgent requirement to permit farmers to protect their farmland ecologies and maintain the sustainable development of agriculture.

Moreover, cassava suffers a high level of economic damage by pests partly due to a long growing period that may take 8 to 24 months to complete depending on genotype and environmental conditions. Under certain conditions, even vigorous genotypes may lose more than 40% of their foliage but, in certain periods, the plant may tolerate higher levels of defoliation without suffering significant reductions in yield [18]. The pest situation in the growing environment and genotype are important in the relationship between damage by pests and yield reductions in cassava. The implication of the long growing period is that plants are subject to continuous attack from pests that cause different types of damage. The most severe attacks usually occur during the dry season, which limits the ability of plants to recover from damage. Although some pests do attack the crop during the rainy season, the plant usually recovers in this period and grows vigorously [18].

The impact of *Z. variegatus* attack on crops increases with time particularly under increased temperature [24]. The pest causes about 25% - 80% yield loss in eggplants or aubergine in Sierra Leone [24] and an estimated 50% fresh root yield loss in cassava based on preliminary investigation in Sierra Leone by Mansaray *et al.* [26]. However, little information exists on the extent of yield and related attribute loss caused by this pest in new varieties cultivated under protected and unprotected cultivation practices. Such information could be relevant for increased production and productivity of the cassava. Thus, the objective of this study was to determine the cassava crop loss as influenced by grasshopper (*Z. variegatus*) incidence and severity damage in the upland of Sierra Leone.

## 2. Materials and Methods

### 2.1. Experimental Site

The study was conducted in three localities of Sierra Leone: Serabu, in the eastern province of Kenema, Gbassia in the northern province of Bombali, and Foya in the southern province of Moyamba, Sierra Leone during the 2020/2021 and 2021/2022 cropping seasons. Kenema is in the rainforest zone characterized with sandy loamy soil texture rich in organic matter content, while Bombali is in savannah grassland with sandy clay loam soil texture. Foya consists of secondary bush or transition rain forest vegetation with gravelly clay loam soil texture. The Serabu crop site in Kenema is situated at an elevation of 38 m above sea level at 07°51.086'N latitude and 011°16.551'W longitude. The Gbassia crop site in Bombali is located at an elevation of 92 m above sea level at 08°46.037'N and 011°59.088'W. The Foya crop site in Moyamba is located at an elevation of 73 m above sea level at 08°07.135'N and 012°04.610'W. The trial sites experience distinct wet and dry seasons with the rainy season starting during April or May and continuing until October or November. The mean monthly air temperature

ranges from 21°C to 23°C with a narrow range of temperature between day and night during the rainy season.

## 2.2. Planting Material, Layout, Design and Management

The experimental materials used in this study were stem cuttings of three genotypes comprising two improved released genotypes (SLICASS 4 and SLICASS 6) and one local variety, Cocoa. Genotypes SLICASS 4 and SLICASS 6 possess high tolerance to grasshopper attack with a high storage root yield, whereas the local variety Cocoa is susceptible to grasshopper infestation with a low fresh storage root yield. A total of six treatment combinations comprising the three genotypes and two crop pest management practices (protected and unprotected) were used across three locations (Serabu, Gbassia and Foya) and during two cropping seasons (2020/21-2021/22). The trial was laid out in a randomized complete block design with three replicates. Planting was done in May, in both years to coincide with the outbreak period of the *Zonocerus variegatus*. About 40 stem cuttings per genotype each measuring 30 cm long were planted at 1 m × 1 m spatial arrangement in a plot measuring 4 m × 10 m (40 m<sup>2</sup>).

In the protected plots, weeding was done frequently and integrated pest management (IPM) options applied using Neem + Moringa + Chlopyriphos as often as needed, with hand picking of grasshoppers conducted from time to time as part of ensuring that the cassava field was relatively grasshopper free. The neem extract was prepared following standard procedure [<https://infonet-biovision.org/natural-pest-control/plant-extract-neem>]. Accordingly, 500 g neem seeds were ground, and the dust was dissolved in 10 L water and then the mixture left overnight. The *M. oleifera* leaf extract was prepared by pounding 500 g freshly harvested matured moringa leaves in a clean mortar and squeezing out the liquid through a filter paper into a container following the procedure of Ndubuaku *et al.* [27]. The lower matured leaves were used because they possess high concentration of photochemicals [27]. The Moringa extract was then mixed with water in a ratio of 1:30. The insecticide was prepared by dissolving 1 L Chlopyriphos in 200 L water. The three extracts comprising Neem + Moringa + Chlorpyrifos were then mixed and applied to the protected plots using the knapsack sprayer, whereas the unprotected plots had no pest control amendment applied. In the unprotected plots, no weeding was done and no pest management options were applied.

## 2.3. Data Collection

Data on incidence and percentage plant damage were collected on plants in the two middle rows per plot at 6, 9 and 12 months after planting (MAP) [26]. The fresh storage root number and weight was determined from the 20 tagged plants in the middle rows of each plot per replication in both the protected (P) and unprotected (UP) plots in the three agro-ecologies for the 2020/21 and 2021/22 planting seasons. The number of storage roots per plot were counted and recorded. The roots were weighed using hanging scale and the weights (kg) was rec-

orded at harvest 12 months after planting (MAP).

$$\text{Mean root weight per plant} = \frac{\text{Weight of roots harvested}}{\text{Number of plants harvested}} \quad (1)$$

The percentage dry matter of storage roots was determined from the random bulk sample of roots selected from each plot (protected and unprotected plots). The soil on the outer skin was washed off and the peels were be shredded. One hundred grams (100 g) sample of each variety harvested was weighed and dried for 72 h in a forced air-drying oven at 70°C [28]. Dry samples were re-weighed to obtain the dry weights, and the percentage dry matter (PDME) was calculated using the formula:

$$\text{PDME} = \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100 \quad (2)$$

The weights of the marketable and nonmarketable roots from the protected and unprotected plots were collected at harvest (12 MAP) from the middle rows of each plot per planting season and the fresh storage root weight was weighed using electronic scale and the weight converted to t·ha<sup>-1</sup>.

Crop loss assessment was conducted based on the formula below:

$$\% \text{loss} = \frac{\text{Parameter estimate from protected plot} - \text{Unprotected plot}}{\text{Parameter estimate from protected plot}} \times 100 \quad (3)$$

## 2.4. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate to randomized Complete Block Design technique using the PROC GLM procedure of Statistical Analysis System (SAS) computer software program, version 9.4. The Student Newman-Keuls (SNK) test was used to compare treatment means at a 0.05 level of probability.

## 3. Results and Discussion

The effects of treatments and the interactive impacts of treatment, location and year on percent incidence and severity damage of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices are presented in **Table 1** and **Table 2**. Generally, treatments and year significantly ( $p < 0.05$ ) affected percent incidence and severity damage of grasshopper infestation assessed at 6, 9 and 12 MAP. Moreover, there were significant interactions between treatment × year for percent severity damage of grasshopper infestation assessed at 12 MAP (**Table 2**). The unprotected genotypes established across years and locations had higher *Zonocerus variegatus* severity damage and incidence relative to their corresponding protected plots assessed at 6, 9 and 12 MAP sampling regimes (**Table 1** and **Table 2**). These findings indicate that the significant variation in treatments (genotype and cultivation technology) and year for grasshopper attack is partly attributable to the population and severity damage of the infesting *Zonocerus variegatus* grasshopper pest.

**Table 1.** Interactive impacts of treatment, location and year on percent incidence of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location						Treatment Mean
	Foya		Gbassia		Serabu		
	2021	2022	2021	2022	2021	2022	
Percent incidence of grasshopper at 6 MAP							
Cocoa P	3.2 <sup>b</sup>	3.8 <sup>b</sup>	3.2 <sup>b</sup>	3.8 <sup>b</sup>	3.2 <sup>b</sup>	3.8 <sup>b</sup>	3.5 <sup>b</sup>
Cocoa UNP	11.7 <sup>a</sup>	13.3 <sup>a</sup>	11.7 <sup>a</sup>	14.0 <sup>a</sup>	11.7 <sup>a</sup>	12.7 <sup>a</sup>	12.5 <sup>a</sup>
SLICASS 4 P	1.2 <sup>b</sup>	1.7 <sup>b</sup>	1.2 <sup>b</sup>	1.7 <sup>b</sup>	1.2 <sup>b</sup>	2.7 <sup>b</sup>	1.6 <sup>c</sup>
SLICASS 4 UNP	12.8 <sup>a</sup>	14.3 <sup>a</sup>	12.8 <sup>a</sup>	13.7 <sup>a</sup>	12.8 <sup>a</sup>	15.0 <sup>a</sup>	13.6 <sup>a</sup>
SLICASS 6 P	3.3 <sup>b</sup>	3.7 <sup>b</sup>	3.3 <sup>b</sup>	4.0 <sup>b</sup>	3.3 <sup>b</sup>	4.2 <sup>b</sup>	3.6 <sup>b</sup>
SLICASS 6 UNP	12.2 <sup>a</sup>	13.7 <sup>a</sup>	12.2 <sup>a</sup>	12.7 <sup>a</sup>	12.2 <sup>a</sup>	13.0 <sup>a</sup>	12.6 <sup>a</sup>
Percent incidence of grasshopper at 9 MAP							
Cocoa P	2.7 <sup>c</sup>	2.8 <sup>c</sup>	2.7 <sup>c</sup>	3.2 <sup>c</sup>	2.7 <sup>c</sup>	2.7 <sup>c</sup>	2.8 <sup>c</sup>
Cocoa UNP	12.8 <sup>ab</sup>	16.3 <sup>a</sup>	12.8 <sup>ab</sup>	14.3 <sup>a</sup>	12.8 <sup>ab</sup>	14.0 <sup>a</sup>	13.9 <sup>a</sup>
SLICASS 4 P	3.3 <sup>c</sup>	3.8 <sup>c</sup>	3.3 <sup>c</sup>	3.3 <sup>c</sup>	3.3 <sup>c</sup>	3.3 <sup>c</sup>	3.4 <sup>c</sup>
SLICASS 4 UNP	10.5 <sup>b</sup>	12.0 <sup>b</sup>	10.5 <sup>b</sup>	12.5 <sup>b</sup>	10.5 <sup>b</sup>	12.3 <sup>b</sup>	11.4 <sup>b</sup>
SLICASS 6 P	3.7 <sup>c</sup>	3.7 <sup>c</sup>	3.7 <sup>c</sup>	4.0 <sup>c</sup>	3.7 <sup>c</sup>	4.0 <sup>c</sup>	3.8 <sup>c</sup>
SLICASS 6 UNP	9.7 <sup>b</sup>	11.2 <sup>b</sup>	9.7 <sup>b</sup>	10.2 <sup>b</sup>	9.7 <sup>b</sup>	10.7 <sup>b</sup>	10.2 <sup>b</sup>
Percent incidence of grasshopper at 12 MAP							
Cocoa P	3.3 <sup>c</sup>	2.8 <sup>c</sup>	3.3 <sup>c</sup>	3.2 <sup>c</sup>	3.3 <sup>c</sup>	3.0 <sup>c</sup>	3.2 <sup>d</sup>
Cocoa UNP	14.3 <sup>a</sup>	14.5 <sup>a</sup>	14.3 <sup>a</sup>	14.0 <sup>a</sup>	14.3 <sup>a</sup>	16.3 <sup>a</sup>	14.6 <sup>a</sup>
SLICASS 4 P	3.8 <sup>c</sup>	3.7 <sup>c</sup>	3.8 <sup>c</sup>	3.3 <sup>c</sup>	3.8 <sup>c</sup>	4.0 <sup>c</sup>	3.8 <sup>d</sup>
SLICASS 4 UNP	10.2 <sup>b</sup>	11.0 <sup>b</sup>	10.2 <sup>b</sup>	10.8 <sup>b</sup>	10.2 <sup>b</sup>	11.2 <sup>b</sup>	10.6 <sup>b</sup>
SLICASS 6 P	6.2 <sup>c</sup>	6.3 <sup>c</sup>	6.2 <sup>c</sup>	6.3 <sup>c</sup>	6.2 <sup>c</sup>	7.5 <sup>bc</sup>	6.4 <sup>c</sup>
SLICASS 6 UNP	10.8 <sup>b</sup>	11.3 <sup>b</sup>	10.8 <sup>b</sup>	11.2 <sup>b</sup>	10.8 <sup>b</sup>	11.3 <sup>b</sup>	11.1 <sup>b</sup>

P = protected; UNP = unprotected; MAP = months after planting.

**Table 2.** Interactive impacts of treatment, location and year on percent severity damage of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location						Treatment Mean
	Foya		Gbassia		Serabu		
	2021	2022	2021	2022	2021	2022	
Grasshopper severity damage (%) at 6 MAP							
Cocoa P	11.0 <sup>cd</sup>	13.3 <sup>cd</sup>	11.0 <sup>cd</sup>	10.0 <sup>cd</sup>	11.0 <sup>cd</sup>	9.2 <sup>cd</sup>	10.9 <sup>d</sup>
Cocoa UNP	56.7 <sup>a</sup>	58.3 <sup>a</sup>	56.7 <sup>a</sup>	58.7 <sup>a</sup>	56.7 <sup>a</sup>	61.0 <sup>a</sup>	58.0 <sup>a</sup>
SLICASS 4 P	6.7 <sup>d</sup>	10.3 <sup>cd</sup>	6.7 <sup>d</sup>	6.3 <sup>d</sup>	6.7 <sup>d</sup>	6.7 <sup>d</sup>	7.2 <sup>d</sup>
SLICASS 4 UNP	46.8 <sup>b</sup>	60.0 <sup>a</sup>	46.8 <sup>b</sup>	51.7 <sup>a</sup>	46.8 <sup>b</sup>	48.3 <sup>b</sup>	50.1 <sup>b</sup>
SLICASS 6 P	14.7 <sup>c</sup>	12.3 <sup>c</sup>	14.7 <sup>c</sup>	13.5 <sup>c</sup>	14.7 <sup>c</sup>	17.3 <sup>c</sup>	14.5 <sup>c</sup>
SLICASS 6 UNP	44.3 <sup>b</sup>	50.0 <sup>a</sup>	44.3 <sup>b</sup>	51.7 <sup>a</sup>	44.3 <sup>b</sup>	49.3 <sup>b</sup>	47.3 <sup>b</sup>

## Continued

		Grasshopper severity damage (%) at 9 MAP					
Cocoa P	15.0 <sup>c</sup>	23.3 <sup>b</sup>	18.3 <sup>c</sup>	26.7 <sup>b</sup>	18.3 <sup>c</sup>	26.7 <sup>b</sup>	21.4 <sup>bc</sup>
Cocoa UNP	45.0 <sup>a</sup>	43.3 <sup>a</sup>	45.0 <sup>a</sup>	41.7 <sup>a</sup>	45.0 <sup>a</sup>	41.7 <sup>a</sup>	43.6 <sup>a</sup>
SLICASS 4 P	13.3 <sup>c</sup>	18.3 <sup>c</sup>	13.3 <sup>c</sup>	20.0 <sup>bc</sup>	13.3 <sup>c</sup>	20.0 <sup>bc</sup>	16.4 <sup>c</sup>
SLICASS 4 UNP	23.7 <sup>b</sup>	24.3 <sup>b</sup>	23.7 <sup>b</sup>	26.7 <sup>b</sup>	23.7 <sup>b</sup>	25.0 <sup>b</sup>	24.5 <sup>b</sup>
SLICASS 6 P	15.3 <sup>c</sup>	18.3 <sup>c</sup>	15.3 <sup>c</sup>	21.7 <sup>bc</sup>	15.3 <sup>c</sup>	26.7 <sup>b</sup>	18.8 <sup>c</sup>
SLICASS 6 UNP	38.3 <sup>a</sup>	36.7 <sup>a</sup>	38.3 <sup>a</sup>	40.0 <sup>a</sup>	38.3 <sup>a</sup>	40.0 <sup>a</sup>	38.6 <sup>a</sup>
		Grasshopper severity damage (%) at 12 MAP					
Cocoa P	17.8 <sup>d</sup>	20.7 <sup>cd</sup>	17.8 <sup>d</sup>	12.7 <sup>d</sup>	17.8 <sup>d</sup>	19.7 <sup>d</sup>	17.8 <sup>e</sup>
Cocoa UNP	55.0 <sup>a</sup>	60.0 <sup>a</sup>	55.0 <sup>a</sup>	56.7 <sup>a</sup>	55.0 <sup>a</sup>	56.7 <sup>a</sup>	56.4 <sup>a</sup>
SLICASS 4 P	19.3 <sup>d</sup>	19.0 <sup>d</sup>	19.3 <sup>d</sup>	15.3 <sup>d</sup>	19.3 <sup>d</sup>	14.8 <sup>d</sup>	17.9 <sup>e</sup>
SLICASS 4 UNP	26.7 <sup>cd</sup>	38.3 <sup>b</sup>	26.7 <sup>cd</sup>	38.3 <sup>b</sup>	26.7 <sup>cd</sup>	36.7 <sup>b</sup>	32.2 <sup>c</sup>
SLICASS 6 P	22.7 <sup>cd</sup>	18.0 <sup>d</sup>	22.7 <sup>cd</sup>	15.7 <sup>d</sup>	22.7 <sup>cd</sup>	29.7 <sup>c</sup>	21.9 <sup>d</sup>
SLICASS 6 UNP	36.7 <sup>b</sup>	43.3 <sup>b</sup>	36.7 <sup>b</sup>	45.0 <sup>b</sup>	36.7 <sup>b</sup>	41.0 <sup>b</sup>	39.9 <sup>b</sup>

P = protected; UNP = unprotected; T = treatment; L = location; Y = year; MAP = months after planting; CV = coefficient of variation; SNK = Student Newman-Keuls; \* = significant at  $p < 0.05$ ; ns = not significant at  $p < 0.05$ .

The interactive impacts of treatment and location on percent incidence of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices are presented in **Supplementary Table A1**. There were significantly ( $P < 0.05$ ) higher levels of grasshopper infestation in all unprotected plots than the protected plots across locations (**Supplementary Table A1**). Similarly, severity of damage at 6, 9 and 12 MAP was significantly ( $P < 0.05$ ) higher in unprotected plots relative to the protected plots (**Supplementary Table A2**).

The effects of treatments and the interactive impacts of treatment, location and year on fresh storage root yield, number of storage roots per plant and root dry matter content of cassava genotypes under protected and unprotected cultivation practices are presented in **Table 3**. Generally, the protected plots exhibited higher fresh storage root yields, mean storage root number and root dry matter content than the unprotected plots across locations and years. Treatment SLICASS 6 P had the highest mean storage root yield of  $21.1 \text{ t}\cdot\text{ha}^{-1}$  and was among treatments with the highest number of storage roots (6.1 - 6.6) and root dry matter content of 33.2% - 33.6% (**Table 3**). Generally, crop loss was highest in Cocoa for fresh storage root yield, number of storage roots per plant and root dry matter content, whereas SLICASS 4 exhibited the lowest for the measured traits (**Table 3, Supplementary Table A3**).

The interactive impacts of treatment and location on fresh storage root yield, number of storage roots per plant and root dry matter content of cassava genotypes under protected and unprotected cultivation practices are presented in **Supplementary Table A3**. Cassava genotypes established in protected plots exhibited

**Table 3.** Interactive impacts of treatment, location and year on fresh storage root yield ( $\text{t}\cdot\text{ha}^{-1}$ ), number of storage roots per plant and root dry matter content (%) of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location						Treatment Mean	Crop loss (%)
	Foya		Gbassia		Serabu			
	2021	2022	2021	2022	2021	2022		
Fresh storage root yield ( $\text{t}\cdot\text{ha}^{-1}$ )								
Cocoa P	12.7 <sup>c</sup>	13.4 <sup>bc</sup>	13.8 <sup>bc</sup>	12.3 <sup>bc</sup>	13.1 <sup>bc</sup>	9.6 <sup>c</sup>	12.5 <sup>c</sup>	
Cocoa UNP	9.4 <sup>c</sup>	9.9 <sup>c</sup>	11.4 <sup>c</sup>	10.8 <sup>c</sup>	10.2 <sup>c</sup>	8.4 <sup>c</sup>	10.0 <sup>d</sup>	20.00
SLICASS 4 P	16.8 <sup>b</sup>	18.4 <sup>b</sup>	17.3 <sup>b</sup>	15.9 <sup>b</sup>	16.9 <sup>b</sup>	14.6 <sup>bc</sup>	16.6 <sup>b</sup>	
SLICASS 4 UNP	14.8 <sup>bc</sup>	13.1 <sup>bc</sup>	16.0 <sup>b</sup>	10.8 <sup>c</sup>	15.8 <sup>b</sup>	14.4 <sup>bc</sup>	14.2 <sup>c</sup>	13.25
SLICASS 6 P	21.4 <sup>a</sup>	19.7 <sup>a</sup>	22.5 <sup>a</sup>	20.1 <sup>ab</sup>	22.3 <sup>a</sup>	20.7 <sup>ab</sup>	21.1 <sup>a</sup>	
SLICASS 6 UNP	18.2 <sup>ab</sup>	16.7 <sup>b</sup>	20.1 <sup>a</sup>	17.5 <sup>b</sup>	19.4 <sup>ab</sup>	18.0 <sup>ab</sup>	18.3 <sup>b</sup>	13.27
Number of storage roots per plant								
Cocoa P	4.0 <sup>c</sup>	6.0 <sup>ab</sup>	3.9 <sup>c</sup>	5.7 <sup>b</sup>	4.0 <sup>c</sup>	5.5 <sup>bc</sup>	4.9 <sup>b</sup>	
Cocoa UNP	2.8 <sup>cd</sup>	2.3 <sup>d</sup>	3.3 <sup>d</sup>	3.3 <sup>d</sup>	2.8 <sup>cd</sup>	2.0 <sup>d</sup>	2.8 <sup>d</sup>	42.86
SLICASS 4 P	5.6 <sup>b</sup>	5.7 <sup>b</sup>	6.0 <sup>ab</sup>	7.5 <sup>a</sup>	5.6 <sup>b</sup>	6.1 <sup>ab</sup>	6.1 <sup>a</sup>	
SLICASS 4 UNP	4.1 <sup>c</sup>	3.0 <sup>c</sup>	5.7 <sup>b</sup>	2.8 <sup>cd</sup>	4.1 <sup>c</sup>	3.1 <sup>c</sup>	3.8 <sup>c</sup>	37.70
SLICASS 6 P	7.0 <sup>a</sup>	7.1 <sup>a</sup>	6.1 <sup>ab</sup>	5.9 <sup>ab</sup>	7.0 <sup>a</sup>	6.7 <sup>ab</sup>	6.6 <sup>a</sup>	
SLICASS 6 UNP	4.8 <sup>bc</sup>	2.8 <sup>cd</sup>	4.9 <sup>bc</sup>	4.2 <sup>c</sup>	4.8 <sup>bc</sup>	2.7 <sup>cd</sup>	4.0 <sup>c</sup>	39.39
Root dry matter content (%)								
Cocoa P	23.7 <sup>cd</sup>	22.3 <sup>cd</sup>	21.3 <sup>cd</sup>	20.7 <sup>cd</sup>	21.3 <sup>cd</sup>	21.3 <sup>cd</sup>	21.8 <sup>d</sup>	
Cocoa UNP	20.3 <sup>d</sup>	19.3 <sup>d</sup>	16.3 <sup>d</sup>	16.3 <sup>d</sup>	17.3 <sup>d</sup>	18.3 <sup>d</sup>	18.0 <sup>e</sup>	17.43
SLICASS 4 P	34.0 <sup>ab</sup>	33.7 <sup>ab</sup>	31.0 <sup>b</sup>	35.3 <sup>a</sup>	35.0 <sup>a</sup>	32.7 <sup>ab</sup>	33.6 <sup>a</sup>	
SLICASS 4 UNP	29.7 <sup>b</sup>	31.3 <sup>b</sup>	31.0 <sup>b</sup>	31.3 <sup>b</sup>	30.3 <sup>b</sup>	29.0 <sup>b</sup>	30.4 <sup>b</sup>	9.52
SLICASS 6 P	32.0 <sup>ab</sup>	32.3 <sup>ab</sup>	34.3 <sup>ab</sup>	34.7 <sup>a</sup>	33.0 <sup>ab</sup>	32.7 <sup>ab</sup>	33.2 <sup>a</sup>	
SLICASS 6 UNP	28.3 <sup>bc</sup>	28.0 <sup>bc</sup>	28.7 <sup>bc</sup>	28.3 <sup>bc</sup>	28.7 <sup>bc</sup>	28.0 <sup>bc</sup>	28.3 <sup>c</sup>	14.94

P = protected; UNP = unprotected; T = treatment; L = location; Y = year; CV = coefficient of variation; SNK = Student Newman-Keuls; \* = significant at  $p < 0.05$ ; ns = not significant at  $p < 0.05$ .

significantly ( $p < 0.05$ ) higher fresh storage root yield, number of storage roots per plant and root dry matter content than those unprotected plots across locations (**Supplementary Table A3**). Variety cocoa had the highest percent fresh storage yield loss (20.0%), number of storage roots per plant loss (42.9%) and root dry matter content loss (17.4%), whereas SLICASS 4 had the lowest of 13.3%, 37.7% and 9.5%, respectively. These findings indicate that the significant variation in genotypic performances under protected and unprotected cultivation practices is partly attributable to the inherent genetic variability in genotypes, environmental and the attack of *Z. variegatus* grasshopper pest.

The overall superiority of SLICASS 6 P results indicate that the inherent genetic differences in genotype are important in determining the highest average yields in

cassava crop but the substantial variability in the influence of *Z. variegatus* incidence and severity damage on cassava crop loss is also affected by environmental factors associated with site traits and differences between cropping seasons. These factors affect grasshopper attacks on crops that contribute to the reductions in leaf longevity and the photosynthetic rate leading to crop loss. Moreover, the population of the infesting pest, type of damage and duration of grasshopper pest attack also determine the level of reduction in storage root yield and related attribute traits. These findings agree with the view of Cock [29], who reported that, severe yield loss causes relate to reductions in leaf longevity and the photosynthetic rate. Moreover, the pest attacks can reduce yields indirectly through consuming and thus reducing leaf area and the photosynthetic rate; attacking and thus weakening stems and preventing nutrient transport; and attacking planting materials, thus reducing their sprouting rates. The percent root dry matter content loss could probably be attributable to high degree of feeding of grasshoppers on the cassava varieties on the unprotected plots compared to the protected plots. This agrees with the findings of Mansaray *et al.* [26] and Torto *et al.* [30] who opined that cassava plants in unprotected plots are more vulnerable to grasshoppers than those in protected plots and thus account for dry matter differences.

Generally, arthropod pests are more damaging to cassava genotypes during dry seasons than the rains [17]. The cassava plant is well adapted to long dry periods and takes advantage of short rainy seasons by reducing evapotranspiration from leaves by partly closing their stomata, thereby increasing their water-use efficiency [31]. During water stress in the dries, both the rapid defoliation of old leaves and the notable loss of photosynthetic activity enable young leaves to play a key role in acquiring carbon for the plant. Because several pests including grasshoppers prefer young apical leaves, dry seasons tend to cause major yield losses in cassava. During the rainy season or cassava established under irrigation system, new leaves sprout in apical parts, thus increasing the photosynthetic rate. The rainy season or irrigation represents potential for recovery and compensates for yield losses caused by pest attack in the dry season [32]. Similarly, Page *et al.* [33] found that continuous defoliation over six weeks at the end of the dry season accounted for mean crop loss of 63%, and simulated debarking caused a mean loss of 49%. *Z. variegatus* confined in plots until the end of the dry season caused a mean cassava loss of 36%, losses being less than those caused by simulated defoliation because cropping took place sooner after the end of defoliation [33]. Findings indicate that defoliation during the dry season caused no significant crop loss when damage occurred before leaf regeneration at the beginning of the following wet season.

Various mitigating strategies of grasshoppers (*Zonocerus variegatus* L) infestation targeted at cassava crop loss reduction are well reviewed by James *et al.* [34]. Accordingly, some of the techniques include biological or microbial control, cultural control, chemical control and integrated pest management (IPM) control. Microbial natural enemies such as fungi have been discovered that kill the variegated grasshopper. The tiny seed-like fungi spores that are spread and land on the

*Z. variegatus* pest, germinate, and the fungus then penetrates the body of the pest, growing and killing it within a few days. When a diseased grasshopper pest dies, its dead body either remains firmly attached to the cassava plant or drops to the ground. Biopesticides that are obtained through the mixing of fungus spores in oil are also known commercial products against the grasshoppers. These products are also effective in killing newly hatched nymphs which gather in large numbers on the weed such as the Siam weed, *Chromolaena odorata*, nymphs and adults of the grasshopper pest. Removal of Siam weed, *Chromolaena odorata*, is a critical mitigating strategy of controlling the pest. Culturally, the egg pods can be destroyed to reduce the numbers of the pest. The variegated grasshopper pest abundance depends largely on the number of egg pods that survive in the soil during the wet season. Cassava farmers control them by locating and marking egg-laying sites early in the wet season. At a later stage, the egg pods are dug up the soil, exposed and destroyed. This exercise is done before the eggs commence hatching in the early dry season, which occur in October in most of West Africa countries. The planting of resistant genotypes to the pest attack is also critical to reducing yield and related attribute loss in cassava.

A plethora of strategies ranging from monitoring, prevention, cultural, phyto-sanitation, use of insecticides, biological, clean seeds systems and host-plant resistance as well as a combination of two or more of these approaches through integrated pest management (IPM) have been deployed to control grasshoppers. Scaling up IPM utilization and adoption in Sierra Leone contributes to address the challenges of food security, climate change, and environmental degradation, paving the way for sustainable agriculture [35]. Implementation of IPM strategies enables cassava producers to achieve long-term pest control while minimizing long-term negative impacts on the environment and human health thereby balancing productivity with ecological responsibility. Torto *et al.* [30] also opined that the utilization of tolerant cassava variety, protection of cassava field from grasshopper infestation and harvesting cassava in December are among good agronomic practices recommended for selection and increased production and productivity of cassava for processing.

#### 4. Conclusion

This study demonstrates that grasshopper attacks can reduce cassava root yield and related traits. The extent of crop loss varies with the inherent genetic potentials of genotype, with some genotypes being more resistant but cultivation technology and differences between cropping season also have significant effects. Usually, adequate rains permit cassava plants to recover from grasshopper damage with minimal reductions in storage root yield. The population of the infesting pest, type of damage and duration of grasshopper pest attack also determine the level of reduction in storage root yield and related attribute traits. Grasshopper attack of cassava plants over prolonged periods reduces yields more than attack over short periods. The most detrimental form of damage is that which continu-

ally reduces the photosynthetic rate. Regular monitoring or scouting for location, identification and determination of infestation severity or incidence of *Zonocerus variegatus* grasshopper pest in a cassava farm throughout the growing season, is the first step towards effective control. Monitoring allows for timely decisions for efficient implementation of management inputs, tools and strategies. Other benefits derived from monitoring include identification of beneficial insects that help control the pests that are non-beneficial. These findings are useful for determination of cassava crop loss using genotypes from diverse genetic backgrounds and cultivation technologies for identification of genotypes with minimal crop loss potential, selection and production of elite cassava genotype with desired end user traits.

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### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Supplementary Materials

**Supplementary Table A1.** Interactive impacts of treatment and location on percent incidence of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location			Treatment Mean
	Foya	Gbassia	Serabu	
Percent incidence of grasshopper at 6 MAP				
Cocoa P	3.5 <sup>b</sup>	3.5 <sup>b</sup>	3.5 <sup>b</sup>	3.5 <sup>b</sup>
Cocoa UNP	12.5 <sup>a</sup>	12.8 <sup>a</sup>	12.2 <sup>a</sup>	12.5 <sup>a</sup>
SLICASS 4 P	1.4 <sup>b</sup>	1.4 <sup>b</sup>	1.9 <sup>b</sup>	1.6 <sup>c</sup>
SLICASS 4 UNP	13.6 <sup>a</sup>	13.3 <sup>a</sup>	13.9 <sup>a</sup>	13.6 <sup>a</sup>
SLICASS 6 P	3.5 <sup>b</sup>	3.7 <sup>b</sup>	3.8 <sup>b</sup>	3.6 <sup>b</sup>
SLICASS 6 UNP	12.9 <sup>a</sup>	12.4 <sup>a</sup>	12.6 <sup>a</sup>	12.6 <sup>a</sup>
Percent incidence of grasshopper at 9 MAP				
Cocoa P	2.7 <sup>c</sup>	2.9 <sup>c</sup>	2.7 <sup>c</sup>	2.8 <sup>c</sup>
Cocoa UNP	14.6 <sup>a</sup>	13.6 <sup>ab</sup>	13.4 <sup>ab</sup>	13.9 <sup>a</sup>
SLICASS 4 P	3.6 <sup>c</sup>	3.3 <sup>c</sup>	3.3 <sup>c</sup>	3.4 <sup>c</sup>
SLICASS 4 UNP	11.3 <sup>b</sup>	11.5 <sup>b</sup>	11.4 <sup>b</sup>	11.4 <sup>b</sup>
SLICASS 6 P	3.7 <sup>c</sup>	3.9 <sup>c</sup>	3.9 <sup>c</sup>	3.8 <sup>c</sup>
SLICASS 6 UNP	10.4 <sup>b</sup>	9.9 <sup>b</sup>	10.2 <sup>b</sup>	10.2 <sup>b</sup>
Percent incidence of grasshopper at 12 MAP				
Cocoa P	3.1 <sup>d</sup>	3.3 <sup>d</sup>	3.2 <sup>d</sup>	3.2 <sup>d</sup>
Cocoa UNP	14.4 <sup>a</sup>	14.2 <sup>a</sup>	15.3 <sup>a</sup>	14.6 <sup>a</sup>
SLICASS 4 P	3.8 <sup>d</sup>	3.6 <sup>d</sup>	3.9 <sup>d</sup>	3.8 <sup>d</sup>
SLICASS 4 UNP	10.6 <sup>b</sup>	10.5 <sup>b</sup>	10.7 <sup>b</sup>	10.6 <sup>b</sup>
SLICASS 6 P	6.3 <sup>cd</sup>	6.3 <sup>cd</sup>	6.8 <sup>c</sup>	6.4 <sup>c</sup>
SLICASS 6 UNP	11.1 <sup>b</sup>	11.0 <sup>b</sup>	11.1 <sup>b</sup>	11.1 <sup>b</sup>

P = protected; UNP = unprotected; MAP = months after planting.

**Supplementary Table A2.** Interactive impacts of treatment and location on percent severity damage of grasshopper infestation at 6, 9 and 12 months after planting of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location			Treatment Mean
	Foya	Gbassia	Serabu	
Grasshopper severity damage (%) at 6 MAP				
Cocoa P	12.2 <sup>c</sup>	10.5 <sup>c</sup>	10.1 <sup>c</sup>	10.9 <sup>d</sup>
Cocoa UNP	57.5 <sup>a</sup>	57.7 <sup>a</sup>	58.8 <sup>a</sup>	58.0 <sup>a</sup>
SLICASS 4 P	8.5 <sup>cd</sup>	6.5 <sup>d</sup>	6.7 <sup>d</sup>	7.2 <sup>d</sup>
SLICASS 4 UNP	53.4 <sup>a</sup>	49.3 <sup>b</sup>	47.6 <sup>b</sup>	50.1 <sup>b</sup>
SLICASS 6 P	13.5 <sup>c</sup>	14.1 <sup>c</sup>	16.0 <sup>c</sup>	14.5 <sup>c</sup>
SLICASS 6 UNP	47.2 <sup>b</sup>	48.0 <sup>b</sup>	46.8 <sup>b</sup>	47.3 <sup>b</sup>

## Continued

Grasshopper severity damage (%) at 9 MAP				
Cocoa P	19.2 <sup>b</sup>	22.5b	22.5b	21.4 <sup>bc</sup>
Cocoa UNP	44.2 <sup>a</sup>	43.3a	43.3a	43.6 <sup>a</sup>
SLICASS 4 P	15.8 <sup>c</sup>	16.7c	16.7c	16.4 <sup>c</sup>
SLICASS 4 UNP	24.0 <sup>b</sup>	25.2b	24.3b	24.5 <sup>b</sup>
SLICASS 6 P	16.8 <sup>c</sup>	18.5 <sup>c</sup>	21.0c	18.8 <sup>c</sup>
SLICASS 6 UNP	37.5 <sup>a</sup>	39.2 <sup>a</sup>	39.2a	38.6 <sup>a</sup>
Grasshopper severity damage (%) at 12 MAP				
Cocoa P	19.3	15.3	18.8	17.8 <sup>e</sup>
Cocoa UNP	57.5	55.8	55.8	56.4 <sup>a</sup>
SLICASS 4 P	19.2	17.3	17.1	17.9 <sup>e</sup>
SLICASS 4 UNP	32.5	32.5	31.7	32.2 <sup>c</sup>
SLICASS 6 P	20.3	19.2	26.2	21.9 <sup>d</sup>
SLICASS 6 UNP	40.0	40.8	38.8	39.9 <sup>b</sup>

P = protected, UNP = unprotected.

**Supplementary Table A3.** Interactive impacts of treatment and location on fresh storage root yield (t·ha<sup>-1</sup>), number of storage roots per plant and root dry matter content (%) of cassava genotypes under protected and unprotected cultivation practices.

Treatment	Location			Treatment Mean	Crop Loss (%)
	Foya	Gbassia	Serabu		
Fresh storage root yield (t·ha <sup>-1</sup> )					
Cocoa P	13.0 <sup>c</sup>	13.0 <sup>c</sup>	11.3 <sup>cd</sup>	12.5 <sup>c</sup>	
Cocoa UNP	9.6 <sup>d</sup>	11.1 <sup>cd</sup>	9.3 <sup>d</sup>	10.0 <sup>d</sup>	20.00
SLICASS 4 P	17.6 <sup>b</sup>	16.6 <sup>b</sup>	15.8 <sup>b</sup>	16.6 <sup>b</sup>	
SLICASS 4 UNP	14.0 <sup>c</sup>	13.4 <sup>c</sup>	15.1 <sup>bc</sup>	14.2 <sup>c</sup>	13.25
SLICASS 6 P	20.6 <sup>ab</sup>	21.3 <sup>a</sup>	21.5 <sup>a</sup>	21.1 <sup>a</sup>	
SLICASS 6 UNP	17.4 <sup>b</sup>	18.8 <sup>ab</sup>	18.7 <sup>ab</sup>	18.3 <sup>b</sup>	13.27
Number of storage roots per plant					
Cocoa P	5.0 <sup>b</sup>	4.8 <sup>c</sup>	4.8 <sup>c</sup>	4.9 <sup>b</sup>	
Cocoa UNP	2.6 <sup>e</sup>	3.3 <sup>de</sup>	2.4 <sup>e</sup>	2.8 <sup>d</sup>	42.86
SLICASS 4 P	5.6 <sup>bc</sup>	6.8 <sup>ab</sup>	5.8 <sup>b</sup>	6.1 <sup>a</sup>	
SLICASS 4 UNP	3.6 <sup>de</sup>	4.3 <sup>cd</sup>	3.6 <sup>d</sup>	3.8 <sup>c</sup>	37.70
SLICASS 6 P	7.1 <sup>a</sup>	6.0 <sup>b</sup>	6.9 <sup>ab</sup>	6.6 <sup>a</sup>	
SLICASS 6 UNP	3.8 <sup>d</sup>	4.5 <sup>cd</sup>	3.7 <sup>d</sup>	4.0 <sup>c</sup>	39.39
Root dry matter content (%)					
Cocoa P	23.0 <sup>d</sup>	21.0 <sup>de</sup>	21.3 <sup>de</sup>	21.8 <sup>d</sup>	
Cocoa UNP	19.8 <sup>e</sup>	16.3 <sup>f</sup>	17.8 <sup>ef</sup>	18.0 <sup>e</sup>	17.43
SLICASS 4 P	33.8 <sup>ab</sup>	33.2 <sup>ab</sup>	33.8 <sup>ab</sup>	33.6 <sup>a</sup>	
SLICASS 4 UNP	30.5 <sup>b</sup>	31.2 <sup>b</sup>	29.7 <sup>c</sup>	30.4 <sup>b</sup>	9.52
SLICASS 6 P	32.2 <sup>ab</sup>	34.5 <sup>a</sup>	32.8 <sup>ab</sup>	33.2 <sup>a</sup>	
SLICASS 6 UNP	28.2 <sup>c</sup>	28.5 <sup>bc</sup>	28.3 <sup>c</sup>	28.3 <sup>c</sup>	14.94

P = protected, UNP = unprotected.