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Disease Control and Integrated Management

e-Xtra*

Smallholder Cassava Planting Material Movement and Grower Behavior in Zambia: Implications for the Management of Cassava Virus Diseases

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ABSTRACT

Cassava (*Manihot esculenta*) is an important food crop across sub-Saharan Africa, where production is severely inhibited by two viral diseases, cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), both propagated by a whitefly vector and via human-mediated movement of infected cassava stems. There is limited information on growers' behavior related to movement of planting material, as well as growers' perception and awareness of cassava diseases, despite the importance of these factors for disease control. This study surveyed a total of 96 cassava subsistence growers and their fields across five provinces in Zambia between 2015 and 2017 to address these knowledge gaps. CMD symptoms were observed in 81.6% of the fields, with an average incidence of 52% across the infected fields. No CBSD symptoms were observed. Most growers used planting materials from their own (94%) or nearby (<10 km) fields of family and friends, although several large transactions over longer distances (10 to 350 km) occurred with friends (15 transactions), markets (1), middlemen (5), and nongovernmental organizations (6). Information related to cassava diseases and certified clean (disease-free) seed reached only 48% of growers. The most frequent sources of information related to cassava diseases included nearby friends, family, and neighbors, while extension workers were the most highly preferred source of information. These data provide a benchmark on which to plan management approaches to controlling CMD and CBSD, which should include clean propagation material, increasing growers' awareness of the diseases, and increasing information provided to farmers (specifically disease symptom recognition and disease management options).

Keywords: cassava, cassava mosaic disease, clean seed system, farmer behavior, planting material movement, Zambia

Cassava (*Manihot esculenta* Crantz) is a perennial shrub of the Euphorbiaceae (spurge) family, native to South America (Allem 2002; Olsen and Schaal 2001) and cultivated as a tuberous crop in tropical and subtropical regions worldwide. It can be propagated by either stem cuttings or seed, where the former is by far the most common (Alves 2002). In Zambia, cassava is one of the most important food crops after maize, and the primary staple in northern parts of the country (Chitundu et al. 2009; Szyniszewska 2019). It is the mainstay for an estimated 30% of the country's population (Simwambana 2005), consumed throughout the year in the Western, Northwestern, Luapula, and Northern provinces.

Cassava use in Zambia ranges from subsistence production, marketed fresh or processed for human consumption, to livestock feed and industrial use (Cadoni 2010). Demand is increasing for both human and industrial consumption in urban and industrial centers because of a surge in industrial applications including bio-ethanol, starch, stock feed, and brewing (Breuninger et al. 2009; Nuwamanya et al. 2011; Taiwo 2006; Tonukari 2004). Notably, production and consumption of cassava is expanding to southern parts of the country, where the Zambian Government and nongovernmental organizations (NGOs) have been promoting cassava in response to an increasing occurrence of drought and heat stresses that have led to the failure of maize crops (Phiri 2011). The production of cassava has also expanded in the Eastern Province (Alene et al. 2013; Barratt et al. 2006). Cassava is propagated using cuttings, i.e., pieces of harvested cassava stem. Upon harvest, these stems can be stored for up to 3 to 4 weeks in a cool, dry space before replanting. Cassava planting in Zambia is typically between November and January, while harvesting is highly flexible and relatively late compared with other countries. Harvesting takes place any time between 16 months and 3 years after planting. Later harvesting is more common among growers planting landraces, while those that use improved varieties typically harvest sooner. Smallholder growers typically have more than one field as a safeguard, and their planting will take place in areas with previously harvested crops.

According to the Food and Agriculture Organization of the United Nations (FAOSTAT) data, despite the importance of cassava, Zambia suffers from low average yields of 5.8 tons per hectare (t/ha) (Chikoti et al. 2019; FAOSTAT 2018). This is considerably lower than the reported average yield of neighboring countries, including Malawi (22 t/ha), Angola (10.9 t/ha), and the Democratic Republic of Congo (8.1 t/ha) (FAOSTAT 2018). The low yield in Zambia is because of several biotic and abiotic constraints such as cold and drought. Among the biotic factors, one of the most important is the high prevalence in most cassava-growing areas of cassava mosaic disease (CMD), caused by cassava mosaic geminiviruses (CMGs, family *Geminiviridae*, genus *Begomovirus*; Chikoti et al. 2013). Two variants of CMGs were confirmed to be present in Zambia: African

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cassava mosaic virus (ACMV) and East ACMV (Chikoti et al. 2013). Strains of the CMGs in Zambia (Chikoti et al. 2013; Mulenga et al. 2016), a reliance on cassava landraces (Alene et al. 2013; Rey and Vanderschuren 2017), and the lack of robust extension services magnify the impact of disease on crop yield. CMD was first reported in Africa in Tanzania, in 1894, and by the 1940s, it had spread to all cassava-growing regions of the African continent (Fargette et al. 2006). CMD was confirmed in Zambia in 1995, but it is likely that it had been present there for much longer (Mkuyamba 1995). CMD symptoms include characteristic patches of yellow and green mosaic, leaf curling and deformation, leaf narrowing, and reduced plant height and tuber root size.

In 2017, cassava brown streak disease (CBSD, caused by potyviruses, family *Potyviridae*, genus *Ipomovirus*), was also confirmed in both Northern and Luapula provinces (Mulenga et al. 2018). CBSD was first documented in 1936 in northeast Tanzania, where in the early 1990s it was reported to be restricted to low-altitude areas below 1,000 meters above sea level along coastal East Africa and lakeshore districts of Malawi (Legg et al. 2011). Since the mid-1990s there has been a reemergence of CBSD around Lake Victoria and across other East and Central African countries (Alicai et al. 2019; Legg et al. 2011). CBSD is caused by two variants of single-stranded RNA viruses: cassava brown streak virus (CBSV) and Ugandan brown streak virus (UCBSV) belonging to the genus *Ipomovirus*, family *Potyviridae* (Mbanzibwa et al. 2009; Winter et al. 2010). CBSD symptoms include root necrosis, radial root constrictions, feathery foliar chlorosis along secondary vein margins that eventually coalesce to form blotches, chlorotic mottling with no veinal association and, infrequently, brown streaks or lesions on stems (Nichols 1950).

These two viral diseases cause considerable losses, estimated at $1 billion per annum across sub-Saharan Africa (Tomlinson et al. 2017). CMD and CBSD have been estimated to cause yield loses of 15 to 24% (Thresh et al. 1997) and 18 to 25% (Gondwe et al. 2003), respectively, and consequently lead to the deterioration of the livelihoods of millions of growers (Abaca et al. 2012; Alvarez et al. 2012; Legg and Thresh 2003; Mbanzibwa et al. 2011; Patil et al. 2015; Winter et al. 2010). Viruses responsible for CMD and CBSD are both transmitted by an insect vector, *Bemisia tabaci* (whitefly), and by human-mediated propagation of infected planting stems (Maruthi et al. 2017). Spread of CBSVs by *B. tabaci* is reported to occur semipersistently and over relatively short distances, usually of the order of tens of meters (Katono et al. 2015; Maruthi et al. 2017). CBSV has a faster acquisition rate in the vector (<1 h) compared with CMV (up to 8 h) but lower persistence (up to 48 h) in the insect vector compared with CMV, which can be retained in the vector for up to 9 days (Maruthi et al. 2017; Thresh and Cooter 2005). Longer virus retention rates for CMV imply that spread is likely to be more efficient and over longer distances (Jacobson et al. 2018). Under experimental conditions, acquisition and transmission of CMV by viruliferous *B. tabaci* on exposed healthy cassava plants occurs primarily within the first 6 h (44 ± 16% disease incidence), whereas for CBSV it was at 22 ± 16% in the same time interval (Njoroge et al. 2017). Maruthi et al. (2017) reported the highest CBSV transmission rate achieved in their experiments at 60% over a period of 24 h. Reported virus transmission rates differ between studies, likely because of different methodologies, laboratory conditions, cassava cultivars, and viral strains. It is difficult to conclude how the rates of spread observed in laboratory conditions compare with the rates of virus spread in the field. The regional epidemiology of cassava virus spread, and existing evidence related to virus retention times, suggest that CMD in the field is spread by *B. tabaci* more efficiently than CBSD (Legg et al. 2011).

Strategies for disease management include the removal of infected plants (“roguing”), the adoption of resistant cultivars, and the use of certified disease-free planting material (known as “certified clean seed” [CCS]; Hillocks and Jennings 2003; Kanju et al. 2003; Legg 1999). Each method faces particular challenges that include difficulties in identifying infected plants, a paucity of resistant varieties (in particular those resistant to both viruses), and unacceptable increases in costs (Legg et al. 2011; Patil et al. 2015; Rwegasira and Rey 2012).

A number of surveys have assessed the impact and extent of CMD and CBSD in sub-Saharan Africa. Many of these have focused on disease incidence at the field scale or disease severity at the regional scale (Alicai et al. 2007; Chikoti et al. 2013; Gondwe et al. 2003; Hillocks et al. 2002, 1999; Mbewe et al. 2015; Mulenga et al. 2018; Rwegasira and Rey 2012). However, surveys are primarily based solely on field observations of disease, without consideration of the growers’ ability to identify CMD and CBSD, their practices related to sourcing and exchange of cassava planting material, or cassava disease control strategies implemented by growers. To understand which method of disease control is most likely to be successful, it is important to understand the decision-making processes of growers; what risks and costs they find acceptable and under what circumstances. Work on CBSD, European corn borer, and Western corn rootworm has shown that grower knowledge and management practices can have significant impacts on the long-term success of disease control, and may represent the difference between success and failure of control (Carrasco et al. 2012; Legg et al. 2017; McQuaid et al. 2017a; Milne et al. 2015).

Effective control of many diseases is based on a knowledge and understanding of how the pathogen spreads between fields as a function of distance. It is widely acknowledged that the incidence of CMD and CBSD can be amplified within an individual field by replanting infected material, i.e., cuttings left from the previous planting seasons (Samura et al. 2017), and on a larger scale by sharing planting material between fields (McQuaid et al. 2017a, b; Patil et al. 2015). However, more work is required to investigate and quantify the physical properties of human-mediated transmission, specifically the volume of (potentially infected) planting material that is exchanged and the distances over which this material is moved. Effective disease management is achieved based on an understanding of these dispersal characteristics.

The primary objective of this study was to quantify and describe the movement of cassava planting material into and out of growers’ fields (specifically the volume of cuttings moved over specified distances), and to identify the sources and recipients of that material. The secondary objective was to ascertain growers’ knowledge (often referred to as “awareness”) of CMD and CBSD, including the symptoms associated with each disease and prevalence in the study area. Lastly, sources and preferences that growers had for obtaining information related to cassava pathogens, planting practices, CCS, and disease management were explored. This information was obtained by a survey of 96 growers in five provinces of Zambia.

MATERIALS AND METHODS

Agro-ecological context of the study area. The study was conducted in five provinces of Zambia: Western, Luapula, Central, Northern, and Eastern (Fig. 1), which are among the major cassava-growing areas and at the time of the survey were known to have CMD infections present, with CBSD infections confirmed in neighboring Tanzania, Malawi, Mozambique, and the Democratic Republic of Congo (Gondwe et al. 2003; Hillocks et al. 2001; Mangana 2003; Mulimbi et al. 2012).

These provinces encompass different agro-environmental conditions. Northern and Luapula provinces are located in Agro-Ecological Zone (AEZ) III, comprising part of the Central African plateau and possessing a monomodal rainfall pattern (Saasa 2003; The World Bank 2006). The rainy season occurs between November and April, and is followed by a dry spell lasting from May to October. Western, Central, and Eastern provinces are located in slightly drier AEZ II (Jain 2007; The World Bank 2006). The rainy season occurs between December and April, followed by a similar dry spell to AEZ III.

Sample selection. Because of poor road infrastructure in Zambia, only fields located along the main motorable roads were selected for the study. A total of 96 smallholder cassava growers were selected in 10- to 15-km intervals along major motorable roads in the regions described above. We maximized the number of interviewees by restricting the survey to roadside fields, as reaching off-road fields was not feasible within the budgetary and time constraints for the survey. The survey was spread over a 2-year period to accommodate staff constraints, while enabling us to maximize the number of respondents and obtain information from across five provinces of Zambia. Growers who were the field owners, or their family members, were informed of the scope and purpose of the survey and asked for permission and a signature confirming their consent to participate in the study, before the questionnaire and field sampling was conducted. A total of 24 growers were interviewed in 2015 in Eastern (9), Luapula (4), and Northern (11) provinces, and 72 growers were interviewed in 2017 in Central (15), Eastern (15), Luapula (15), Northern (14), and Western (13) provinces (Fig. 1; Table 1). The research team comprised a senior scientist and two research assistants, all conversant with the local languages and with experience in cassava production. The study was conducted between January and May in both years, alongside a survey to assess the prevalence of CMD and CBSD, following the protocol outlined by Sseruwagi et al. (2004). During the survey period most plants were assumed to be between 3 and 9 months old, at which age cassava plants are regarded as ideal for the assessment of foliar and root symptoms, before the shedding of their leaves.

Questionnaires. Structured interviews with a mix of closed- and open-ended questions were conducted with cassava growers who voluntarily agreed to participate. Local agriculture extension officers and, where available, village leaders, were informed and asked for consent for the interviews to take place. A copy of the questionnaire template and results are available in an online repository (https://figshare.com/s/9c3331b503cc1c7401de; Szyniszewska et al. 2019). The names of the surveyed farmers and geographic coordinates of the locations were removed to ensure anonymity of respondents. The questionnaire was pretested on a small group of growers before the survey and adjustments were made to ensure that the questions were phrased clearly and understood correctly by the growers. To mitigate the risk of bias because of respondents' recollection of events over a longer period of time, the majority of critical questions were related to events that happened in the most recent year or harvest preceding the questionnaire. To encourage wider participation, the interviews and discussions were conducted in the local languages familiar to most growers: Bemba in Northern, Luapula, and Central provinces; Lozi in Western Province; and Nyanja in Eastern Province. Some of the questions were repeated and rephrased to enable growers to understand and respond fully, without changing the original meaning of the question.

In the first section of the questionnaire, general information on growers' field location, altitude, and field size were recorded. Surveyors inspected the field for visual symptoms of CMD and CBSD, and visually assessed the number of varieties grown. Growers were asked open questions about planting and harvesting frequencies, and varietal preferences including the number of varieties in their fields. They were presented with a selection of reasons for choice of planting material and asked to order them according to their importance to the grower.

The second section of the questionnaire comprised questions related to the trade of planting material. Growers were asked how many bags (one bag of cuttings was defined as a bundle of 100 cuttings, each of 1-meter length) went to, or were obtained from, the following resources: their own fields; their own stored-away planting material; friends or family; markets; middlemen; NGOs; or research

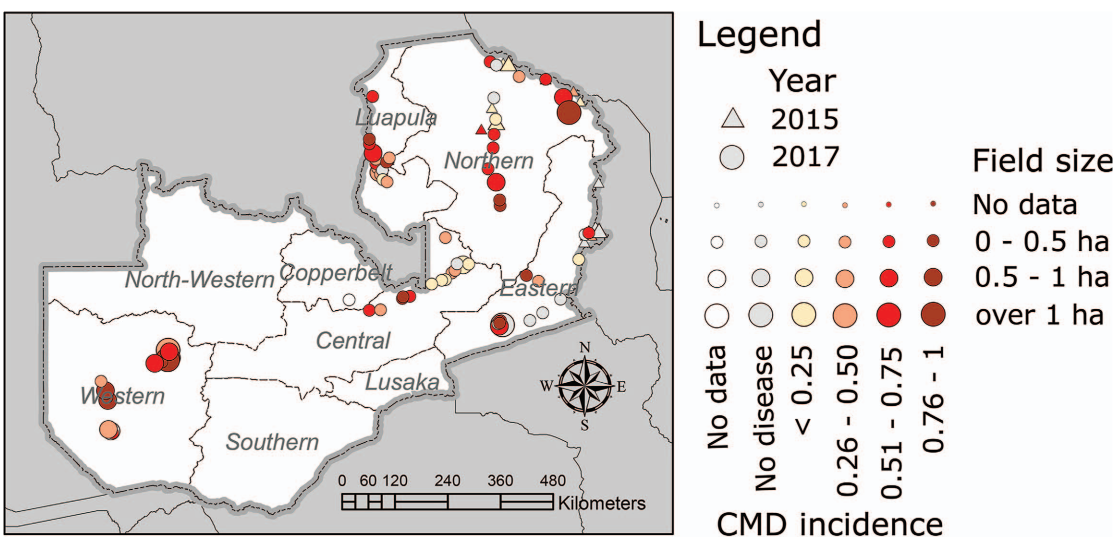

Fig. 1. Locations of interviewed growers in five provinces of Zambia, showing field size and cassava mosaic disease incidence (proportion of infected plants within the field).

TABLE 1. Summary of the number and per-province distribution of interviewed growers, average field size, number of varieties planted in the field, and planting frequency

Province	Number of growers 2015	Number of growers 2017	Field size (ha) Mean	Field size (ha) SE[a]	Median number of in-field varieties	Planting frequency, with number of respondents: Biennial	Yearly	2× year
Central	–	15	0.26	0.06	2	0	2	2
Eastern	9	15	0.82	0.43	1	0	22	2
Luapula	4	15	0.29	0.06	3	1	18	0
Northern	11	14	0.45	0.09	2	0	23	0
Western	–	13	1.25	0.29	3	0	12	1

[a] SE = standard error.

stations. Growers were also asked how far away the sources or recipients were located. Growers were presented with a selection of planting material sources and asked to order them according to their importance to the grower, as well as to identify how frequently they used each source (i.e., number of individual transactions).

The third section of the questionnaire comprised a set of open-ended questions to assess growers' awareness of CMD and CBSD in terms of symptom recognition, presence of the diseases in their fields and surrounding areas, and the mechanism of disease spread. After growers' knowledge related to CMD and CBSD was assessed, they all surmised it was a disease. Subsequently, they were asked whether they controlled for disease and, if yes, how they did so; whether they were aware of CCS and, if so, where they would access it; and finally, what their sources of information were for advice on cassava planting material and methods.

The fourth and final section of the questionnaire was related to the sources and frequencies of obtaining information related to cassava diseases and CCS, and the ranking of predefined sources of information according to preference. These questions did not specify a timeframe, and the events could occur at any time in the past. Questions on the frequency of obtaining information were open-ended, and were classified by the researchers into five categories: often, sometimes, rarely, once, and never. Unless explicitly stated by the grower, we classified "often" as once a month or more frequently; "sometimes" as quarterly or several times a year; and "rarely" as once a year.

Growers were also asked open-ended questions about the factors that influenced their decisions related to disease control, including disease pressure, their concern about the disease, and market prices that they would be willing to pay for CCS at the time of the survey.

Disease incidence and severity. Plants at the fields visited were assessed for the presence and severity of CMD and CBSD foliar symptoms as part of a larger nation-wide survey monitoring cassava disease presence in Zambia. In each field, a total of 30 plants were inspected, with15 plants on each diagonal line across the field, following methodology outlined by Sseruwagi et al. (2004). The per-field disease incidence was calculated using the number of plants with visual foliar symptoms present in the field divided by the total number of sampled plants. Foliar symptom severity for CMD was recorded on each plant using a 5-point ordinal rating scale outlined fully in Hahn et al. (1980), where 1 = no disease symptoms; 2 = mild disease symptoms, with a mild chlorotic pattern; 3 = moderate mosaic pattern throughout the leaf; 4 = severe mosaic pattern, with distortion of the leaflets and general reduction in size; and 5 = severe mosaic pattern, and/or distortion of the entire leaf and plant stunting. Similarly, the presence or absence of CBSD symptoms on the leaves and stems was recorded for each plant using an ordinal scale of 1 to 5, fully described by Gondwe et al. (2003) where 1 = no apparent symptoms; 2 = mild disease symptoms, displaying slight leaf feathery chlorosis with no stem lesions; 3 = pronounced leaf feathery chlorosis with mild stem lesions; 4 = severe leaf feathery chlorosis with severe stem lesions; and 5 = defoliation with severe stem lesions and dieback.

Collection and extraction of virus isolates. For CMD, a total of 208 leaf samples with CMD symptoms were collected from 96 fields during the survey. In each field, three to four leaf samples were collected, some with mild and others with severe mosaic symptoms wherever they occurred, using brown envelopes to avoid contamination. The samples were transported to the Plant Virology Laboratory at the Zambia Agriculture Research Institute's Mt. Makulu Central Research Station in Chilanga. The leaf samples were stored at −20°C until use. Total nucleic acid (TNA) was extracted from 50 mg of each cassava leaf sample using the cetyltrimethylammonium-bromide protocol (Lodhi et al. 1994). The extraction buffer contained 2% cetyltrimethylammonium bromide, 1.4 M of NaCl, 100 mM of Tris-HCl, 25 mM of EDTA, 2% polyvinylpyrrolidone, and 2 M of NaCl; 2% mercaptoethanol was added to the extraction buffer just before use. The leaf samples were individually ground in 1,000 µl of extraction buffer using a mortar and pestle. Extracts of 800 µl were transferred into 2-ml microcentrifuge tubes and incubated at 65°C for 15 min with regular shaking at intervals of 5 min and then cooled at room temperature. An equal volume of chloroform/isoamyl alcohol (24:1) was added to the cooled extract, vortexed for 1 min, and centrifuged at 12,000 rpm for 15 min. The supernatant (500 µl) was transferred into new microcentrifuge tubes to which an equal volume (500 µl) of cold isopropanol was added, followed by incubation at −20°C for 30 min. The contents were centrifuged at 13,000 rpm for 25 min and the supernatant discarded. The TNA pellet was washed once in 1,000 µl of 70% ethanol and air-dried at room temperature. The dried TNA pellet was resuspended in 50 µl of nuclease-free water. Partial fragments of 774 bp (DNA-A AV1/CP) and 556 bp (DNA-B) were amplified for both 2015 and 2017 CMD-symptomatic leaf samples using the specific primers JSP001/2 and EAB555F/R (Fondong et al. 1998) for the detection of ACMV and East ACMV, respectively (Table 2; Supplementary Fig. S1). PCR was performed using a model no. 500 Techne thermal cycler (Cole-Parmer, Vernon Hills, IL) following the conditions published in Chikoti et al. (2013).

To detect CBSD virus, a two-step reverse-transcription PCR protocol was used for virus detection. Complementary DNA was synthesized from 3 µg of total RNA in a 20-µl reaction mixture using M-MuLV reverse transcription primed with random hexamers according to the manufacturer's protocol and then for PCR with primers CBSDDF2 and CBSDDR (Table 2; Mbanzibwa et al. 2011). PCR reaction and cycling conditions followed were as published in Munganyinka et al. (2018).

Electrophoresis was performed to detect the PCR products in a 1% agarose gel, stained in phenol blue, at 100 V for 60 min in gels buffered with 1× Tris-acetate-EDTA using a gel apparatus. The gels were visualized using a gel documentation system (Gel Doc XR; Bio-Rad, Hercules, CA).

Data analysis. Descriptive statistics including means, standard errors, and cross tabulations were calculated to summarize the growers' responses and disease incidence. Results were expressed as percentages or absolute frequencies of responses obtained from growers, excluding records where data were not available (therefore the total may differ in each question). The answers were analyzed using the R Language for Statistical Computing (R Core Team 2016) and plotted with the *ggplot2* package (Wickham 2016). The

TABLE 2. Primers used to detect variants of cassava mosaic viruses using PCR in cassava leaf samples collected; cassava mosaic disease was diagnosed using primers for African cassava mosaic virus (ACMV) and East African cassava mosaic virus (EACMV), and cassava brown streak disease (CBSD) was diagnosed using primers for cassava brown streak viruses (CBSV) and Ugandan cassava brown streak virus (UCBSV)

Primer	Sequences (5′–3′)	Specificity	Product size
JSP001[a]	ATGTCGAAGCGACCAGGAGAT	ACMV	774
JSP002[a]	TGTTTATTAATTGCCAATACT	ACMV	
EAB555/F[a]	TACATCGGCCTTTGAGTCGCATGG	EACMV	556
EAB555/R[a]	CTTATTAACGCCTATATAAACACC	EACMV	
CBSDDF2[b]	GCTMGAAATGCYGGRTAYACAA	CBSV, UCBSV	344, 440
CBSDDR[b]	GGATATGGAGAAAGRKCTCC		

[a] Cassava mosaic begomovirus-specific primers used for the study as described by Fondong et al. (1998).
[b] CBSV-specific primers described by Mbanzibwa et al. (2011).

relationship between growers' disease awareness as an independent binary response and disease incidence as a dependent variable was investigated with a logistic regression using the "glm" function in the *lme4* package and a "chisq.test" function (Bates et al. 2015). Growers were classified as being "aware" or "not aware" of CMD based on their responses to the question "what do you know about CMD?" We compared responses of two groups of growers (ones informed about cassava diseases in the past, and those who never had information about cassava diseases) regarding their concern about cassava diseases on a 10-point scale to see if there were significant differences in the responses of two groups using a nonparametric Mann–Whitney *U* test in the "wilcox.test" function of R.

RESULTS

Field properties, disease status, and varieties preferences. Most growers' fields were small (mean = 0.59 ha; standard error [SE] = 0.12) and planted annually (92.9% of participants) (Table 1). Harvesting was based on need for own daily consumption or for sale (40% of participants). All survey sites in the Western Province were infected with CMD, based on visual symptoms assessment, with mean conditional incidence of 65.9%, where conditional incidence refers to mean incidence across infected fields only (Table 2). Approximately 90% of survey sites in Central, Luapula, and Northern provinces had plants with CMD foliar symptoms apparent, with mean conditional incidence of 39.5 to 53.5%. Less than half (47.8%) of survey sites in Eastern Province were infected with CMD, with mean conditional incidence of 54.5%. In the infected fields, the highest ratio of plants with high severity scores (4 and 5) were observed in Eastern and Western provinces of the country, with the percent of plants having severity score 4 being ~38% and those with severity score 5 being ~5%. In contrast, plants with severity score of 4 ranged from 4.5 to 6.15%, and plants having severity score 5 ranged from 0 to 0.30%, in Central, Luapula, and Northern provinces. No CBSD was observed in any of the study fields. Growers typically planted more than one variety of cassava in their fields (66.5% of growers) with a range of one to seven varieties. Good taste and associated sweetness (31 growers), for a grower's own consumption and food security (22 growers), and with a high yield and large tubers (21 growers) were the most commonly cited traits determining varietal choice (Fig. 2). Early maturing and bulking (19 growers), and the availability of planting material (15 growers) were also cited as a priority determining choice. Among six preference criteria influencing choice of planting material presented to the respondents, varietal preference was the highest ranked, while availability-related answers were ranked second and third (Fig. 3).

Planting material movement and trade. Most planting material was recycled from the previous crop (83 growers) or stores (planting material stored previously, as opposed to material cut and immediately replanted, at 11 growers), while a large proportion of growers (52:96) reported that they discarded some planting material. While sharing did occur with family and friends (55 and 39 growers, respectively), this was generally within the same or nearby villages, with 94% of recipients located within a radius of 1 to 10 km (Fig. 4). However, some movement of planting material did occur over a greater distance, including a small number of large transactions with markets (100 bags over an average of 7.43 km), middlemen (9.5 bags over an average of 55 km), or NGOs (15 bags over an average of 28.5 km). Given the paucity of data on movement of cassava planting material, we provide some additional detail on selected individual transactions to illustrate the range of behaviors evident in a relatively small cohort. One transaction involved moving a large amount of planting material (100 bags) from a single grower with a large field of 4 ha to a market 40 km away. Three further transactions with markets occurred, including 10 bags sold at a market a reported 0.05 km from the 1.5-ha field, and two smaller transactions of seven and one bags over longer distances (3 and 8 km, respectively) from very small fields (field size up to 0.25 ha). Growers who obtained their planting material from middlemen (intermediate suppliers) indicated material was moved over distances of 50 to 60 km, while six growers exchanged their planting material with an NGO or another organization over distances between 0 and 350 km.

CMD and CBSD awareness. Most of the growers surveyed (81%) responded that they did not know what CMD was when explicitly asked "what do you know about cassava mosaic disease?" After growers surmised it was a disease, most (60.5%) were unable to recognize it by its symptoms, or specify its mechanism of dispersal (75.6%), or likely effect on yield (39%). In a logistic regression model (Table 4), higher CMD incidence in a field was a significant predictor of growers' CMD knowledge. Nearly half of growers (44%) did not know whether the disease had an impact in their area, while 44% had

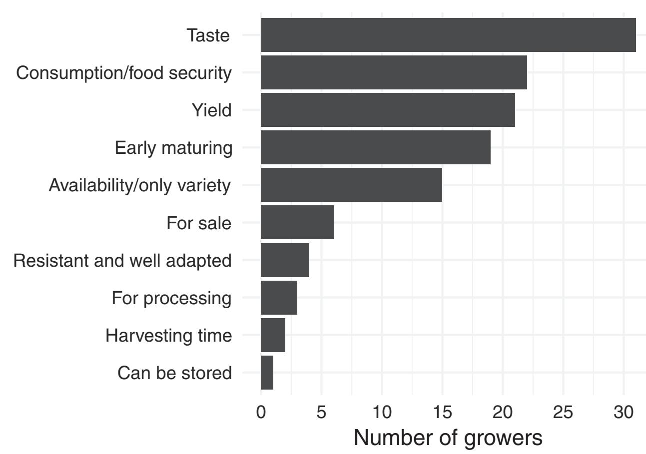

Fig. 2. Different cassava traits dictating varietal choice cited by growers, where multiple answers were permitted. "Resistant" refers to resistance to disease. Number of respondents = 96.

TABLE 3. Summary of cassava mosaic disease (CMD) per-province presence in the fields of interviewed growers

Province	Prevalence[a] (%)	Absolute incidence (%)[b] Mean	SE	Conditional incidence (%)[c] Mean	SE	Mean per-field percent of plants classified in each disease severity category (%)[d] 1	2	3	4	5
Central	92.9	36.7	7.4	39.5	7.7	60.5	12.1	2.1	6.1	0.3
Eastern	47.8	26.1	7.2	54.5	9.6	41.5	5.1	10.0	38.5	4.9
Luapula	89.5	47.9	6.0	53.5	5.1	46.5	10.4	38.6	4.5	0.0
Northern	91.7	43.8	6.3	47.7	6.4	54.1	3.0	33.8	8.9	0.2
Western	100.0	65.9	6.3	65.9	6.3	34.1	1.3	20.8	38.2	5.6

[a] Prevalence, the proportion of fields with any disease symptoms observed.
[b] Absolute incidence, the incidence among all fields (both infected and where disease was not reported). SE = standard error.
[c] Conditional incidence, the incidence among infected fields only.
[d] Mean per-field incidence was calculated based on visual foliar symptoms across 30 surveyed plants, where disease symptoms severity score 1 = no observed CMD symptoms; 2 = mild disease symptoms with mild chlorotic pattern; 3 = moderate mosaic pattern throughout the leaf; 4 = severe mosaic pattern with distortion of the leaflets and general reduction in size; and 5 = severe mosaic pattern and/or distortion of the entire leaf and plant stunting (Hahn et al. 1980).

observed an impact on the crop. Of those that had observed an impact of the disease, 25.9% identified yield losses.

Overall, when asked how concerned they were about CMD on a scale from 1 (not worried) to 10 (very worried), 53% of growers responded they were not at all or only slightly worried (1 to 3), 17% of growers were moderately worried (4 to 6), and 28% were very worried (7 to 10). When the respondents were grouped by whether they had heard about CMD at some point in the past ("informed" growers), or never heard about the disease ("not informed"), growers who had heard about CMD were more concerned compared with those who had not (Mann-Whitney U test $P = 0.0002$, $W = 1{,}235$) (Fig. 5).

None of the growers had an awareness of CBSD, and no disease symptoms were detected in the surveyed fields.

Disease control and management. Disease management for CMD was rare among growers. Three-quarters of growers (74.7%) declared that they did not practice any control measures ($n = 83$). In contrast, of the few growers that applied control measures, five used clean planting material while two, who were seeking help from agricultural extension workers, rogued the diseased plants and sprayed for insects. The majority of growers who used control measures were in Eastern Province (eight out of 12), which had the lowest mean disease prevalence and absolute incidence among surveyed farms. Most growers who implemented disease management cited their own experience as a source of disease control knowledge (seven) while two cited agricultural extension workers, one cited a parent, and one a cooperative group.

CCS sourcing and awareness. Nearly half of the growers were aware of CCS (47.7%, $n = 88$), where 33.3% would seek it from agricultural extension workers if there was a need for it and 10.8% had used it in the past. At the same time, of those who were unaware of CCS (48.9%), after an explanation the majority (58%) responded that they would be happy to use it if it were available, while no growers indicated that they would not be happy to use CCS if it were provided to them. The remaining 3.4% of respondents stated that they were either aware of CCS for other crops or that CCS was not relevant to them. Northern and Western provinces had the highest awareness of CCS with 20 out of 24 and 9 out of 13 respondents declaring they knew about CCS, respectively. In Central

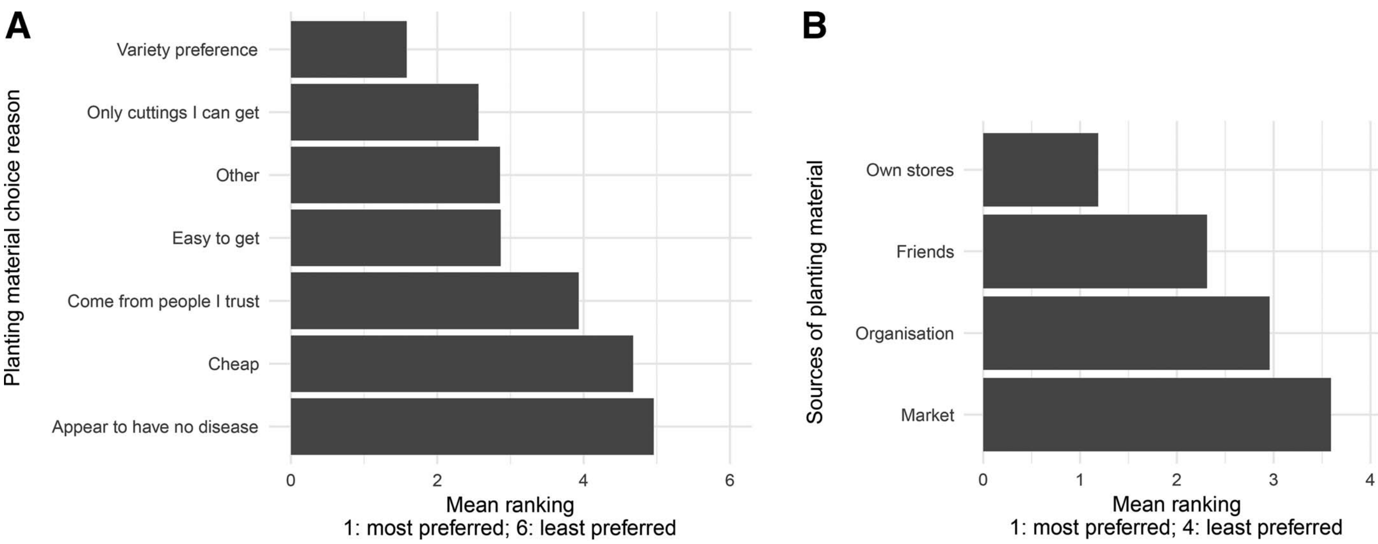

Fig. 3. Planting material **A,** reason for choice and **B,** preferred source. Ranking 1 indicates most preferred, while **A,** rankings 6 and **B,** 4 indicate least preferred (number of respondents = 96).

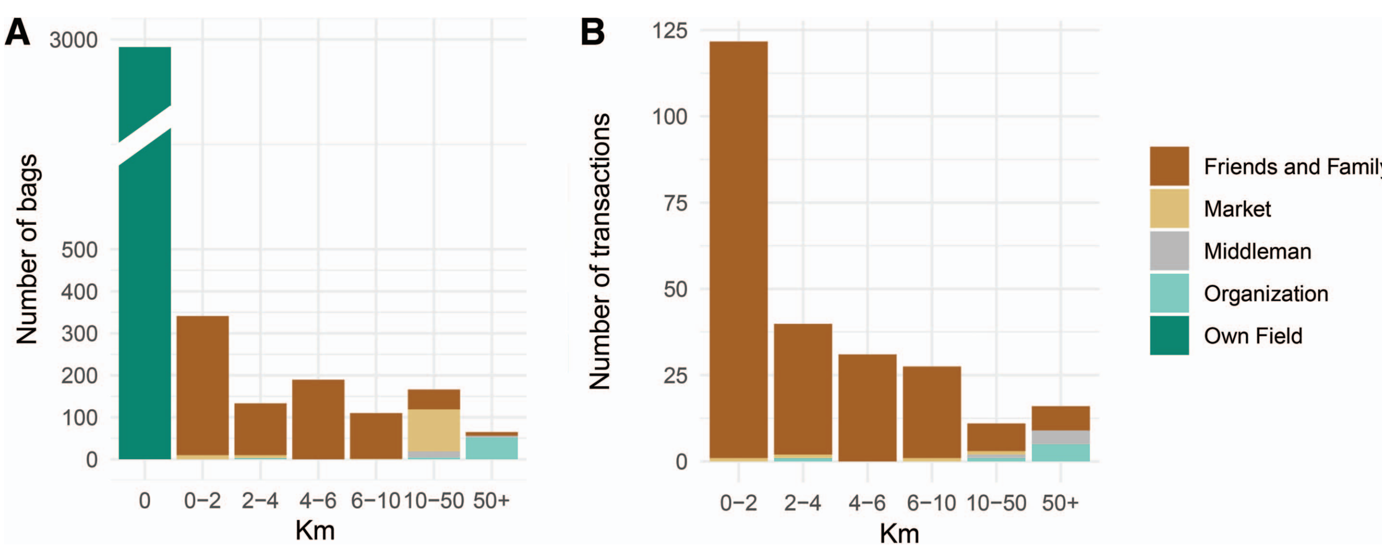

Fig. 4. Total number of **A,** bags of planting material moved (received or given away/sold) and **B,** individual transactions over a given distance. One bag of cuttings is defined as a bundle of 100 cuttings, each of 1 meter length. An organization was defined as a nonprofit entity involved in the movement of cuttings, such as a nongovernmental organization or research station (number of respondents = 96).

Province, only 1 out of 12 respondents knew about CCS, and in Luapula, only 4 out of 19. In Eastern Province, about half of the respondents (9 out of 17) declared they were aware of CCS.

Information sources. Among the surveyed growers, 30% relied on information passed on from their parents or grandparents as their source of cassava planting knowledge; slightly over one-quarter (27.4%) relied on their own experience; and 21.4% relied on information obtained from agriculture extension workers ($n = 84$). Other sources included friends (11.9%), other relatives (3.6%), other growers (1.2%), the radio (9.5%), researchers (3.6%), neighbors (2.4%), or NGOs (2.4%).

Information on cassava diseases and CCS had reached half of growers on at least one occasion in the past (50.6 and 51.8%, respectively), although no single source of information reached the majority of individuals. The most frequent sources of information included nearby friends, family and neighbors, and the radio (Fig. 6A).

In terms of preferences for information, growers preferred to hear from extension workers, TV and radio, and people within the village (Fig. 6B), while village leaders and friends or relatives located in a different village were less preferred. Nearly 90% of growers who were aware of CMD had access to frequent information about it, while the majority of growers who were unaware of the disease had no access to information (Fig. 7). The most informed growers were located within Northern and Eastern provinces, where over half of growers had often heard about CMD from various sources. The least informed growers were located in Luapula and Western provinces, where over two-thirds of growers reported never receiving information about CMD.

Making decisions. High yield, low cost, and absence of disease were the most frequently reported factors (27.4, 25, and 22.6%, respectively) influencing growers' decisions on whether or not to use CCS. The majority of growers indicated they would consider adoption of CCS to control for CMD if two to four neighbors were affected by the disease. Similarly, they would consider using CCS if two to four neighbors were using it too (Supplementary Fig. S2).

TABLE 4. Logistic regression model of in-field cassava mosaic disease (CMD) incidence to predict growers' answer to the question "do you know what CMD is?," where cases are represented by "no" answers and controls by "yes" answers (number of respondents = 84)

Model	β-estimate	SE[a]	*Z* value	*P* (>|*z*|)
Intercept	2.1223	0.1042	20.36	<0.001
CMD incidence	−1.8838	0.1674	−11.26	<0.001

[a] SE = standard error.

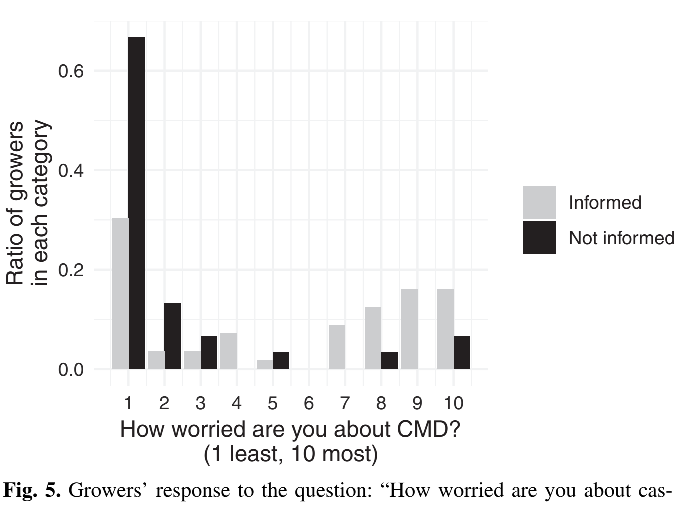

Fig. 5. Growers' response to the question: "How worried are you about cassava mosaic disease, on a scale of 1 to 10, where 1 is the least worried and 10 is the most worried?" Growers are categorized based on whether they reported hearing about cassava mosaic disease in the past on at least one occasion (defined as "informed") or never ("not informed"). Number of respondents = 87.

Growers were classified according to their answer to the question on CMD knowledge. Depending on their response, they were classified as "having knowledge," "some knowledge," and "did not know." Into those three categories fell 40, 18, and 8% of growers, respectively. However, differences between these groups were not statistically significant (χ^2 test $P = 0.19$, $df = 2$). When growers were classified into two groups (with or without knowledge), the differences were still not significant (χ^2 test $P = 0.16$, $df = 1$). The intention to buy CCS decreased with increasing price (Supplementary Fig. S3), where 20 KWZ per bag of 100 cuttings represented a key decision-point for many growers (prices as presented to respondents and not inflation-adjusted for publication).

DISCUSSION

Cassava virus diseases constitute a major constraint to the production of cassava in sub-Saharan Africa, yet there have been few studies looking into some of the key aspects of human-mediated disease spread and control. These include awareness of the diseases, and the practices and decision making of cassava growers themselves (Delaquis et al. 2018). Our study provides a valuable insight into the movement of planting material in Zambia, where we show that the cassava planting material trade is largely informal, with a limited number of commercial growers involved in the production and sale of planting materials. We found that growers mostly recycled materials from their own fields, attributing this to varietal preference as well as the fact that the material was readily available. This tendency to recycle material is consistent with previous studies, which have shown that a majority of planting material is recycled within the same field, while a considerable portion is also exchanged with close friends or family (Chikoti et al. 2016; Gnonlonfin et al. 2011; Houngue et al. 2018; Ntawuruhunga et al. 2007; Teeken et al. 2018). Although markets, NGOs, or research organizations and intermediate suppliers (i.e., middlemen) were rarely involved in the movement of planting material for respondents in this study, the large scale of the distances and quantities of material moved in those transactions does indicate that these agents could transmit pathogens across large distances. This could lead to the establishment of new disease foci, which previous work has demonstrated could be severely detrimental to disease control (Delaquis et al. 2018; Legg et al. 2014; McQuaid et al. 2017a, b). Increasing the distance and quantity of movement of infected planting material increases the importance of the material over the whitefly vector in the dispersal of pathogens (McQuaid et al. 2017b).

In general, most growers in our study indicated that markets were >7 km from their homesteads. It has been shown in a previous study that the closer a household is to a market, the higher the probability it will adopt improved varieties because of greater market accessibility (Salasya et al. 2007). Growers further away from markets are at a disadvantage, because of an increased difficulty in selling their own planting material and a reduced opportunity for information exchange, and are thus more inclined to subsistence production. Growers are also sensitive to the price of planting material, and an increase in the price of CCS relative to the local variety reduces adoption rates (Langyintuo and Mekuria 2008). However, while it seems likely that a lack of awareness of cassava diseases and control methods will affect cropping practices, our findings regarding this did not prove to be statistically significant.

There are inevitably sources of error and bias in the conduct of surveys that need to be borne in mind. Our survey was conducted over 2 years, but in each case critical questions were related to experience from the previous (i.e., most recent) year or harvest, in an effort to enhance comparability. Because of the poor road infrastructure in Zambia, participating growers were also located along the main motorable roads. Our inferences about movement distances therefore relate strictly to growers based along motorable routes. The

Agricultural Extension System under the Ministry of Agriculture in Zambia spearheads activities that facilitate access of grower, their groups, organizations, and other market actors to information and technologies. It groups all growers into camps that are irrespective of their proximity to either motorable or nonmotorable locations. All the camps and growers therein are therefore provided with the same agricultural amenities, technical information, and services, ensuring that all growers are at a par. Our inferences about access to information are therefore likely to hold for growers in motorable or nonmotorable locations because both classes are targeted by communication from the Agricultural Extension Service in Zambia. The implications of small sample size and bias in the location of participating growers mean that additional work is required to confirm our findings. Particularly, it may be that the participants in our survey were more likely to have access to information than growers located further from motorable roads. It is important when considering issues of equity that these growers are not neglected, and future studies should attempt to identify whether our findings are consistent for these growers. Additionally, the sample size of our survey makes it more susceptible to stochastic differences among growers, so our findings should be viewed as exploratory, requiring further collection of evidence to support them. Sampling over multiple years may also have affected both the disease incidence and awareness we might expect to see, with both presumed to increase over time. Participant gender was not recorded, which raises a further limitation to the results. While the majority of smallholder growers are expected to

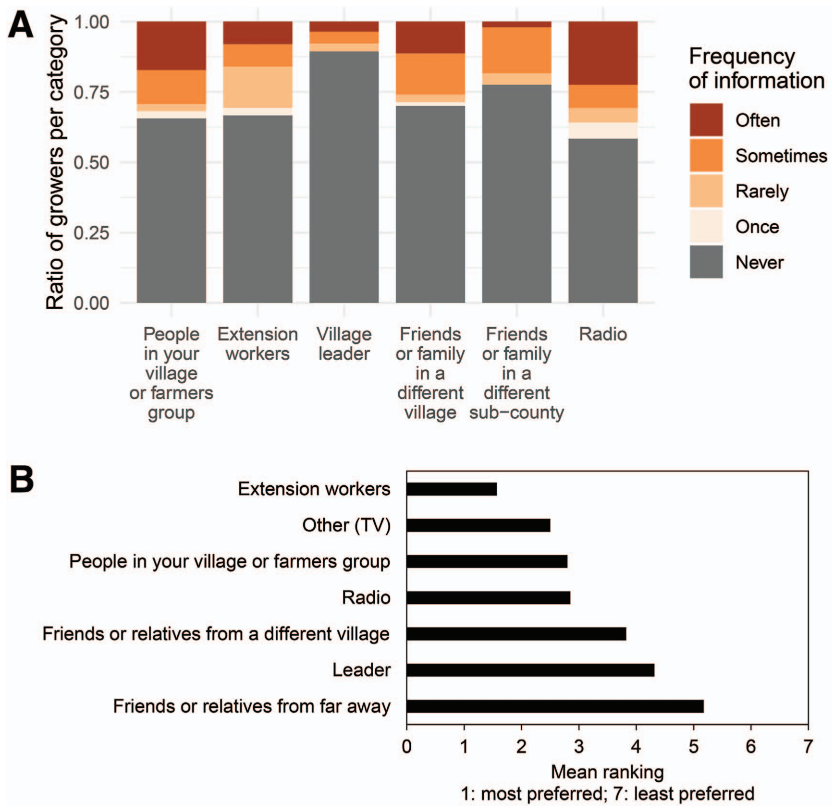

Fig. 6. A, Frequency of receiving information on cassava and **B,** ranking of source of information on cassava diseases from the most (1) to least preferred (7). Friends and relatives from a different village are classified as "friends or relatives from far away" (number of respondents = 75).

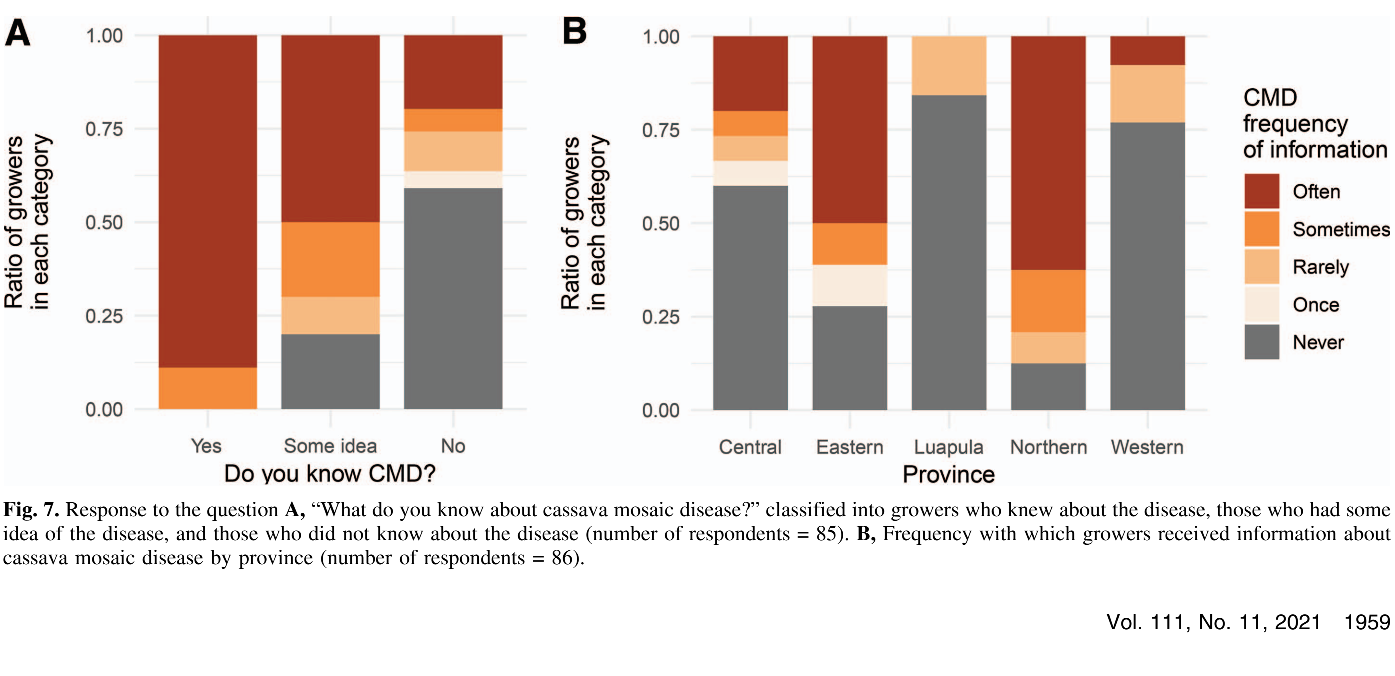

Fig. 7. Response to the question **A,** "What do you know about cassava mosaic disease?" classified into growers who knew about the disease, those who had some idea of the disease, and those who did not know about the disease (number of respondents = 85). **B,** Frequency with which growers received information about cassava mosaic disease by province (number of respondents = 86).

be female, we might expect to see important behavioral and awareness differences between growers of different gender, as well as differences in obtaining access to information.

Our work supports previous studies that have shown that culinary properties and varietal taste are key factors in planting material selection, followed by economic traits such as yield, while the presence of disease makes little to no difference on choice (Houngue et al. 2018; Kombo et al. 2012; Njukwe et al. 2013; Ntawuruhunga et al. 2007). With this in mind, efforts to use CCS to control disease epidemics need to address growers' varietal preferences and needs (Evenson and Gollin 2003; Kiros-Meles and Abang 2008), something that also applies to the use of disease-resistant or -tolerant varieties. If new varieties are not suited to local tastes the level of adoption is likely to be low, a factor to be considered by both cassava breeders and CCS producers alike. At the same time, the importance of yield to varietal choice presents an opportunity to educate and reassure growers about the economic advantages of CCS and the adoption of improved varieties.

Our study findings show a striking lack of awareness of cassava diseases among growers. While this is unsurprising for CBSD, the result for CMD was unexpected. CMD was widespread in growers' fields as evidenced from detected cassava mosaic virus variants in this study, and has been present across the country for more than two decades, with estimated yield losses of 50 to 70% (Muimba-Kankolongo et al. 1997). This lack of disease awareness is likely to be a reflection of the scarcity of information about diseases available to growers; only half of growers received any information on disease or its control at some point, and few received information frequently or on a regular basis. Access to information is critical to decision making, and this lack of information increases concerns about the disease. Our results indicate that a reduced awareness as well as reduced receipt of information about disease can significantly affect growers' concerns and perceptions of the diseases, as well as their willingness to apply control measures.

In particular, a lack of awareness of the risk and impact of disease on yield could lead to the failure of disease control measures implemented at a wider level, where it is necessary for a large proportion of growers to engage in disease management for effective, sustainable control to work (McQuaid et al. 2017a). It is certainly highly likely that the lack of awareness, combined with high incidence, contributes significantly to the spread of the disease. The high rate of reuse of planting materials by growers within the same field, due often to a lack of alternative sources, could also result in a low genetic potential with an increase in susceptibility of the material to pests and diseases, as observed in Malawi (Chipeta et al. 2016). Although replanting material resistant to disease could potentially protect growers from the arrival of infected cuttings from their own or other fields, no cassava variety has been found that is fully resistant to both CMD and CBSD (Kawuki et al. 2016; Mukiibi et al. 2019; Tomlinson et al. 2017). Ultimately, therefore, uninformed growers who do not practice management strategies will still be vulnerable to disease acquired from whitefly infections and, as a consequence of high rates of recycling of material, a rapid buildup of disease over seasons. Nonetheless, although there are improved cassava varieties bred by the Zambia Agriculture Research Institute that are tolerant to CMD, early bulking, and high yielding, most of the farmers grow local varieties that are susceptible to CMD in Zambia (Alene et al. 2013; Chikoti et al. 2013). Persuading farmers to use CMD-resistant varieties is a challenge because of farmers' preferences for particular cassava traits other than disease resistance.

Lastly, our results underscore the important role of two key sources in providing information to growers: radio (as well as the less widely available TV) and extension workers. While our study demonstrated that extension workers were a highly trusted source of information, only a small proportion of growers were reached by these workers. Growers were more likely to share information within their network of neighbors, friends, and relatives. This does suggest, however, that information received by a grower from an extension worker or the media could percolate (albeit with reduced trust in the source) through the grower's networks to reach a larger number of growers.

The combination of low levels of knowledge and information seen in our results suggests that there is a need for grower education, through extension workers and media, to improve awareness that is vital to controlling cassava disease. Reducing the presence of cassava virus diseases, and increasing the yields of small-holder growers across Zambia and cassava-growing regions in Africa as a whole, will not happen without well-informed growers acting at an individual level to implement disease control.

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