Cassava Bacterial Blight and Postharvest Physiological Deterioration Production Losses and Control Strategies
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Purpose

This brief was prepared to support the Roots, Tubers, and Bananas team evaluate the current severity of cassava bacterial blight (CBB) and postharvest physiological deterioration (PPD) production impacts in Sub-Saharan Africa (SSA). It compiles estimates of production losses of these constraints as compared to other major cassava constraints, describes management interventions to combat CBB and PPD, and identifies research gaps.

Abstract

Cassava production is prone to many constraints throughout the production cycle, including biotic, abiotic, and management constraints. This brief reviews the literature on the production impacts of two key cassava stressors of interest to the Bill & Melinda Gates Foundation: cassava bacterial blight (CBB) and postharvest physiological deterioration (PPD). We summarize available estimates of the frequency and magnitude of these constraints relative to other drivers of cassava production losses that affect smallholder farmers in Sub-Saharan Africa (SSA), review the control strategies proposed in the literature, report on the views of several experts in the field, and identify research gaps where relatively little appears to be known about CBB or PPD yield impacts or best practices for CBB or PPD management.

Introduction

The tuberous root of cassava (*Manihot esculenta* Crantz) is the fourth most important food source for carbohydrates in the tropics after rice, maize, and sugar cane; it is a staple food for more than 500 million people (Moorthy, 2002; Davis, Supatcharee, Khandelwal et al., 2003; Tonukari, 2004; Blagbrough, Bayoumi, Rowan et al., 2010) [as cited in EPAR Request 295]. However, cassava production is prone to many stressors throughout the production cycle, including biotic, abiotic, and management constraints both during the growing season and in crop storage (Fermont, Van Asten, Tittonell et al., 2009a; Waddington, Li, Dixon et al., 2010). This brief reviews the literature on the production impacts, including yield gaps and economic consequences, of two key constraints to cassava production of interest to the Bill & Melinda Gates Foundation: cassava bacterial blight (CBB) and postharvest physiological deterioration (PPD).

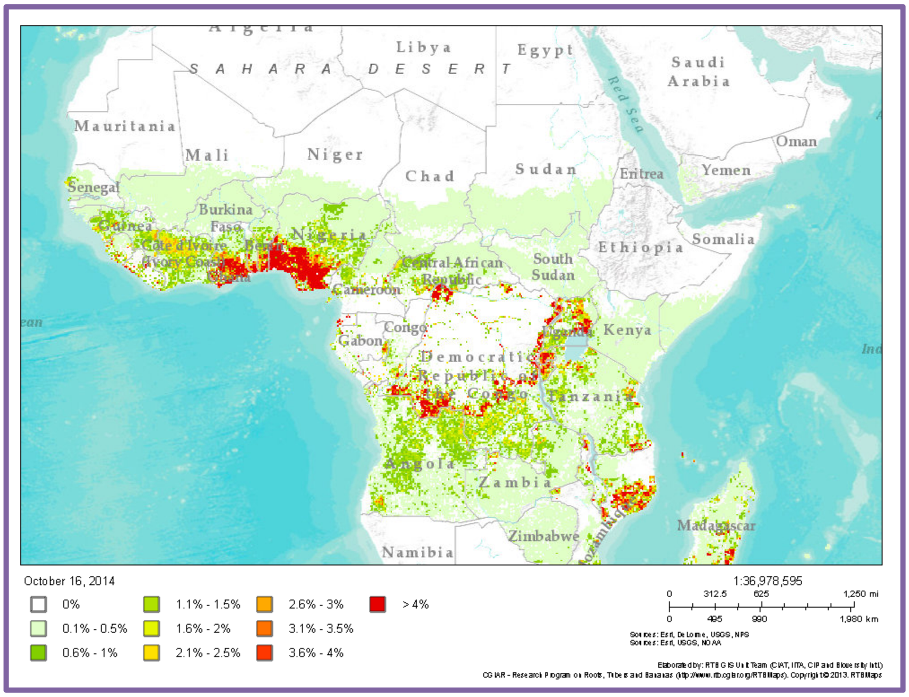
Numerous diseases hinder cassava growth and have received extensive attention in the agronomic literature, particularly cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) (Fargette, Fauquet & Thouvenel, 1988; Legg & Thresh, 2003; Legg & Fauquet, 2004; Bouwmeester, Heuvelink, Legg et al., 2012). Cassava bacterial blight (CBB) caused substantial yield losses throughout Sub-Sarahan Africa in the 1970s, though much less research is available on the current impact of the disease on yields (Wydra & Verdier, 2002).

Postharvest damage and spoilage is another source of substantial food waste and economic losses. The exact duration of cassava shelf life depends on the cultivar, harvest practices and handling, and storage conditions, but the process of postharvest physiological deterioration (PPD) normally sets in within 24-48 hours of harvest. This rapid onset of decay has become an even greater problem with increased urbanization: markets are now at greater distances from cassava fields and processing can entail delays, making PPD a major source of post-harvest loss, especially in areas with less developed transportation networks (Han, Gomez-Vazquez, Buschmann et al., 2001; Reilly, Gomez-Vazquez, Buschmann et al., 2004).

The economic impacts of PPD present an especially severe problem in raw cassava value chains (as opposed to markets for processed cassava products) as the time between harvest and ultimate consumption or end-consumer processing is typically longer (Naziri et al., 2014).

This brief is organized as follows. We first briefly review cassava production and processing practices in Sub-Saharan Africa, highlighting major threats to cassava yield and post-harvest storage. We next review available estimates of the severity of CBB and PPD constraints relative to other major drivers of cassava production losses that affect smallholder farmers in Sub-Saharan Africa (SSA). We then consider each constraint separately – reviewing how CBB and PPD impact yields and control strategies currently proposed in the literature. We conclude by identifying research gaps where relatively little appears to be known about CBB or PPD yield impacts or best practices for CBB or PPD management.

Map 1: Cassava area harvested (% of total crop area harvested)



Source: Adapted from CGIAR, 2014. Dataset from Monfreda, et al., 2008

Cassava Production in Sub-Saharan Africa

Worldwide production of cassava has doubled from 118 million to 276 million metric tons (t) in the past three decades, with the majority of the increase from smallholder farms in SSA. In 2013, Africa accounted for 56% of all cassava production; Nigeria (where cassava is the top-produced commodity) is the world's largest producer at 54 million tonnes (FAOSTAT, 2013). Per capita consumption of cassava is estimated at 80 kilograms per year in Africa, supplying an estimated 37% of all dietary energy (IITA, 2014).

Cassava is an important food security crop, in part because it can grow in marginal soils and can tolerate many abiotic stressors, and because its storage roots grow slowly in the soil and can be harvested progressively between six months and three years after planting (El-Sharkawy, 2006; Alves, 2002; Fermont et al., 2009a) [as cited in EPAR Request 228]. Smallholder farmers in SSA have traditionally grown cassava for home consumption, but it is increasingly grown as a cash crop, particularly in Nigeria and Ghana (Nweke, Spencer, & Lynam, 2002) and parts of East Africa (Fermont et al., 2010).

Increased production in recent decades is mainly attributable to increases in the amount of land under cultivation, rather than increases in yield (Fermont, 2009b). Cassava is currently harvested over a wide geographic area in SSA, with concentrations throughout West, Central and East Africa and in Madagascar (see Map 1). Cassava can be intercropped with many other crops such as vegetables, coconut, oil palm, coffee, yam, sweet potato, melon, maize, rice, groundnut, and other legumes (IITA, 2009) [as cited in EPAR Request 295].

Cassava must be processed before consuming due to the presence of cyanide, a toxic substance to humans (Hahn & Keyser, 1985). Cassava processing can vary greatly, from simple peeling and boiling to more complicated procedures for pounded products, including peeling, grating, pressing, fermenting, sifting, and roasting. In some areas of Africa, cassava leaves are consumed as vegetables. Common cassava products include *gari* (a fermented, roasted cassava pulp), *lafun* (fermented, dried cassava pulp, also referred to as *cossettes* in the Democratic Republic of the Congo and Rwanda, *kanyanga* and *mapanga* in

Malawi, and *makopa* in Tanzania), *kumkum* (smoked cassava balls), *chickwangue* (fermented pulp consumed in plantain leaves), and *fufu* (a fermented, pounded cassava paste) (Hahn & Keyser, 1985) [as cited in EPAR Request 295].[1]

Constraints to Cassava Production

Key stressors affecting cassava production include several pests and diseases, as well as the unusually poor storage qualities of harvested roots which can result in significant wasted resources and effort [as cited in EPAR Request 228]. Severe production constraints to cassava yield, as categorized by Waddington et al. (2010), are summarized in Table 1.

Table 1: Production Constraints Contributing to Yield Gaps

Biotic	Abiotic	Management	Socio-economic
Diseases Weeds Inappropriate varieties	Nutrient deficiency Drought	Unsuitable planting time or late planting Poor choice of varieties	Difficult access to finance Unavailability of markets High price of fertilizer Inadequate farmer knowledge

Source: Waddington et al., 2010

Relatively few comparative estimates of yield losses caused by the various cassava constraints are available in the literature, and comparative studies published in the last 20 years have typically examined only preharvest losses (not postharvest losses). In Africa, cassava mosaic disease (CMD) is generally recognized as the most serious disease afflicting cassava, and some sources rank CBB as the second most important (Hillocks & Wydra, 2002). Table 2 summarizes how key cassava diseases and other stressors affect yield as estimated in the published literature.

Table 2: Effects of Cassava Stressors on Yield

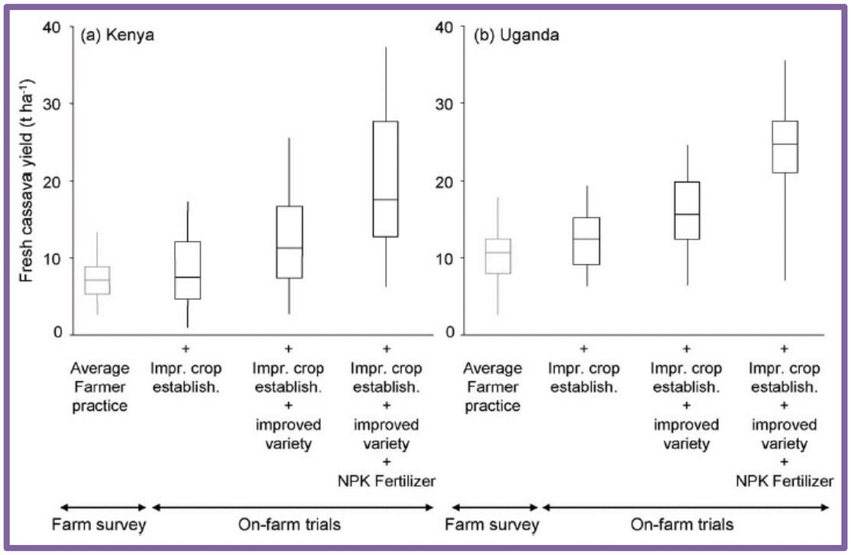
Stressor	Estimated Tuber Yield Reduction*	Source
Cassava mosaic disease (CMD)	20-90%	EARRNET, 2015
	12-82%	Owor, 2002
	Up to 47%	Bouwmeester et al., 2012
	37%	Fargette et al., 1988
	30-40%	Thresh et al., 1997; Legg & Thresh, 2003
Cassava bacterial blight (CBB)	13-100%	Hillocks & Wydra, 2002
	30-80%	Lozano, 1986
	20-100%	EARRNET, 2015
	13-50%	Wydra et al., 2001 (cited in Hillocks & Wydra, 2002)
Weeds	Up to 95%	Melifonwu, 1994
	40-70%	Agahiu et al., 2011
	50-65%	Fermont et al., 2009a
Drought	83%	Vandegeer et al., 2013
	32-60%	Omonona & Akinpelu, 2012
	39%	Okogbenin, 2002 (cited in Okogbenin et al., 2011)
Cassava root rot	Up to 80%	Msikita et al. 2005 (cited in Okechukwu et al., 2009)
	15-25%	Mwangi et al., unpublished; Messiga et al., 2004 (cited in Bandyopadhyay et al., 2006)
Cassava green mite	13-80%	Bellotti, 2002
	Up to 40%	EARRNET, 2015
Cassava mealybug	Up to 80%	EARRNET, 2015
Cassava brown streak disease	60-70%	Hillocks & Thresh, 2001; Cuambe et al., 2007 (cited in Zacarias & Labuschagne, 2010)
	17-70%	Hillocks et al., 2001
Whitefly-associated stressors	13-65%	Gold, 1990
Whitefly direct damage (feeding - affects CMD-resistant varieties only)	12.5-44.6%	Stansly & McKenzie, 2008
Postharvest physiological deterioration (PPD)	5-25%	Wenham, 1995
	19% worldwide 29% in Africa	Salcedo, 2010

*Yield reduction estimates are collected from multiple sources and may not represent consistent estimation methods.

[1] Cassava also has many industrial uses ranging from sweeteners to glues, plywood, textiles, paper and drugs. Cassava chips are widely used in animal feed (IITA, 2009). Cassava starch is suitable for specialty uses in food processing, textiles, and paper (Blagbrough, Bayoumi, Rowan et al., 2010). Cassava varieties of poor cooking quality and high cyanogenic potential can be used for production of starch, glucose, adhesives, fuel alcohol and other industrial materials (Aryee, Oduro, Ellis et al., 2005).

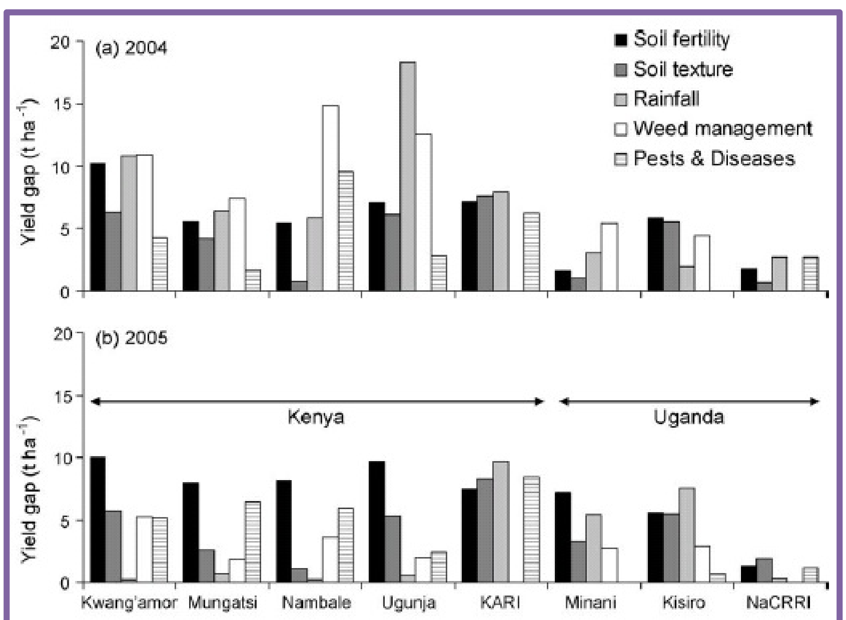
The International Institute of Tropical Agriculture (IITA) has played a role in developing improved cassava varieties that are high-yielding and resist CMD, CBB, green mite, mealybug, anthracnose disease, root rot, and some abiotic stressors including drought [as cited in EPAR Request 228]. Improved varieties are now grown in most cassava-growing countries in SSA (IITA, 2014) [as cited in EPAR Request 295].

Figure 1: Cassava Yields under Varying Farming Practices in Kenya and Uganda



Source: Fermont et al., 2009a

Figure 2: Yield Gaps Caused by Cassava Constraints in Kenya and Uganda



(c)	Soil fertility	Soil texture	Rainfall	Weed Management	Pests & Diseases
Overall	6.7 ± 4.9	4.3 ± 4.7	5.4 ± 5.5	5.0 ± 6.2	3.8 ± 3.7
Kenya	7.9 ± 4.9	4.7 ± 5.0	6.1 ± 6.2	6.0 ± 6.4	5.3 ± 3.5
Uganda	4.3 ± 4.2	3.2 ± 4.0	4.0 ± 3.1	3.0 ± 5.4	0.6 ± 1.3

Source: Fermont et al., 2009a

Other authors have found that management practices and socioeconomic factors may limit cassava production more than biotic stressors do (Fermont et al., 2009a; Waddington et al., 2010). Fermont and colleagues (2009a) conducted farm surveys and agronomic trials in Uganda and Kenya and identified poor soil fertility, water stress, and sub-optimal weed management as the top yield limitations, noting that "pests and diseases were relatively unimportant." Figure 1 shows estimates of how cassava yields change with better management practices, improved varieties, and use of fertilizer.

Figure 2 shows estimated yield losses from each category of cassava constraint. In their farmer survey, Fermont et al. (2009a) also collected data on farmers' perception of production constraints. Though weed growth can limit yield by 40-95% if uncontrolled (Agahiu, Udensi, Tarawali et al., 2011; Melifonwu, 1994), only 12% of farmers surveyed perceived weeds as an important production constraint. In contrast, pests and diseases were cited as a concern by 68% of farmers, yet had only a small effect on measured yield. This discrepancy is believed to be due to the more readily observable impacts of pests and disease than weed competition. Sixty-two percent of the farmers perceived soil fertility as a problem, and 22% perceived it as the most important problem, which aligned more closely with the results of scientific trials (Figure 2). The study did not consider the implications of postharvest losses (Fermont et al., 2009a).

In a similar but broader multi-crop and multi-region study, Waddington et al. (2010) conducted surveys of crop experts to determine the most severe production constraints for six staple crops. For cassava in SSA, they calculated a smallholder farm yield gap (defined as the difference between the highest yield achieved on smallholder farms and the average yield) of 8-12%, depending on the farming system. Of this gap, roughly 29% was due to socioeconomic constraints, 21% abiotic constraints, 23% biotic constraints, and 26% management constraints. The findings of Waddington et al. (2010) are summarized in Table 3. CBB and PPD did not rank among the top ten limitations for cassava; however, many of the most important cassava constraints identified cannot be addressed by the development of improved varieties (as CBB and PPD in theory can) and would instead require broader policy interventions.

Table 3: The Ten Most Severe Production Constraints for Cassava in Four Farming Systems

Cassava Constraint	Yield Loss (root wet weight, kg/ha)	% of yield gap	Cassava Constraint	Yield Loss (root wet weight, kg/ha)	% of yield gap
SSA – Root Crop System			*SSA – Cereal-Root Crop Mixed System*		
Difficult access to finance	722	9	Difficult access to finance	653	7
Lack of policy support for crop	691	8	Use of unimproved or unsuitable varieties	491	5
Unavailability of stable formal market for roots	542	7	Weed competition	471	5
Excessively long occupation of field by crop	445	5	Lack of policy support for crop	471	5
Weed competition	436	5	Inadequate fertilizer management	421	5
African cassava mosaic virus	362	4	Unavailability of stable formal market for roots	384	4
Soil fertility depletion	336	4	Soil fertility depletion	377	4
Use of unimproved or unsuitable varieties	326	4	African cassava mosaic virus	351	4
Inadequate fertilizer management	288	3	Excessively long occupation of field by crop	329	4
Poor choice of planting time; late planting	215	3	Early harvest of roots	273	3
TOTAL	**4364**	**53**	**TOTAL**	**4221**	**47**
SSA – Maize Mixed System			*East Asia – Upland Intensive System*		
Use of unimproved or unsuitable varieties	603	5	Soil physical degradation	1058	6
Poor quality stakes/cuttings (or seed) for planting	528	4	Soil fertility depletion	984	5
Weed competition	491	4	Weed competition	936	5
Soil fertility depletion	482	4	Inadequate fertilizer management	895	5
N deficiency	449	4	Fertilizer expensive and in short supply	890	5
Inadequate fertilizer management	445	4	Use of unimproved or unsuitable varieties	804	4
Inadequate farmer production and utilization knowledge or training	424	3	Drought, dry periods, with the growing crop	744	4
African cassava mosaic virus	383	3	Poor quality stakes/cuttings (or seed) for planting	631	3
Continuous cropping, reduced bush fallow period	349	3	Lack of policy support for crop	604	3
Soil physical degradation	346	3	Difficult access to finance	590	3
TOTAL	**4499**	**37**	**TOTAL**	**8134**	**42**

Source: Adapted from Waddington et al., 2010

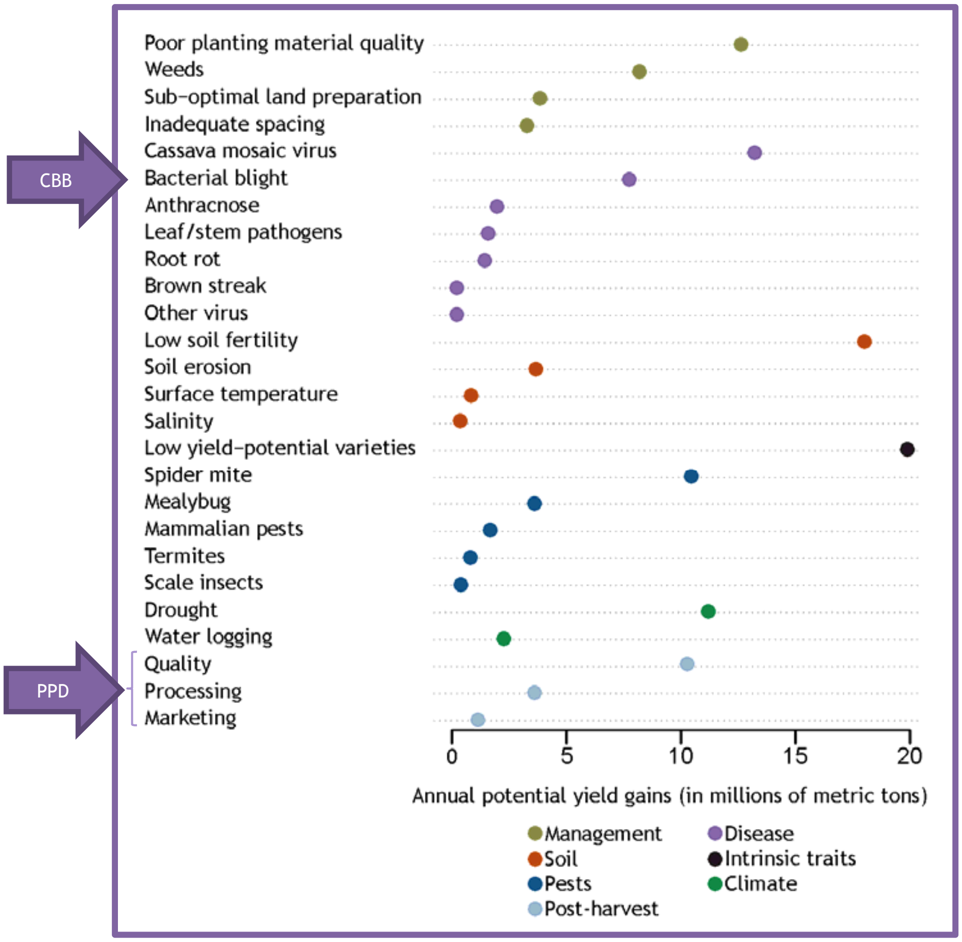
In the mid-1990s, scientists at the International Center for Tropical Agriculture (CIAT) conducted an extensive survey of global cassava trends, including an in-depth comparison of pre- and postharvest constraints (Henry & Gottret, 1996). The authors based yield loss and potential yield gain estimates on surveys of cassava scientists and extensionists about production and processing constraints. They found that the most severe constraints varied by continent and by agroecology. In Africa, pests and diseases accounted for 30% of losses, while management practices accounted for 20%. Post-harvest losses including quality, processing, and marketing losses were also substantial (note PPD is involved in all these post-harvest losses but its effects were not isolated in this study). The estimated yield impacts of cassava constraints in Africa as reported in this 1996 CIAT study are summarized in Figure 3.

Early research in Uganda by the International Institute for Tropical Agriculture (IITA) also cited disease, insect pests, insufficient storage systems, weeds, poor quality planting material, lack of improved varieties and rodent damage as important constraints (IITA, 2001a).[2] Parallel reports in the Democratic Republic of Congo (IITA, 2001b) identified diseases (cassava mosaic disease, bacterial blight, and root rot), lack of mechanization for land preparation, labour, low yields, lack of planting material, and pests (mealybug, green mite, and root scale) as key limitations, while diseases, lack of planting material, pests, lack of land, and theft have been cited as the main problems affecting cassava production in Rwanda (IITA,

[2] In a 2013 dissertation, Tumuhimbise conducted a participatory rural appraisal in Uganda and found that disease (in general) was the most important constraint, followed by the lack of early bulking cultivars, and thirdly rodents, specifically mole rats, squirrels and porcupines. Insect pests including green spider mites, whiteflies, and termites were the fourth most important constraint, while poor storability of roots was identified only as a minor constraint relative to the four most important.

2001c). Mbwika (2002) summarized these cross-country results, identifying pests, diseases, and lack of planting materials as the most important constraints to cassava production in Burundi, Madagascar, Rwanda, Kenya, and Democratic Republic of Congo (see Appendix B).

Figure 3: Yield Losses from Cassava Constraints in Africa (1996 yield gap estimates)



Source: Adapted from Henry & Gottret, 1996 (Annex 3, p. 45).

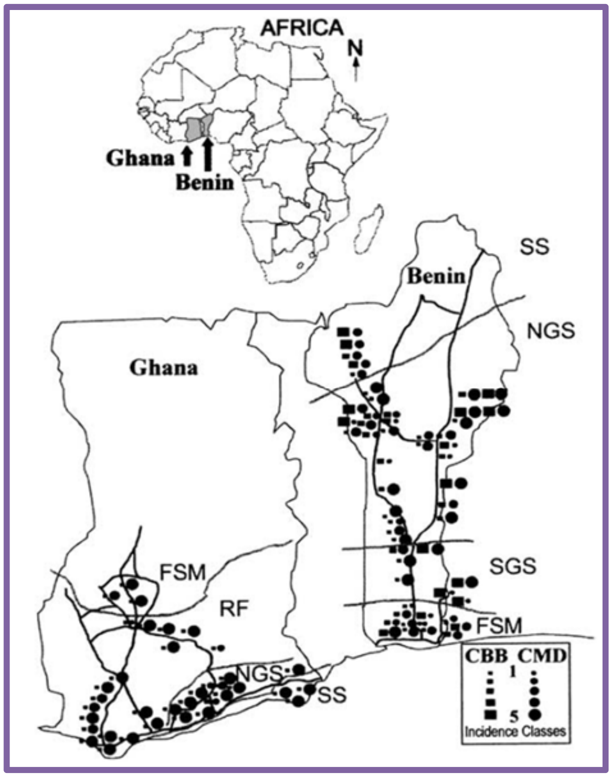
Most recent cassava research has either not considered the production and post-production impacts of CBB or PPD, or has provided insufficient data to judge the relative importance of CBB and PPD as cassava constraints. For example a recent study in Cambodia found that only soil quality and crop duration were significant factors affecting cassava yield, while no serious insect or disease damage was observed (Sopheap, Patanothai, & Aye, 2012). In Africa, Zinga et al. (2013) conducted a large-scale plant epidemiological survey in Central African Republic. Though they screened for it, they found no incidence of CBB, and determined that CMD was the most serious threat to cassava in Central African Republic, followed by cassava green mite and mealybug, which had much lower incidence (Zinga, Chiroleu, Legg et al., 2013). This study observed only disease severity and did not measure yield losses, nor did it consider post-harvest losses (such as PPD). Similarly, in a field survey in Taraba State, Nigeria, Yuguda et al. (2013) found that diseases ranked below access to funds, labor, land or extension services, and below general price concerns and input costs as important constraints to the 120 farmers surveyed. Yet reports are inconsistent, even within Nigeria - for example, in a 2010 study in Enugu State, Akinnagbe (2010) found pests and diseases along with poor processing to be among the most severe agronomic problems (contrary to Yuguda et al.'s 2013 results).

The following sections review the limited published empirical data available on CBB and PPD to date.

Cassava Bacterial Blight

In periods of severe outbreaks cassava bacterial blight (CBB) has been considered the second most severe cassava disease in terms of yield losses, after cassava mosaic disease (CMD) (Hillocks & Wydra, 2002). Without control strategies, root yield losses can reach 90% in CBB-infected crops (Lozano, 1986).

Figure 4: CBB Incidence in Ghana and Benin



Source: Wydra & Verdier, 2002

The pathogen *Xanthomonas axonopodis* pv. *Manihotis* (*Xam*) causes CBB (Lopez et al., 2007) and is present wherever cassava is grown (Lozano, 1986). *Xam* bacteria penetrate cassava leaf surfaces in order to multiply in the vascular system (Jorge et al., 2001). Symptoms include blocked vascular tissues, leaf wilt and blighting, stem necrosis, and dieback (Jorge et al., 2000; Verdier et al., 1998). Within a plot, *Xam* bacteria typically spread during periods of heavy rainfall through splashing (Jorge et al., 2000; Restrepo et al., 2000). *Xam* bacteria cannot survive in the soil during the dry season, but can survive asymptomatically in stem tissue, seeds, and plant debris for extended periods (Restrepo et al., 2000; Verdier et al., 1998, Wydra & Verdier, 2002). As cassava is planted through vegetative propagation, the widespread use of infected cuttings spreads the pathogen from one cassava plot to another (Jorge et al., 2000; Verdier et al., 1998).

CBB Prevalence and Severity

Several devastating outbreaks of CBB occurred in Nigeria, Cameroon, Ghana, Congo, Benin, Togo, Rwanda, and Uganda in the 1970s (Wydra & Verdier, 2002), and an outbreak in 1975 caused root yield losses of 75% and widespread starvation in the Democratic Republic of the Congo (Lozano, 1986; Kemp et al., 2005). However, the extent of CBB in SSA today is difficult to determine, since disease surveys since the 1970s have been relatively infrequent (Wydra & Verdier, 2002).

As shown in Table 4, the relatively few surveys undertaken in recent years have found great variation in rates of CBB. A 1993 survey in West Africa found CBB at 34 of 54 randomly selected fields in Benin, but only one of 36 in Ghana, as shown in Figure 4 (cited in Wydra & Verdier, 2002). Onyeka's (2008) surveys in Nigeria found CBB in over 70% of sampled fields in 2001. In East Africa, CBB affected only 14% of fields and 2% of plants surveyed in Rwanda (Night et al., 2011), while a field experiment in Uganda under natural disease conditions observed CBB in 89% of fields studied (Abaca et al., 2014).

Table 4: Surveys of Cassava Bacterial Blight Incidence by Location

Plants affected	Sites/fields affected	Country	Region	Study type	Source
Not reported	89%	Uganda	East Africa	Experiment	Abaca et al., 2014
2%	14%	Rwanda	East Africa	Survey	Night et al., 2011
27-73%, varied by ecozone	53-91%, varied by ecozone	Togo	West Africa	Survey	Banito et al., 2007
Not reported	More than 70% (2001), 34-90%, varied by ecozone (2003)	Nigeria	West Africa	Survey	Onyeka, et al., 2008
44%	63%	Benin	West Africa	Survey	Wydra & Verdier, 2002
3%	3%	Ghana	West Africa	Survey	Wydra & Verdier, 2002

CBB incidence and severity also varies by ecozone. Wydra & Verdier found that drier ecozones in Benin and Ghana tended to have greater incidence of CBB (2002). 90.5% of fields in dry savanna ecozones in Togo were infected with CBB, compared to 70% in forest-savanna transition zones, 64% in the wet savanna, and 52.6% in the forest zone (Banito et al., 2007). Although Onyeka's (2008) survey in Nigeria found consistent CBB incidence in over 70% of fields for all ecozones in 2001, rates varied from 33.7% (humid forest) to over 90% (Southern Guinea savannah, Northern Guinea savannah, Sudan savannah) in 2003.

CBB Yield Losses and Economic Effects

CBB is capable of causing devastating root yield losses. In 1996, CIAT estimated that 7.5 million tons of cassava yields were lost annually to CBB in SSA (Henry & Gottret, 1996). Lozano's (1989) field experiments in Brazil using a susceptible cultivar found that cassava tuber yields generally decreased as the percentage of CBB-infected cuttings used increased, with yield reductions as great as 72% (from an average 28.9 t/ha down to 8.1 t/ha) in fully CBB-infested fields, as shown in Table 5.

However, the overall impact of CBB on cassava yield under natural conditions is difficult to estimate. Firstly, accurate identification of the disease can be difficult without plant pathology equipment, as CBB often occurs alongside secondary bacterial, fungal or viral infections, and cassava severely infected with bacterial blight looks similar to drought-afflicted cassava (R. Bart, personal communication, February 27, 2015). Moreover, although yield losses may be significant within a single growing season, a season of low infection may follow, as reported in Ghana and Benin (Wydra & Verdier, 2002). Some cultivars have endured the disease without yield losses, and others inoculated with the disease actually had increased root yield compared to controls (Zinsou et al., 2005). Fokunang et al. (2000) did not find a significant correlation between measures of disease severity and root yield, but did find a significant negative correlation between CBB incidence and root yield. Symptom severity is not clearly correlated with root yield loss, making yield losses under specific conditions difficult to predict (Zinsou et al., 2005; Wydra & Verdier, 2002; Otim-Nape, 1980).

Table 5: Yield Reduction Due to the Use of CBB-infected Cuttings

% of CBB-infected cuttings planted	Yield (t/ha)	Yield reduction
0	28.9	--
25	20.4	29.4%
50	15.8	45.3%
75	17.9	38.1%
100	8.1	72.0%

Source: Lozano, 1989

CBB Control Strategies

CBB has long been considered as a disease that can be controlled or prevented via multiple means including selection of clean planting materials and effective pest management (Lozano, 1986). Key to CBB prevention is selection of healthy cuttings for planting. In already-infected fields or in areas where the likelihood of infection is high, a number of control strategies are available, including several reportedly CCB-resistant cultivars.

Resistant cultivars

In the recent literature the most commonly cited strategy for controlling CBB is the use of resistant cultivars (Trujillo et al., 2014). However, several factors make CBB resistance in cassava complex. Resistance is quantitative, meaning that vascular tissues in resistant cultivars are colonized by *Xam* bacteria at a slower rate than in susceptible cultivars; in other words, *Xam* infection is *limited*, but not completely avoided (Jorge et al., 2000). It is also possible for cassava cultivars to be resistant to some strains of *Xam* bacteria, but not others (Sanchez et al., 1999), or resistant to leaf inoculation but not stem inoculation, or vice versa (Wydra & Banito, 2007; Zinsou et al., 2005). Most significantly, the resistance of cultivars to CBB varies by ecozone, with no cultivar judged as resistant across forest-savanna transition, wet savanna, and dry savanna ecozones in Benin (Zinsou et al., 2005). A very preliminary analysis of recent unpublished data by Bart et al. (R. Bart, personal communication, March 23, 2015) reveal no significant difference in CBB susceptibility across 14 diverse cassava varieties, including some varieties widely considered "CBB-susceptible" and others once thought to be "CBB-resistant" (Appendix C).

Table 6 is a summary of recent studies of CBB control strategies. The International Institute of Tropical Agriculture (IITA) was the source for all improved cultivars tested. Field experiments were conducted under natural disease conditions, while Banito et al.'s (2010) laboratory experiment used stem inoculation of the CBB pathogen. TMS30572, the most widely used CBB-resistant cassava cultivar (Banito et al., 2010), was recommended by three of the four studies investigating improved cultivars.

Table 6: CBB Control Strategies

Control strategy	Results	Study Type	Location	Source
Improved cultivars TMS30572, TMS91/02316	Moderate resistance, high tuber yield	Laboratory experiment	Togo	Banito et al., 2010
Improved cultivar 94/0026	High resistance, high tuber yield	Field experiment	Nigeria (humid forest zone)	Nwafor et al., 2010
Improved cultivars TMS30572, CVTM4, TMS92/0429, TMS91/02316	Low CBB symptom severity, high tuber yield across ecozones	Field experiment	Togo (forest, forest-savanna transition, wet savanna)	Wydra et al., 2007
Improved cultivar TMS30572	Moderate resistance across ecozones, high tuber yield	Field experiment	Benin (forest-savanna transition, wet savanna, dry savanna)	Zinsou et al., 2005
Intercropping (cassava-taro and cassava-maize)	Reduction in bacterial blight severity by 6-23%, yield effects generally not significant	Field experiment	Togo (forest highland, forest savanna transition, forest lowland, wet savanna)	Banito, 2003
Intercropping (cassava-maize)	Reduction in bacterial blight by up to 53%, yield effects not significant	Field experiment	Nigeria (forest savanna transition)	Fanou, 1999 (cited in Banito, 2003)
Intercropping (cassava-sorghum)	Reduction in disease severity in 14 of 22 treatments, reduced cassava root yields in 10 of 22 treatments	Field experiment	Benin (forest-savanna transition, dry savanna)	Zinsou et al., 2004
Delayed planting[3]	Reduction in disease severity in 24 of 36 treatments, reduced cassava root yields in 9 of 36 treatments	Field experiment	Benin (forest-savanna transition, dry savanna)	Zinsou et al., 2004

In spite of increasing availability, cassava cultivars resistant to CBB are not often used, since other cultivars may be better adapted to particular ecozones, or may have other desirable yield or flavor characteristics. The majority of commercial cassava cultivars today remain susceptible to CBB (Lopez & Bernal, 2012). Zinsou et al. (2005) recommend continued attempts at breeding high-yield cassava cultivars resistant to CBB under different combinations of *Xam* strains and environmental conditions.

Other strategies

Table 6 also includes recent studies on other control strategies for CBB. These include weeding, burying infected plant debris, crop rotation, grasshopper control (Wydra & Verdier, 2002), intercropping (Banito, 2003), delayed planting (Zinsou et al., 2004), as well as biological control through antagonistic bacteria (Boher & Verdier, 1994). Of these recommended strategies, only intercropping and delayed planting appear to have been tested.

Intercropping is believed to prevent the spread of CBB since the other crop acts as a physical barrier to rain splash (Banito, 2003; Zinsou et al., 2004). Banito (2003) cautiously recommends intercropping as part of a CBB control strategy, noting that significant reductions in disease incidence did not correspond to significant increases in cassava root yield in his study. However, a combination of resistant cultivars and intercropping may increase per-hectare yields, as long as the cropping system is adapted to environmental conditions. For example, Zinsou et al. (2004) find that although cassava-sorghum intercropping sometimes reduced cassava root yield, additional sorghum yield in such systems could partially compensate for lost cassava yield (Zinsou et al., 2004).

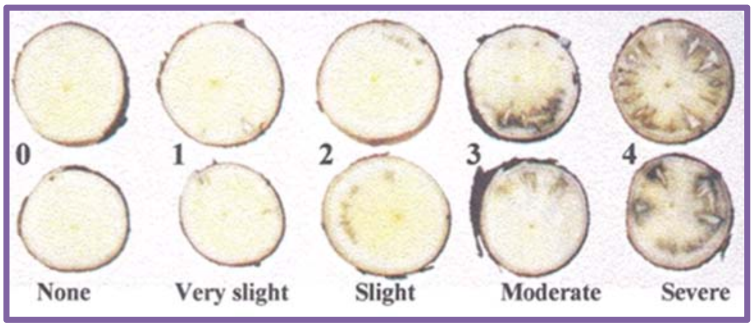
Other CBB-mitigation strategies such as delayed planting largely lack empirical backing, with some research actually advising against late planting since root yields were significantly lower in some experimental treatments, especially in the dry savanna zone (Zinsou et al., 2004). Both Banito (2003) and Zinsou et al. (2004) also tested the effect of KCl fertilizer and mulch on CBB severity, but did not find strong enough results to recommend either for CBB control.

[3] Early trials in Colombia also showed that planting near the end of the rainy season could reduce losses from CBB (Hershey, 2012).

Postharvest Physiological Deterioration
Cassava deteriorates much more rapidly than other tuber and tuberous root crops such as yam and sweet potato. Physiological deterioration occurs two to three days after harvesting, followed by microbial deterioration three to five days after that (Karim & Fasasi, 2009) [as cited in EPAR brief 228]. This process, known as postharvest physiological deterioration (PPD), begins at the wounded root terminal and is influenced by the cultivar as well as environmental conditions (Salcedo et al., 2010) [as cited in EPAR brief 228]. Symptoms include blue/black vascular streaking, brownish occlusions, and chemical deposits from wound sites, followed by discoloration of the storage tissues and an unpleasant flavor and odor (see Figure 5) (Reilly et al., 2007) [as cited in EPAR brief 228]. Significant quantities of cassava root are also damaged or rot during transportation to markets or processing facilities (Wenham, 1995) [as cited in EPAR brief 228].

Cassava's low level of required inputs, including tolerating low soil fertility and field labor, contrasts sharply with the high risk and postharvest input levels involved in transporting, marketing, and selling the crop after harvest (Fernando Cortes et al., 2002). Traditional methods and a variety of researcher developed storage techniques have been developed to mitigate the onset of PPD; however many are not suited to mass settings due to the high cost of materials involved, or other restrictions such as transportability of roots (Zidenga et al., 2012). With the rising urbanization of cassava producing countries, PPD is becoming an increasingly important constraint as the time and distance between farm and market or processor lengthen (Blagbrough et al, 2010).

Figure 5: Scale for Evaluating Postharvest Physiological Deterioration Severity



Source: Acedo & Acedo, 2013

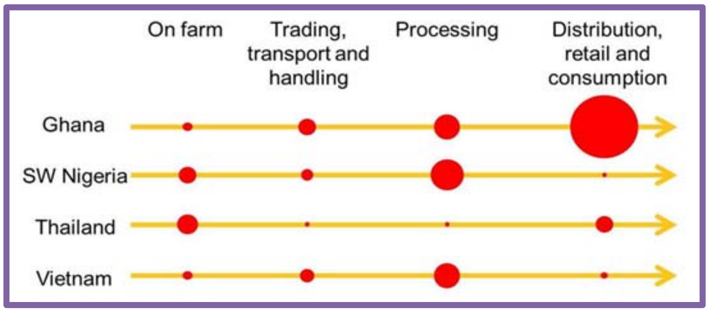
PPD Prevalence and Severity
PPD is differentiated from many other constraints on cassava use and production in that it is not a pest or disease, but rather an abiotic process characteristic of the plant itself. Though not totally understood, PPD is thought to be an incomplete wound response to mechanical damage unavoidable in the harvesting process, which initiates a variety of biochemical responses (Fernando Cortes et al., 2002). The factors causing PPD are variable and wide ranging, but scientific research on the processes and pathways leading to PPD seem to be converging to oxidative stresses that may be associated with alternative respiratory pathways and potentially cyanide production (Sayre et al., 2011; Xu et al., 2013; Vanderschuren et al., 2014).

Because the process does not seem to be controlled by a single chemical pathway, many questions remain surrounding the causes of PPD and the reasons why different cultivars - and even different plants of the same cultivar - can have different levels of PPD susceptibility.

Recent grey and published literature, as summarized on the University of Greenwich Natural Resources Institute (NRI) Postharvest Loss Reduction Centre website, highlights extreme variation in post-harvest loss across and within countries depending on how cassava is produced, processed, and consumed, and on the level of coordination between the different actors in the supply chain[4]. Naziri et al. (2014) estimated physical losses (i.e., cassava lost entirely to spoilage) at 12% in Ghana, 7% in South-West Nigeria, 3% in Vietnam and 2% in Thailand, with losses occurring at different stages of the value chain (Figure 6). Losses at the distribution, retail and consumption level are particularly high in Ghana due to the large percentage of cassava that reaches the final consumer in a fresh root form, and the value of the loss reflects the high price (and therefore expensive waste) of cassava at this end point in the value chain. There is less loss at this point in the value

[4] See NRI Postharvest Loss Reduction Centre website at http://postharvest.nri.org/scenarios/roots-and-tubers

Figure 6: Relative Extent of Physical Losses in Cassava Value Chains



Source: NRI Postharvest Loss Reduction Centre, 2014

chain in Southwest Nigeria, in part because most cassava in the region is distributed and retailed in a processed form (Naziri et al., 2014).

PPD Yield Losses and Economic Effects

Most of the papers reviewed in the preparation of this brief sought to explain the biochemical pathways that cause PPD, rather than estimating current yield losses (Owiti et al., 2011; Buschmann et al., 2000; Bayoumi et al., 2008). However, researchers are increasingly recognizing PPD as a major problem for cassava, with some ranking it as among the most important next to CMD (Sayre et al., 2011). Overall postharvest losses due to PPD in Sub-Saharan Africa are difficult to estimate because most large-scale studies do not separate postharvest losses from PPD from other postharvest losses (Wenham, 1995). Summarizing one of the few PPD-specific loss studies, Table 7 presents estimates of cassava affected by PPD in four countries with different markets for cassava products (Naziri et al., 2014).

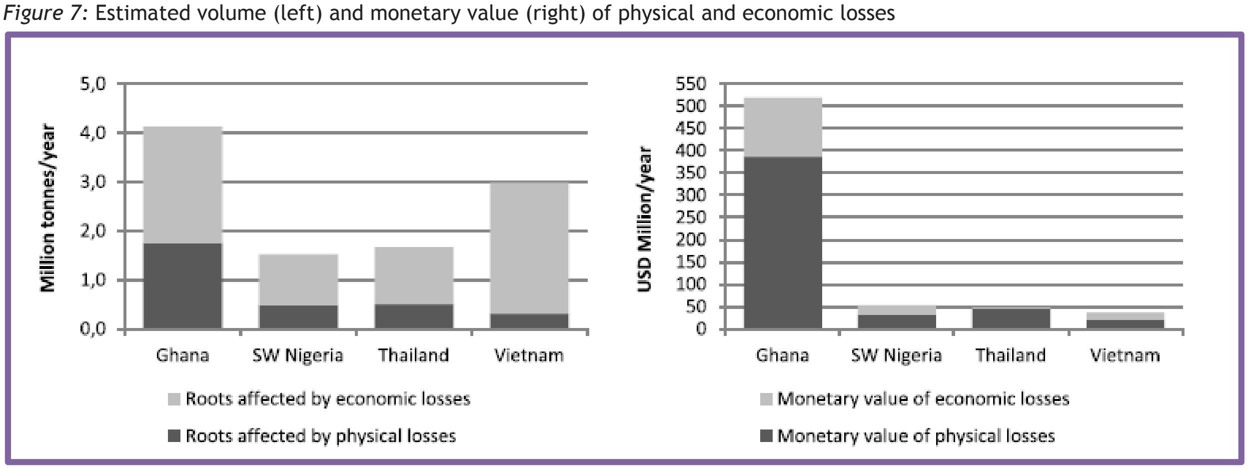
Table 7: Estimation of PPD Incidence by Country.

Country	Overall harvest or sub-chain	Percentage of harvest affected	Volume of cassava affected
Ghana **Production: 14,240,867 t/yr**	Overall harvest	19%	2.4 million tonnes per annum
	Fresh cassava root (FCR)	28%	
SW Nigeria **Production: 7,500,820 t/yr**	Overall harvest	16%	1.0 million tonnes per annum
Thailand **Production: 21,912,416 t/yr**	Overall harvest	5.5%	1.2 million tonnes per annum
Vietnam **Production: 9,870,000 t/yr**	Overall harvest	28%	2.7 million tonnes per annum
	Wet starch	90%	
	Dry starch	25%	
	Chips	25%	

Source: Naziri et al., 2014

In addition to the physical loss of a crop that spoils entirely due to PPD, the deterioration in cassava quality resulting from PPD often leads producers to offer price discounts or use the harvested cassava to create lower valued products, resulting in additional (often difficult-to-quantify) economic losses (Naziri et al., 2014; Wenham, 1995; Westby et al., 2002). Figure 7 presents an approximation of the physical tonnage affected (million tonnes/year) versus the monetary impacts of losses ($USD millions/year) in the four countries studied by Naziri et al. (2014). While a much larger tonnage of cassava suffers economic losses (declining crop quality) as opposed to physical losses (total crop spoilage), in all countries the monetary value of economic losses overall is lower than the monetary value of physical losses. This is because physical losses are a "total loss", while degraded roots still have some value – a fact that makes calculating the economic impacts of PPD all the more difficult.

Figure 7: Estimated volume (left) and monetary value (right) of physical and economic losses



Source: Naziri et al., 2014

Table 8 summarizes the full cross-country post-harvest physical loss estimates as calculated by Naziri et al. (2014). Surveys or interviews conducted with 99 or more experts in each of four countries (Ghana, SW Nigeria, Thailand and Vietnam) were used to perform a value chain analysis (VCA) broken down into sub-chains of different cassava products in each country context. The study further differentiated between physical post-harvest losses (i.e., total loss of roots measured in kilograms) and economic post-harvest losses (i.e., loss of economic value of roots due to partial degradation). Although Naziri et al. (2014) did not explicitly isolate PPD losses from other causes of postharvest loss, PPD was reported as a primary cause of losses in all four countries (Naziri et al., 2014). As summarized in Table 8, there were substantial differences among countries based on the cassava products produced and the distances fresh cassava is typically transported prior to processing.

Table 8: Estimation of physical losses by stage of the sub-value chains

	Physical Loss Value Chain								
	Sub-value chain	Allocation FCR by sub-chain (%)	On farm (t)	Trading, transport and handling (t)	Processing (t)	Retail and consumption (t)	Total physical losses	Share by sub-chain (%)	
Ghana Production: 14,240,867 t/yr	Own-consumption	5%	0 (NEGL)	N/A	N/A	N/A	0	0%	0%
	Fresh root	48%	33,822 (0.5%)	67,306 (1%)	N/A	1,332,657 (20%)	1,433,785	21.20%	82%
	Gari	24%	0 (NEGL)	16,911 (0.5%)	168,265 (5%)	0 (NEGL)	185,176	5.50%	11%
	Agbelima	17%	0 (NEGL)	12,176 (0.5%)	121,151 (5%)	0 (NEGL)	133,327	5.50%	8%
	Kokonte	6%	0 (NEGL)	N/A	N/A	0 (NEGL)	0	0%	0%
	Total	100%	33,822	96,393	289,415	1,332,657	1,752,287	12.40%	100%
	Losses by stage (%)		2%	6%	17%	76%	100%		
SW Nigeria Production: 7,500,820 t/yr	Own-consumption	20%	0 (NEGL)	N/A	N/A	N/A	0	0%	0%
	Gari	52%	39,004 (1%)	19,307 (0.5%)	307,369 (8%)	0 (NEGL)	365,681	9.40%	76%
	Fufu	27%	18,002 (1%)	8,911 (0.5%)	88,664 (5%)	O (NEGL)	115,577	6.40%	24%
	Total	100%	57,006	28,218	396,033	0	481,258	6.70%	100%
	Losses by stage (%)		12%	6%	82%	0%	100%		
Thailand Production: 21,912,416 t/yr	Starch	55%	192,829 (1.5%)	1186 (0.01%)	1,186 (0.01%)	0 (NEGL)	195,201	1.60%	39%
	Chips	45%	157,769 (1.5%)	970 (0.01%)	970 (0.01%)	145,513 (1.5%)	305,223	3.10%	61%
	Total	100%	350,599	2,156	2,156	145,513	500,424	2.30%	100%
	Losses by stage (%)		70%	0.40%	0.40%	29%	100%		
Vietnam Production: 9,870,000 t/yr	Dry starch	55%	0 (NEGL)	27,154 (0.5%)	27,018 (0.5%)	0 (NEGL)	54,172	1.00%	18%
	Wet starch	5%	2,455 (0.5%)	9,772 (2%)	4,788 (1%)	4,740	21,755	4.40%	7%
	Chips	39%	19,248 (0.5%)	19,152 (0.5%)	190,565 (5%)	0 (NEGL)	228,965	5.90%	75%
	Total	100%	21,704	56,078	222,371	4,740	304,893	3.10%	100%
	Losses by stage (%)		7%	18%	73%	2%	100%		
Note: In brackets the share of cassava roots and products affected by physical losses; N/A= not applicable; NEGL= negligible									

Source: Naziri et al., 2014

Available economic estimates suggest delaying PPD and thereby providing increased time to get produce from producer to consumer could be very valuable: Wenham (1995) estimated that increasing the storage life of cassava to two weeks, whether through transgenic or marker assisted breeding or with improved storage methods, could potentially resolve 90% of deterioration constraints (Wenham, 1995). In Ghana alone, the combined monetary impact of the physical and economic losses of cassava (almost entirely occurring post-harvest) has been estimated at more than $500,000,000 annually (Naziri et al., 2014). In an ex ante analysis comparing conventional breeding to marker-assisted breeding, Rudi et al. (2010) estimated the total worth of improved varieties with both disease-resistance and PPD-resistance to be significantly higher than disease-resistance alone: with disease- and PPD-resistance worth $2.9 billion for Nigeria, $855 million for Ghana and $280 million for Uganda over 20 years (as opposed to $1.5 billion for Nigeria, $676 million for Ghana and $53 million for Uganda for only disease resistance) (Rudi et al., 2010). Outside SSA, a study in Thailand estimated that extending cassava's shelf life to 45 days could create 35 million dollars of economic value per year (Vlaar et al., 2007). Largely absent from the literature are esstimates of smallholder and subsistence farmer PPD impacts. In the past some authors have argued that in subsistence farming cassava production losses are negligible as farmers can harvest cassava as needed and use deteriorated product for animal feed - however even if not traded in the market, cassava degradation in subsistence systems entails substantial opportunity costs as the land could otherwise be used to grow other crops (Hall et al., 1998; Westby et al., 2005).

PPD Control Strategies

Improved Varieties

The variety of attempts at creating PPD resistant cultivars show some promise for industrial cassava production, however the gradual loss of starch over the storage process even within PPD-resistant cultivars limits the time for which cassava can be stored. Stored cassava loses starch at a rate of about 1% per day, so after as little as a week it may no longer be useful for industrial applications (Sanchez at al., 2013).

Breeding for PPD resistance is complicated by the multiple chemical pathways and genes that contribute to resistance, and also interact with other desirable qualities in cassava. For example, high dry matter content in cassava is typically desired by industrial producers, but PPD is positively (though weakly) associated with dry matter content (Sanchez et al., 2006). PPD is also negatively associated with carotenoid content: high carotenoid content may delay PPD by 1-2 days. This positive relationship suggests the potential for breeders to develop PPD-resistant cultivars that also have positive nutritive effects (Sanchez et al., 2006). Sayre and colleagues found that overexpression of Arabidopsis alternative oxidase in cassava delayed the onset of PPD by as much as three weeks, and additionally that transgenic plants with elevated β-carotene content had a shelf life of four weeks (Sayre et al, 2011).

Figure 8: Wild Cultivar and High Β-carotene cultivar

Source: Sayre et al., 2011

Breeding for varieties with high carotenoid content could also be useful in animal feed industries, although the starch industry's preference for high dry matter content has led to a focus on high dry matter varieties (less common in currently-developed high carotenoid cultivars). Industrial users also typically prefer a white cassava product, while high-carotenoid cultivars are typically deeper in color as shown in Figure 7 (Sanchez et al., 2006).

Recent research also provides evidence that dry matter content and carotenoid content are independent of one another, suggesting the potential for increasing carotenoid content without interfering with industrial applications of cassava starch (Sanchez et al., 2014).

Ultimately, while improved cassava varieties can improve yields, overall yield per hectare in Africa is far below the maximum yield achieved with existing cultivars. Maximum recorded yield is 90 tons/ha, while Africa's average yield is 8.8 tons/ha. This means that distribution of improved cultivars may make a difference, but production will likely remain constrained by soil quality and agronomic practices (Blagbrough et al., 2010).

Table 9: PPD Mitigation Strategies

Control Strategy	Method of Control	Change in Shelf Life or PPD incidence	Source
Traditional storage methods (such as storage clamps)	Prevents further mechanical damage, creates an optimal temperature and humidity for cassava storage	Up to 2 months	Lebot, 2009

Pre-harvest pruning	Changes physical and biochemical properties in plant, a long standing method.	Pruning 8 days before harvest could reduce PPD susceptibility by 50% and 15 days before harvest could reduce susceptibility by 65% for highly susceptible cultivars	Van Oirschot et al., 2000
Late-harvesting	PPD is instigated by harvesting, but has a flexible harvest date	On demand	Karim & Fasasi, 2009; Wenham, 1995
Hot-water dip and modified atmosphere packaging	Creates an optimal storage situation for cassava	Decreases susceptibility by 11-22%	Acedo & Acedo, 2013
Breeding for overexpressed Arabidopsis alternative oxidase	Reducing cyanide-dependent Reactive Oxygen Species (ROS)production and accumulation through overexpression of the Arabidopsis alternative oxidase (AOX)	Up to 3 weeks	Sayre et al., 2011
Breeding for elevated β-carotene content	Quenching ROS production by the overaccumulation of anti-oxidants (in this case, β-carotene)	Up to 4 weeks	Sayre et al., 2011
GM 905-66 (improved cultivar)	High carotenoid content as a PPD susceptibility reduction tool	At least 40 days	Morante et al., 2010
Breeding for overexpression of superoxide dismutase (SOD) and catalase (CAT)	Scavenging of ROS	Not specified	Xu et al., 2013
Value-chain coordination	If the value chain is coordinated, producers can virtually eliminate losses to PPD by shortening time elapsed between harvest and processing to less than 48 hours	Makes PPD less relevant, as value-chain is developed to fit within the constraints of PPD	Naziri et al., 2014

Other strategies

A variety of traditional and modern approaches have been developed to mitigate the significant postharvest losses of cassava. These include a number of traditional storage methods such as shaded pits or boxes lined with sawdust or coconut husks in which cassava can last up to four weeks in areas with temperatures of 22-24°C. In India, cassava is often stored in "clamps" created by placing 300-500 kg of fresh roots on a bed of straw or grass and covering them with soil and more straw; storage as long as two months is common. Late harvesting is another traditional postharvest loss mitigation strategy – cassava is sometimes harvested late or buried immediately after harvest as a means of storage, particularly in smallholder subsistence farm systems (Karim & Fasasi, 2009; Wenham, 1995) [as cited in EPAR brief 228]. However, leaving cassava in the ground past maturity can lead to loss of starch content and an increase in cooking time due to increased fiber content (Salcedo et al., 2010) [as cited in EPAR brief 228]. Depending on the cultivar, leaving cassava in the ground also leads to a loss in weight and quality after a certain length of time (Lebot, 2009) [as cited in EPAR brief 228].

A variety of modern storage techniques have been developed for cassava, including packing in moist media, freezing, waxing, canning, and storage of fungicide-treated roots in plastic bags. A 2013 study by Acedo & Acedo recommended a 10 minute hot water dip in 54-56°C water in combination with modified atmosphere packing in order to decrease PPD by a further 11-22%. While they mitigate PPD, the technical or financial requirements of these techniques are often out of reach for most smallholder farmers in SSA and SA (Wenham, 1995) [as cited in EPAR brief 228]. Dried cassava is easier to store than fresh cassava, but is vulnerable to losses from fungi, bacteria, insects, and rodents (Lebot, 2009) [as cited in EPAR brief 228].

Crop management practices including pruning the aboveground vegetation of cassava have also been shown to reduce susceptibility to PPD. Van Oirschot et al. (2000) report pruning aboveground cassava vegetation eight days before a planned harvest could reduce cassava susceptibility to PPD by 50%, with a 15 day interval reducing susceptibility by 65% among highly vulnerable cultivars. However they also note this strategy, though promising for some uses of cassava, is unlikely to be adopted for industrial uses as pre-harvest pruning leads to reduced dry matter content, an important consideration for industrial producers looking to extract starch (Van Oirschot et al., 2000).

Finally, value chain coordination is also an effective strategy to mitigate PPD losses. Farmers and producers can eliminate much of the spoilage and deterioration of cassava by minimizing transportation distance and time elapsed between harvest and processing. Naziri et al. (2014) note that in Thailand processors coordinate staggered planting, supply farming inputs, schedule harvests and arrange for transportation so they can minimize delays, and accordingly, minimize losses. Value chains in SSA may present substantial opportunities for post-harvest loss reduction through improved farmer-processor coordination and technical interventions (including relocation of processors closer to farmers), however, these solutions must be specifically designed to fit the characteristics of each unique value chain (Naziri et al., 2014).

Conclusions and Research Gaps

The limited published studies on CBB and PPD to date concur that both can cause substantial yield and economic losses in SSA. But due to a lack of recent disease surveys, varying methods of measuring yield loss, and the potentially multiplicative effect of cassava constraints it is difficult to determine how much the effective control of these constraints could contribute to yield or economic gains (Waddington, 2010; R. Bart, Personal communication, February 27, 2015; J. Onyeka, Personal communication, March 15, 2015).

While CBB can cause large yield losses, recent estimates of the frequency and magnitude of such losses are not yet available. Cassava experts interviewed in the preparation of this brief posited that since CBB has a similar appearance to other diseases and stresses, farmers and scientists may under-report CBB severity while the more dramatic impacts of viruses on cassava production in Africa drives a concentration of research on viral diseases (to the detriment of adequate understanding of other biotic constraints such as CBB) (R. Bart, Personal communication, February 27, 2015; J. Onyeka, Personal communication, March 15, 2015). The cyclical nature of bacterial diseases – with both CBB and associated bacterial and fungal secondary infections related to a host of environmental factors – also makes CBB yield losses and economic impacts difficult to identify. As one expert observed, the disease may disappear for years, and then re-emerge in force in concert with a severe drought or other environmental stressor (making the relative impacts of CBB and drought difficult or impossible to disentangle) (R. Bart, Personal communication, February 27, 2015). "In general, unhealthy plants with abiotic stresses (e.g., drought, nutrient deficiency) tend to be more susceptible to diseases and pests. This means that trying to tease apart the relative impacts of CBB and other diseases will be almost always challenging even with controlled experiments and may not be that meaningful. The bacteria will be around and when crops are stressed damage due to diseases are likely to be amplified" (Soo-Hyung Kim, personal communication, March 20, 2015). Moreover, since CBB is a foliar disease that sets in at the stage when root initiation and bulking have already started, farmers may overlook the potential impact of CBB on productivity since the vigorous foliar growth of cassava plants masks the disease's impacts and, ultimately, at the end of the season farmers still have roots to harvest (unlike other biotic constraints which damage or destroy the root itself) (J. Onyeka, Personal communication, March 15, 2015).

As for PPD, as a primary driver of post-harvest losses PPD is widely acknowledged as an important constraint to overall net yields of cassava, but little reliable information is available on loss figures, and few studies attempt to distinguish between the various causes of loss and waste post-harvest (Wenham, 1995). What limited recent PPD economic research is available tends to address losses in cassava value chains outside Africa (Vlaar et al., 2007). Furthermore, because data may be better collected or more easily economically quantifiable in more developed cassava value chains for processed cassava products, PPD losses may be underestimated in local and subsistence based value chains where fresh cassava is more common. Other studies purport to estimate the possible economic benefits of using marker assisted breeding as opposed to conventional breeding (Rudi et al., 2010), but do not explicitly measure current economic losses caused by PPD. Indeed, even the limited body of recent scholarship seeking directly to quantify PPD impacts (e.g., Naziri et al., 2014) relies upon fairly rough approximations of PPD-related losses, most often derived from expert interviews. Such studies suffer from a number of un-tested assumptions about cassava losses and also fail to take into account non-traded cassava (i.e., all own-consumed cassava lacks a market price and is thus currently excluded from analyses).

Adding to the challenge, farmers may not recognize or select against constraints like CBB or PPD, instead reporting problems and selecting cultivars based on other factors. Kombo et al. (2012) found that smallholder farmers in the Republic of Congo identified high root yields (33%), large sized roots (7%), early maturity (5%), taste (17%), quality for *cossette* food product (15%), friability (4%), and starch content (4%) as the most important preference criteria. Resistance to biotic stressors was much less frequently mentioned as a desired trait: 1.5% of farmers preferred cultivars with resistance to root rot, and less than 1% preferred cultivars tolerant to weeds or mealybugs (Kombo et al., 2012). In a survey focused on women's groups in Kilifi County, Kenya, Mwango'mbe and colleagues (2013) found that farmers selected varieties based on good cooking qualities (over 80% of responses), high yield, and readily available seed. Nearly 60% of respondents in Tajarika selected varieties based on pest resistance, but in Kibanda Meno, fewer than 10% did so[5] (Mwango'mbe et al., 2013). Notably, neither disease resistance nor delayed deterioration were specifically identified as preferred characteristics by either study - although both are at least partially reflected in yield, size, taste and quality preferences.

In terms of CBB and PPD prevention, while the mechanics of cassava resistance to CBB-causing *Xam* bacteria are still not completely understood at the genetic level (Trujillo et al., 2014), Cohn et al. (2014) recently made progress by identifying an apparent susceptibility gene. But overall development of CBB resistant cultivars appears to have made little progress in recent years, with higher crop yields in CBB-infested areas most commonly associated with favorable environmental conditions (good soil nutrients, predictable rainfall) rather than improved varieties (R. Bart, Personal communication, February 27, 2015). Emerging findings such as work by Bart et al. (2012) summarizing the most commonly conserved effector proteins among several strains of *Xam* spanning different continents and countries may help identify resistance proteins and associated genes to develop CBB resistance or at least tolerance. In terms of PPD prevention and control, several traditional and inexpensive methods are widely used to mitigate the effects of PPD, but to varying degrees of success. Recent research suggests oxidative stress may be a major cause of PPD (Sayre et al., 2011; Xu et al., 2013; Vanderschuren et al., 2014), and such research may contribute to the understanding necessary to develop improved cassava varieties with delayed PPD in addition to other farmer-preferred and nutritional traits. Tumuhimbise (2013) notes that farmers' indigenous environmental knowledge and awareness of key agronomic and quality traits for their localities are important to the cassava improvement process, concluding that "it is imperative that breeding programs provide forums for input from the farmers" (Tumuhimbise, 2013). This sentiment was echoed in expert interviews.

Ultimately most published work and the experts consulted in the preparation of this review bemoaned the paucity of data on the yield and economic impacts of under-studied constraints on cassava production including CBB and PPD. Summarily, opportunities to overcome these data deficiencies include:

Expert surveys based on anecdotal knowledge of biotic and abiotic constraints: A relatively low-cost and rapid assessment of the incidence and severity of CBB, PPD and other cassava constraints could be provided through a survey of experts from various target countries (and ideally from different regions within those countries to account for substantial geographic variation in both CBB and PPD). For example, one expert interviewed in the preparation of this brief stated that "incidence of CBB in farmers' fields could be as high as 90% in most cassava producing countries of West and Central Africa depending on the year and season. Although there are not enough scientifically derived data to unequivocally place figures on the yield, and consequently economic impact of the disease in cassava production, it is certainly an important constraint to closing the cassava yield gap" (J. Onyeka, Personal communication, March 15, 2015). An expert survey, drawing on the precedents set by past yield gap expert surveys by Waddington et al. (2010) and others, and perhaps supplemented with an expert convening to allow cross-region and cross-country discussion of CBB and PPD impacts and mitigation strategies, could provide valuable insights into the relative importance of these diseases at the country- or region-level. Even rough approximations based on expert opinion would be an improvement over existing published data.

Support for data cleaning and analysis of existing data. While published data on CBB incidence and severity remains scarce, expert interviews revealed several potential sources of unpublished data, including substantial ongoing farm-level data collection efforts by crop scientists and graduate student researchers in Kenya, Nigeria and Uganda (R. Bart, Personal communication, February 27, 2015; J. Onyeka, Personal communication, March 15, 2015; T. Alicai, Personal communication, March 16, 2015). Additional data on PPD-related losses and economic impacts may also be available through market vendor records and cassava processing centers. Leveraging such existing data sources may provide relatively low-cost (depending on data quality) information on CBB and PPD incidence and impacts in areas where such data exist.

Direct data collection. The most effective, yet also most costly and time-intensive, response to current data deficits on CBB and PPD incidence and severity is the collection of new, systematic data on CBB and PPD impacts. This review and expert interviews have suggested several considerations for such a study, including: (i) sampling should deliberately target regions and agro-ecologies where problems are most severe (e.g., CBB in relatively inaccessible areas of Nigeria, or PPD in the predominantly raw cassava markets of Ghana); (ii) studies should collect data over a prolonged time period,

[5] N=200 farmers (69% women)

with experts suggesting at least 5 years of continuous monitoring in the case of CBB to account for substantial seasonal variation in disease incidence and severity in any given year (R. Bart, Personal communication, February 27, 2015); and (iii) data collection should include multiple biotic and abiotic constraints on cassava, as the co-occurrence of CBB with viral and fungal diseases is common in most agroecological zones of Sub-Saharan Africa (J. Onyeka, Personal communication, March 15, 2015) and, as noted in this brief, the variety of causes of postharvest losses are rarely disaggregated sufficiently to isolate the specific impacts of PPD.

Finally, for both CBB and PPD there is an especially noteworthy gap in knowledge of the yield and economic impacts of these constraints on smallholder and subsistence farmers, most notably those whose products never enter the formal marketplace.

Please direct comments or questions about this research to Leigh Anderson at eparx@u.washington.edu.

Appendix A. Literature Review Methods

This review was conducted using Scopus, Google Scholar, and the University of Washington Online Libraries, and by consulting experts (geneticists, plant breeders, and scholars) via telephone and email. As a final step, we used supplementary web searches to confirm no key literature or recent research efforts were missed.

Scopus Results

Keywords Searched	Search Date	Search Results	Relevant - First Cut Focus on cassava constraints, not duplicate	Relevant - Second Cut Describes impact on production OR describes constraint control strategies
TITLE-ABS-KEY ((cassava OR manihot) AND (disease OR deterioration) AND (yield) AND NOT (“bacterial blight” OR cbb OR ppd)) AND (LIMIT-TO(SUBJAREA,"AGRI"))	1-22-15	110	76	9
TITLE-ABS-KEY((cassava OR manihot) AND ("bacterial blight" OR cbb)) AND (LIMIT-TO(SUBJAREA,"AGRI"))	1-19-15	60	57	22
TITLE-ABS-KEY ((cassava OR manihot) AND (“post-harvest physiological deterioration” OR “postharvest physiological deterioration” OR “post-harvest deterioration” OR “physiological deterioration”))	2-10-15	137	54	27

Google Scholar Results

Keywords Searched	Search Date	Search Results	Studies Screened	Relevant, Non-Duplicate - First Cut	Relevant - Second Cut
“cassava bacterial blight” AND (yield OR “yield losses”)	2-9-15	956	80	4	4
((cassava OR manihot) AND ("bacterial blight" OR cbb) AND yield)	2-3-15	2160	20	3	2
((cassava OR manihot) AND ("post-harvest physiological deterioration") AND yield)	2-7-15	219	20	0	-
cassava “production constraint”	2-16-15	433	50	2	0

Expert Correspondence

Expert Name	Affiliation	Contact Date(s)
Rebecca Bart, PhD	Plant Pathologist, Assistant Member, Donald Danforth Plant Science Center, St. Louis, Missouri	27 February, 2015 23 March, 2015
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Appendix B. Supplementary Tables

Table B1: Cassava Production Constraints as Identified by Farmers in Busia, Jinja, and Mukono Districts in Uganda

Production constraints	Survey districts* Busia (%)	Jinja (%)	Mukono (%)	Mean (%)
Diseases, especially CBSD and CMD	100.0	92.5	100.0	97.5
Lack of early maturing cultivars	77.5	50.0	67.5	65.0
Rodents (mole rats, squirrels, porcupines)	50.0	70.0	17.5	45.8
Insect pests (green mites, white flies termites)	47.5	50.0	22.5	40.0
Inaccessibility of high yielding cultivars	17.5	47.5	25.0	30.0
Weeds	37.5	22.5	10.0	23.3
Poor underground storability	10.0	-	7.5	5.8
Bitterness of storage roots	17.5	32.5	-	16.7
Declining soil infertility	30.0	20.0	12.5	20.8
Erratic droughts	10.0	25.0	12.5	15.8
Scarcity of labour	25.0	2.5	10.0	12.5
Theft	32.5	25.0	10.0	22.5
Lack of farm implements and inputs	10.0	7.5	2.5	6.7
Land shortage	2.5	27.5	15.0	15.0
Lack of agricultural credit facilities	7.5	5.0	2.5	5.0
Lack of markets	25.0	32.5	10.0	22.5
Lack of extension services	7.5	10.0	32.5	16.7

*Number of respondents per district = 40; CBSD = cassava brown streak disease; CMD = cassava mosaic disease

Source: Tumuhimbise, 2013

Table B2: Main Constraints to Cassava Production by Country

Constraints	Country Burundi	Madagascar	Rwanda	Kenya	DRC
Diseases	62.4%	18.1%	56.1%	47.1%	34.8%
Pests	16.2%	22.3%	22.3%	13.0%	4.6%
Theft	17.6%	41.1%	13.5%	0.3%	1.7%
Lack of planting materials	22.4%	37.7%	54.1%	12.8%	29.8%
Lack of land	12.9%	22.6%	21.6%	--	3.1%
Hails	11.9%	--	--	0.3%	--
Price	---	29.5%	--	0.6%	4.3%
Weed	0.3%	--	16.0%	32.7%	5.2%
Appr.e materials	0.4%	--	17.0%	16.8%	4.5%
Labour	--	0.5%	6.8%	13.8%	13.5%
Mechanisation	--	--	--	--	9.7%

Source: Mbwika, 2002 (cited in ASARECA, n.d.)

Table B3: Cassava Constraints by Region in Africa: Lowland Humid Tropics

Constraint	% yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	33	80	26	6,966,000
Soil erosion	15	35	5	1,385,000
Salinity	0	0	0	0
Surface temperature	0	0	0	0
Total soil category			**32**	**8,352,000**
Sub-optimal land preparation	8	50	4	1,055,000
Poor planting material quality	27	70	19	4,987,000
Inadequate spacing	5	50	3	600,000
Weeds	20	80	16	4,222,000
Total management category			**41**	**10,924,000**
Low yield-potential varieties	25	85	21	5,807,000
Total intrinsic traits category			**21**	**5,807,000**
Drought	3	10	0	79,000
Water logging	40	10	4	1,055,000
Total climate category			**4**	**1,135,000**
Root rot	20	15	3	792,000
Bacterial blight	20	60	12	3,166,000
Anthracnose	10	50	5	1,319,000
Cassava Mosaic Virus	25	100	25	6,597,000
Other virus	0	0	0	0
Brown streak	0	0	0	0
Leaf/stem pathogens	0	0	0	0
Total disease category			**45**	**11,874,000**
Spider mite	10	10	1	264,000
Mealybug	8	10	1	158,000
Termites	0	0	0	0
Mammalian pests	5	40	2	528,000
Scale insects	0	0	0	0
Total pests category			**4**	**950,000**
Quality	25	50	13	3,298,000
Processing	15	30	5	1,187,000
Marketing	10	15	2	396,000
Total post-harvest			**19**	**4,882,000**

Source: Henry & Gottret, 1996

Table B4: Cassava Constraints by Region in Africa: Lowland Sub-Humid Tropics

Constraint	% yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	25	81	20	6,865,000
Soil erosion	10	25	3	848,000
Salinity	10	5	1	170,000
Surface temperature	0	0	0	0
Total soil category			**23**	**7,882,000**
Sub-optimal land preparation	10	60	6	2,034,000
Poor planting material quality	20	50	10	3,390,000
Inadequate spacing	10	50	5	1,695,000
Weeds	15	50	8	2,543,000
Total management category			**29**	**9,662,000**
Low yield-potential varieties	25	80	20	6,780,000
Total intrinsic traits category			**20**	**6,780,000**
Drought	23	70	16	5,458,000
Water logging	20	15	3	1,017,000
Total climate category			**19**	**6,475,000**
Root rot	9	11	1	336,000
Bacterial blight	20	50	10	3,390,000
Anthracnose	5	20	1	339,000
Cassava Mosaic Virus	22	80	16	5,966,000
Other virus	0	0	0	0
Brown streak	0	0	0	0
Leaf/stem pathogens	3	100	3	1,017,000
Total disease category			**30**	**10,031,000**
Spider mite	30	80	24	8,136,000
Mealybug	10	80	8	2,034,000
Termites	5	20	1	339,000
Mammalian pests	5	55	3	932,000
Scale insects	3	15	0	153,000
Total pests category			**34**	**11,594,000**
Quality	25	50	13	4,238,000
Processing	15	30	5	1,526,000
Marketing	10	10	1	339,000
Total post-harvest			**18**	**6,102,000**

Source: Henry & Gottret, 1996

Table B5: Cassava Constraints by Region in Africa: Semi-Arid Tropics

Constraint	% Yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	20	90	18	771,000
Soil erosion	10	50	5	214,000
Salinity	0	0	0	0
Surface temperature	10	100	10	643,000
Total soil category			**43**	**1,528,000**
Sub-optimal land preparation	5	70	4	150,000
Poor planting material quality	30	100	30	1,285,000
Inadequate spacing	5	60	3	129,000
Weeds	15	30	5	193,000
Total management category			**41**	**1,756,000**
Low yield-potential varieties	46	100	46	1,971,000
Total intrinsic traits category			**46**	**1,971,000**
Drought	24	100	24	1,028,000
Water logging			0	0
Total climate category			**24**	**1,028,000**
Root rot	0	0	0	0
Bacterial blight	8	50	4	171,000
Anthracnose	1	10	0	4,000
Cassava Mosaic Virus	9	80	5	231,000
Other virus	0	0	0	0
Brown streak	0	0	0	0
Leaf/stem pathogens	2	100	2	55,000
Total disease category			**10**	**407,000**
Spider mite	10	30	3	129,000
Mealybug	20	47	9	403,000
Termites	10	30	3	129,000
Mammalian pests	0	0	0	0
Scale insects	5	20	1	43,000
Total pests category			**16**	**703,000**
Quality	25	50	13	536,000
Processing	15	30	5	193,000
Marketing	10	10	1	43,000
Total post-harvest			**18**	**771,000**

Source: Henry & Gottret, 1996

Table B6: Cassava Constraints by Region in Africa: Highland Tropics

Constraint	% Yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	20	75	15	1,070,000
Soil erosion	20	40	8	571,000
Salinity	0	0	0	0
Surface temperature	0	0	0	0
Total soil category			**23**	**1,641,000**
Sub-optimal land preparation	15	25	4	268,000
Poor planting material quality	15	80	13	913,000
Inadequate spacing	10	50	5	357,000
Weeds	10	50	5	357,000
Total management category			**27**	**1,895,000**
Low yield-potential varieties	55	90	50	3,532,000
Total intrinsic traits category			**50**	**3,532,000**
Drought	40	80	32	2,284,000
Water logging	0	0	0	0
Total climate category			**32**	**2,284,000**
Root rot	8	15	1	86,000
Bacterial blight	10	50	5	357,000
Anthracnose	1	20	0	14,000
Cassava Mosaic Virus	10	20	2	143,000
Other virus	0	0	0	0
Brown streak	2	10	0	14,000
Leaf/stem pathogens	0	0	0	0
Total disease category			**8**	**614,000**
Spider mite	20	80	16	1,142,000
Mealybug	10	50	5	357,000
Termites	10	20	2	143,000
Mammalian pests	0	0	0	0
Scale insects	0	0	0	0
Total pests category			**23**	**1,641,000**
Quality	25	50	13	892,000
Processing	15	20	3	214,000
Marketing	10	10	1	71,000
Total post-harvest			**17**	**1,177,000**

Source: Henry & Gottret, 1996

Table B7: Cassava Constraints by Region in Africa: Subtropics

Constraint	% Yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	30	80	24	2,141,000
Soil erosion	10	50	5	446,000
Salinity	0	0	0	0
Surface temperature	0	0	0	0
Total soil category			**29**	**2,587,000**
Sub-optimal land preparation	5	30	2	134,000
Poor planting material quality	12	90	21	1,846,000
Inadequate spacing	5	50	3	223,000
Weeds	15	50	8	669,000
Total management category			**32**	**2,872,000**
Low yield-potential varieties	25	80	20	1,784,000
Total intrinsic traits category			**20**	**1,784,000**
Drought	30	80	24	2,141,000
Water logging	0	0	0	0
Total climate category			**24**	**2,141,000**
Root rot	2	3	0	5,000
Bacterial blight	10	50	5	446,000
Anthracnose	2	40	1	71,000
Cassava Mosaic Virus	5	15	1	67,000
Other virus	2	5	0	9,000
Brown streak	0	0	0	0
Leaf/stem pathogens	3	100	3	268,000
Total Disease category			**7**	**852,000**
Spider mite	15	43	6	575,000
Mealybug	10	50	5	446,000
Termites	0	0	0	0
Mammalian pests	0	0	0	0
Scale insects	0	0	0	0
Total Pests category			**11**	**1,021,000**
Quality	25	50	13	1,115,000
Processing	15	20	3	268,000
Marketing	10	10	1	89,000
Total post-harvest			**17**	**1,472,000**

Source: Henry & Gottret, 1996

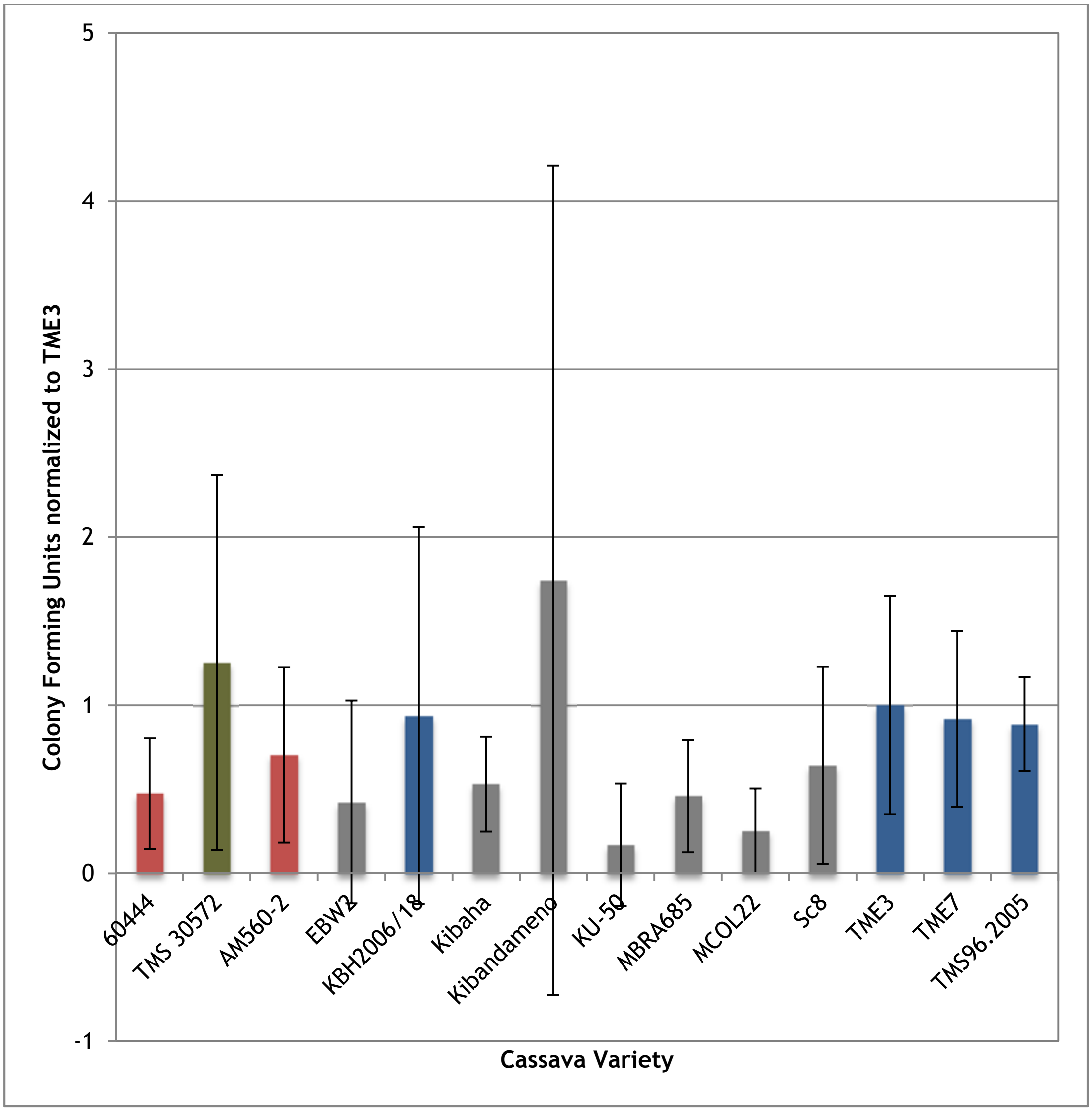
Table B8: Cassava Constraints in Africa: All Regions

Constraint	% Yield gain in affected area	% area affected	total % yield gain	potential MT yield gain
Low soil fertility	27	81	22	17,813,000
Soil erosion	12	34	4	3,464,000
Salinity	11	2	0	170,000
Surface temperature	10	8	1	643,000
Total soil category			**27**	**22,089,000**
Sub-optimal land preparation	9	51	5	3,641,000
Poor planting material quality	23	68	15	12,422,000
Inadequate spacing	7	51	4	3,063,000
Weeds	17	59	10	7,983,000
Total management category			**34**	**27,109,000**
Low yield-potential varieties	29	84	24	19,674,000
Total intrinsic traits category			**24**	**19,674,000**
Drought	25	54	14	10,990,000
Water logging	28	9	3	2,072,000
Total climate category			**16**	**13,062,000**
Root rot	14	11	2	1,218,000
Bacterial blight	17	53	9	7,531,000
Anthracnose	7	31	2	1,748,000
Cassava Mosaic Virus	22	73	16	13,004,000
Other virus	2	0	0	9,000
Brown streak	2	1	0	14,000
Leaf/stem pathogens	3	56	2	1,370,000
Total Disease category			**29**	**23,524,000**
Spider mite	26	48	13	10,245,000
Mealybug	11	40	4	3,398,000
Termites	6	12	1	610,000
Mammalian pests	5	34	2	1,460,000
Scale insects	3	7	0	195,000
Total Pests category			**20**	**15,909,000**
Quality	25	50	13	10,078,000
Processing	15	28	4	3,387,000
Marketing	10	12	1	938,000
Total post-harvest			**18**	**14,404,000**

Source: Henry & Gottret, 1996

Appendix C. Supplementary Figures

Figure C1. Relative bacterial growth on 14 diverse cassava varieties.



Bacteria were injected into the leaf mesophyll at an OD600 = 0.01. Five days post inoculation, the number of bacteria at the infection site were counted. Data from at least 5 independent experiments were combined and for each experiment, data was normalized to TME3. Blue: reported to be tolerant/resistant to CBB. Red: reported to be susceptible to CBB. Grey: unknown. Each variety was tested at least independent times and the mean and standard deviations are displayed. No significant differences were observed.

Source: Unpublished data. R. Bart, personal communication, March 23, 2015.

Figure C2: Leaf damage due to Cassava Bacterial Blight

Source: Durroux, 2014

Source: Infonet-Biovision

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