Closing the cassava yield gap: an analysis from small-holder farms in East Africa

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This article is in press as:
Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from small-holder farms in East Africa. Field Crops Research, doi:10.1016/j.fcr.2009.01.009

Abstract

Cassava yields in Africa are small and it remains unclear which factors most limit yields. Using a series of farm surveys and on-farm and on-station trials in Uganda and western Kenya, we evaluated the importance of abiotic, biotic and associated crop management constraints for cassava production in a range of socio-economic settings as found in smallholder farms in the region. Average yields under farmer management were 8.6 t ha^{-1}, but these were more than doubled to 20.8 t ha^{-1} by using improved crop establishment, improved genotypes and 100-22-83 kg ha^{-1} of single-nutrient N-P-K fertilizers. A farm survey revealed large yield differences between farms. Less endowed farmers harvested less cassava per unit area than better endowed farmers (difference of 5.9 and 9.7 t ha^{-1} in Kenya and Uganda, respectively); differences were associated with less access to labour, poorer soils, and premature harvesting by less endowed farmers. Analysis of 99 on-farm and 6 on-station trials showed that constraints for cassava production varied strongly between sites and years. Poor soil fertility, early water stress and sub-optimal weed management limited cassava production by 6.7, 5.4 and 5.0 t ha^{-1}, respectively, when improved crop establishment and genotypes were used. Pests and diseases were relatively unimportant, while weed management was particularly important in farmer fields during a dry year in Kenya (yield gap of 11.6 t ha^{-1}). The use of complementary analytical tools such as multiple regression and boundary line analysis revealed that many fields were affected by multiple and interacting production constraints. These should be addressed simultaneously if significant productivity improvements are to be achieved. This will be more difficult for less endowed than for better endowed farm households, since the former lack social and financial capital to improve management.

Keywords: Agriculture; Boundary line analysis; Drought; Nutrient management; Production constraints; Soil fertility; Weed management

1. Introduction

Cassava research and extension efforts in Africa have successfully focused on breeding and integrated pest management (IPM) strategies to control major pests and diseases, most notably mosaic virus, mealy bugs and green mites (Alene et al., 2006; Legg et al., 2006; Zanou et al., 2007). While the major focus of such efforts was placed on coping with biotic constraints, relatively little attention has been given to abiotic, crop management and socio-economic constraints. Understanding the relative importance of these factors to the yield gap is a necessary step to guide the design of relevant research for development interventions aimed at improving cassava productivity. This has been acknowledged by scientists who recently initiated a worldwide exercise to gather expert knowledge on the contribution of various constraints to the cassava yield gap in the main agro-ecological regions where cassava is grown (Generation Challenge Programme, 2008, p. 82). The yield gap is generally defined as the difference between actual farmer yields and potential yield, whereby potential yield is the maximum yield that can be achieved in a given agro-ecological zone. For practical purposes it is, however, more interesting to study the gap between the actual and attainable yield, whereby the attainable yield can be defined as the maximum yield observed in a given agro-ecological zone with a given management intensity.

The mid-altitude zones of East Africa constitute a major cassava-growing region in Africa and cover a wide range of agro-ecological conditions. Some of these are well represented in areas of Kenya and Uganda. Average fresh yields at country level in 2007 were 10.6 t ha^{-1} in Kenya and 12.0 t ha^{-1} in Uganda, which was just above the African average of 9.9 t ha^{-1} (FAO, 2009), but far below typical average fresh yields of 15-40 t ha^{-1} obtained in on-farm breeding trials in these countries (Ntawuruhunga et al., 2006; Fermont et al., 2007). According to Cock et al. (1979) the ideal cassava plant, consisting of a late branching genotype that possesses large leaves with a long leaf life, would have a potential yield of 25-30 t ha^{-1} dry roots, equivalent to fresh root yields in the range of 75-90 t ha^{-1}. Such fresh root yields have been attained in experimental conditions in Colombia and India (El-Sharkawy, 2004). The largest fresh root yields recorded under experimental conditions in East Africa are 50-60 t ha^{-1} (Obiero, 2004; Ntawuruhunga et al., 2006). In the past fifteen years, the most obvious constraint to cassava production in East Africa was the cassava mosaic virus disease pandemic. This virus caused a mean yield loss of 72% in landraces, but has been controlled due to the widespread introduction and adoption of resistant genotypes (Legg et al., 2006). Nonetheless, actual cassava yields have remained low. Therefore, the question remains what the most limiting factors are for cassava production.

This study thus aims to quantify the relative importance of abiotic, biotic and management constraints for cassava production across a range of socio-economic settings in smallholder farms in East Africa. The study is based on data from a series of farm surveys in Uganda and western Kenya, complemented with a range of on-farm and on-station trials for a period of two years. We first quantify average and attainable yields for smallholder farmers under increasingly improved crop management, comparing: (i) current farmer practice; (ii) improved crop establishment; (iii) regime ii + improved genotypes; (iv) regime iii + NPK fertilizer. Secondly, we explore which management practices, in relation to socio-economic settings, determine yields under current farmer practice (regime i). Thirdly, we study the abiotic, biotic and associated crop management factors limiting cassava productivity at management regime iii (improved genotypes and crop establishment). We use multiple regression and boundary line analysis (Shatar and McBratney, 2004) to identify the relevant yield loss factors, to explore possible interactions and to quantify their contribution to the yield gap. We conclude by discussing the scope to overcome the production constraints identified.

2. Materials and methods

2.1 Site description

The farm surveys and agronomic trials were carried out in a range of sites in western Kenya and central and eastern Uganda. The sites were chosen to represent a range of environments and management practices in cassava-based cropping systems in the mid-altitude zone of East Africa. The farm surveys were carried out in three sites in western Kenya, which included Kwang’amor (0°29’N; 34°14’E), Mungatsi (0°27’N; 34°18’E) and Ugunja (0°10’N; 34°18’E) in Teso, Busia and Siaya districts, respectively. In Uganda, the sites included Kisiro (0°67’N; 33°80’E), Kikooba (1°40’N; 32°38’E) and Chelekura (1°14’N; 33°62’E) in Iganga, Nakasongola and Pallisa district, respectively. On-farm trials in western Kenya were installed in the same sub-locations and in Nambale (0°28’N, 34°14’E) in Busia district, while on-farm trials in Uganda took place in Kisiro and Minani (0°80’N; 33°57’E) in Iganga district. In addition, on-station trials were installed at the Kenyan Agricultural Research Institute (KARI) in Alupe, Busia district (0°30’N; 34°08’E) and at the Ugandan National Crops Resources Research Institute (NaCRRI) in Namulonge, Wakiso district (0°32’N; 32°37’E). Main soils in the region include ferric and orthic Acrisols and orthic and haplic Ferralsols; soils that are derived from strongly weathered granite or sedimentary parent material (KARI, 2000; Jaetzold and Schmidt, 1982). The climate in all sites is sub-humid with a bimodal rainfall distribution. This allows for the production of most annual crops during both the long (March-June) and the short rains (September-November). Altitude ranges between 1100 and 1260 masl. Cassava is planted in the first two months of the short or long rains and remains in the field for about a year. Agricultural systems are diverse with farmers growing 4-6 main crops on average (Fermont et al., 2008 – Chapter 3).

2.2 Farm surveys

At the start of the farm surveys in Kenya (June-September 2004) and Uganda (October 2005-April 2006), three to four key informants per site ranked all households in three wealth categories; poorer, medium and richer. Twenty households per site were randomly selected, with a minimum representation of three households per wealth category. Structured interviews, in combination with a visit to all fields of each household, were used to collect data on main production constraints, socio-economic settings, farm management, and cassava crop management. Essential information was cross-checked by triangulating interview data with field measurements during a series of field visits. Farmers were asked to estimate average cassava yield in the past few years, by estimating the number of bags of fresh or dry cassava product per unit land. Dry matter yields were converted to t ha^{-1} fresh cassava yields, using an average dry matter content of 33% (Alves, 2002). More detail on the data collection methods is given in Fermont et al. (2008 – Chapter 3).

2.3 Trials

Two consecutive sets of on-farm cassava trials were planted in 2004 (49 farms) and 2005 (50 farms) across the six on-farm sites in Kenya and Uganda; we refer to them as the ‘2004 trials’ and ‘2005 trials’, respectively. In addition, six researcher-managed trials with similar treatments and four repetitions were installed at KARI (Kenya) and NaCRRI (Uganda) experimental stations. The 2004 trials were planted with two genotypes, TMS 30572 (released in Uganda as ‘Nase 3’) and TMSI92/0067 in Uganda and Nase 3 and MM96/5280 in Kenya, while the 2005 trials were planted with only TMSI92/0067 in Uganda and MM96/5280 in Kenya. Nase 3 has been widely adopted by farmers in both countries (Legg et al., 2006), while the other two genotypes are more recently developed by the national cassava breeding programmes. In all trials these genotypes were grown without and with fertilizer. Per crop cycle 100-22-83 kg ha^{-1} N-P-K (e.g. 100-50-100 kg ha^{-1} N-P2O5-K2O) was applied. P was applied as basal application of triple super phosphate at planting, and N and K as urea and potassium sulphate in two equally split broadcast applications at 1 and 3 months after planting (MAP). In all trials, a package of improved management practices at crop establishment was used that consisted of a 1 m x 1 m plant spacing, no intercropping, and early planting at the start of the rainy season. We refer to this package as ‘improved crop establishment’. Manual weeding was done by farmers, according to their own judgement, while on-station trials were kept weed-free by manual weeding. Total cassava storage roots fresh yield was determined at 11.5-13 and 12-15 MAP in the on-farm and on-station trials, respectively.

Composite soil samples (0-20 cm) were taken from each field. Samples were oven-dried, sieved through a 2 mm sieve, and analysed for pH, available P, exchangeable K, Ca, Mg, total N, soil organic carbon and texture following Okalebo et al. (2002). Daily precipitation data were recorded using rainfall gauges at all sites. Total precipitation (mm) and rain days were calculated for the entire crop cycle duration and the periods of 0-3, 3-6, 6-9, 9-12, 12-15, and 0-6 MAP. Research technicians scored overall weed management (WM) in each field on a scale from 1 (very poor) to 5 (very good). Twenty plants in the centre of each plot were scored at 3, 6 and 9 MAP for incidence (yes/no) and severity (1-5 scale; IITA, 1990) of cassava mosaic disease, bacterial blight, green mites, anthracnose disease and mealy bugs; no disease data were recorded in the 2004 on-farm trials in Uganda. Severity scores at 3, 6, and 9 MAP were used to calculate the area under severity index progress curves (AUSiPC) for all pests and disease, except for mealy bug, which was not found in any of the trials. AUSiPC values range from 0 for a pest/disease-free plot to 750 for a plot where all plants were consistently rated severely infected.

2.4 Data analysis

2.4.1 Management regime i: current farmer management

To explore the relationship between crop management, farm management, and socio-economic variables with average farm yields under current farmer management, we first calculated Pearson bivariate correlations. Explanatory variables that had a correlation coefficient (r) larger than 0.25 with yield and/or exhibited a pattern of co-variation with cassava root yields were included in the further analysis. We then classified average farm yields into three groups per country: lowest yielding farms (first quartile), average yielding farms (second and third quartile) and highest yielding farms (fourth quartile). For each yield class, average values for the retained explanatory variables were calculated. Chi-square tests (SPSS 12.0) were carried out to explore significant differences between yield classes.

2.4.2 Management regime iii: explaining yield variability

To identify the variables that best explain yield differences at management regime iii (improved crop establishment and improved genotypes), we carried out a linear regression analysis on data from the 2004 and 2005 trials, whereby abiotic, biotic and management factors were taken as independent variables and cassava root yield of the two genotypes MM96/5280 and TMSI92/0067 as the dependent variable. Analyses were done for the entire data set and for each country separately, using GenStat (version 10.1). Where required, variables were transformed to normality using Box-Cox power transformations. Subsequently, Spearman’s and Pearson’s correlation analyses were used. For any pair of abiotic, biotic and management variables with inter-correlations (r) greater than 0.7 only one variable was retained in the regression model. The all subsets regression routine in GenStat and Mallow’s criteria were used in addition to other model diagnostics to select the best model. We computed the square of the semi-partial correlation coefficients to approximate the relative contribution of each explanatory variable to yield variability, while controlling for other variables in the equation (Snedecor and Cochran, 1980; Cohen et al., 2003). As many variables were highly variable, we checked that the impact of the measurement error for each explanatory variable on the regression coefficients was <10% (Warton et al., 2006).

2.4.3 Management regime iii: identifying yield gaps

To explore in more detail the contribution of individual abiotic, biotic and management factors to the yield gap at management regime iii, we slightly adapted the boundary line approach as used by Webb (1972), van Asten et al., (2003) and Shatar and McBratney (2004). Our approach consisted of following steps:

1. After sorting the independent variables in ascending order and removing outliers, we defined boundary lines that represented the maximum yield response (the dependent variable) to the various independent variables (e.g. rainfall). Boundary lines were fitted through selected boundary points (Schnug et al., 1996) following the model:

   $$y_l = \frac{y_{\max}}{(1+(K \times EXP(-R \times x)))} \qquad (1)$$

   whereby ymax is the observed attainable yield level at management regime iii, x is the independent variable and K and R are constants. The best boundary line model was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line (yl) and the boundary points (yp).

2. Individual boundary lines were used to calculate for each field and each independent variable the maximum cassava yield that could have been obtained if production would only have been limited by the independent variable in question (y_max_{ij})
3. Individual boundary lines were then combined in order to create a multivariate model, assuming responses according to von Liebig's law of the minimum (von Liebig, 1863; Shatar and McBratney, 2004). The model was used to predict yields for each field.
4. Lastly, we determined the yield gap caused by each independent variable in each field as the attainable cassava yield minus y_max_{ij}.

3. Results

3.1 Yield steps between intensifying regimes of management

Average cassava yields under current farmer practice (regime i) in Kenya and Uganda ranged from 6.1 to 11.7 t ha^{-1} (Table 1). The complete management package (regime iv), consisting of improved crop establishment, an improved genotype and NPK fertilizer use, more than doubled average yields on farmer fields, from ca. 9 to 21 t ha^{-1} (P<0.001) and increased attainable yields from ca. 18 to 37 t ha^{-1} (Figure 1). This effect was observed in both Kenya and Uganda, albeit with somewhat different patterns of response at each individual site (Table 1). Improving crop establishment (regime ii) increased average yields by 1.5 t ha^{-1}, but the effect varied strongly (-0.9 to +4.4 t ha^{-1}) across sites. Replacing the widely adopted Nase 3 with the improved genotypes MM96/5280 or TMSI92/0067 (regime iii) increased average yields further by 3.5 t ha^{-1} (P<0.001), with a range of 0.9 to 6.1 t ha^{-1} between sites. Adding NPK fertilizer (regime iv) increased average yields by another 7.2 t ha^{-1} (P<0.001), with a range of 5.8 to 9.2 t ha^{-1} between sites, except for the fertile NaCRRI site. Whereas average yields varied between sites under farmer practice (P<0.001), with improved crop establishment (P<0.01) or using improved genotypes (P<0.05), the application of NPK fertilizers tended to equalize yields across sites (Table 1). Whereas boundary lines could be identified under unfertilized conditions that showed increasing yields with increasing SOC, available P and exchangeable K, no functional relationships (i.e. boundary lines) could be derived when fertilizer was applied (Figure 2a-c).

Table 1: Effect of increasing management on average cassava yields (t ha-1) in Kenya and Uganda

Regime	i	ii	iii	iv	SED
	Farmer management[1]	+ improv. crop establishment[2]	+ improved genotype[3]	+ NPK fertilizer[4]	
Kenya					
Kwang'amor	7.9 (4.4-13.3)	9.9 (5.5-17.3)	10.8 (3.0-16.2)	20.0 (8.5-34.3)	2.02
Mungatsi	6.4 (2.7-9.8)	10.8 (6.0-15.5)	14.4 (5.8-22.7)	20.2 (10.3-35.2)	2.39
Nambale	-	7.4 (2.7-14.3)	13.5 (3.5-25.5)	21.0 (8.5-35.0)	2.88
Ugunja	6.1 (2.7-8.9)	5.2 (1.0-14.3)	10.1 (2.8-23.8)	19.3 (6.4-37.3)	2.62
KARI	-	10.8 (3.3-17.6)	12.7 (4.3-20.6)	17.9 (7.7-25.4)	2.36
Uganda					
Minani	-	13.0 (9.0-19.3)	16.4 (9.8-24.5)	25.3 (20.5-31.0)	1.78
Kisiro	8.3 (2.7-12.0)	11.9 (6.4-18.0)	15.1 (6.5-22.8)	23.2 (7.1-35.5)	2.72
Kikooba	11.2 (5.3-17.8)	-	-	-	-
Chelekura	11.7 (6.7-17.8)	-	-	-	-
NaCRRI	-	15.5 (11.6-18.9)	21.3 (15.5-27.3)	21.5 (14.8-30.4)	3.13
Overall mean	8.6	10.1	13.6	20.8	0.93
SED	0.89	2.54	2.78	3.32	

[1] Farmer estimates of average cassava yield in their farm. Data from 108 household surveys

[2] Yield of Nase 3 in the 2004 trials with improved crop establishment (1 m x 1 m spacing, no intercrop, timely planting). Data from 57 fields. Nase 3 had similar yields as landraces (Fig. 3d)

[3] Yield of improved genotypes MM96/5280 (Kenya) and TMSI92/0067 (Uganda) in the 2004 and 2005 trials with improved crop establishment. Data from 111 fields.

[4] Yield of improved genotypes MM96/5280 (Kenya) and TMSI92/0067 (Uganda) in the 2004 and 2005 trials with improved crop establishment and fertilizer use (100-22-83 N-P-K). Data from 112 fields.

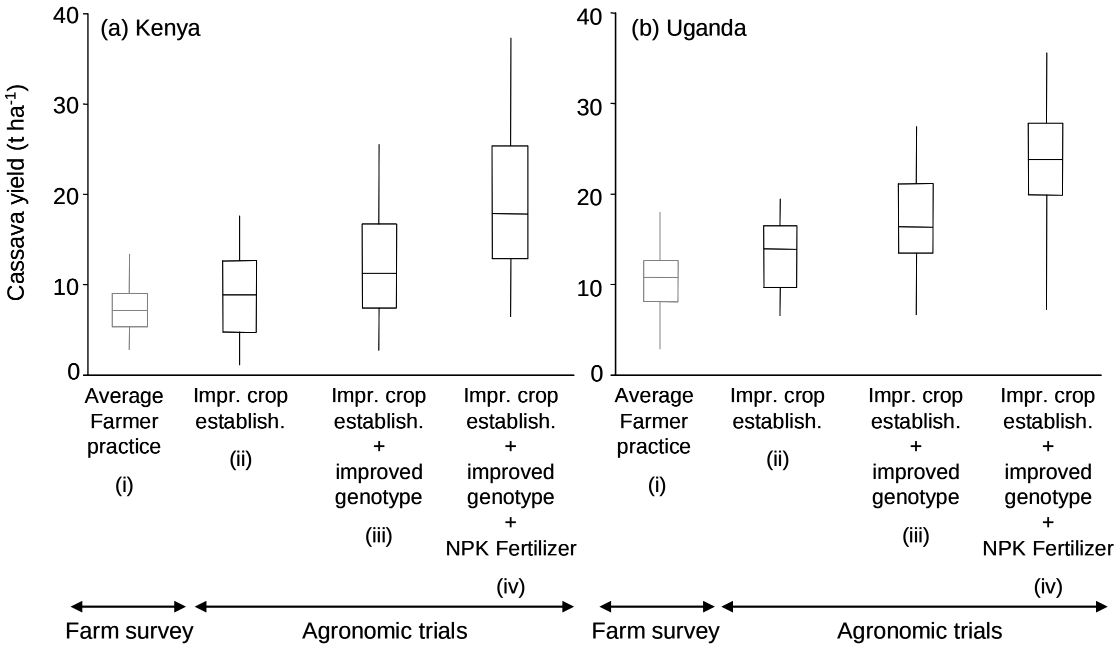

Figure 1: Cassava yields in (a) Kenya and (b) Uganda at four regimes of increasing management. See footnotes at Table 1 for more details. Box-whisker diagrams include the range of 50% of the observations (rectangular box), the median (cross bar) and the min. and max. values (vertical lines).

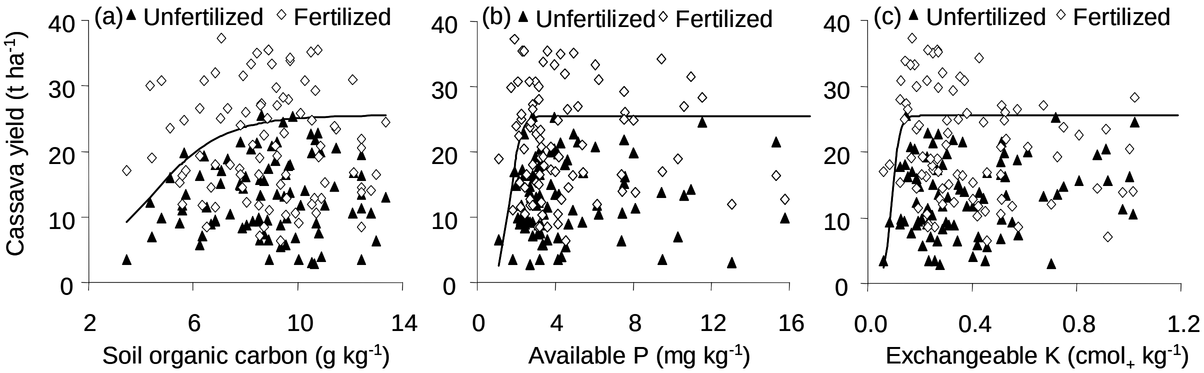

Figure 2: Cassava yields under management regime iii (improved crop establishment and genotypes) and regime iv (level iii + NPK fertilizer use) in the 2004 and 2005 trials versus (a) soil organic carbon; (b) available P and; (c) exchangeable K.

Yield variability at each management regime was large (Table 1). In the next paragraphs management regime i (current farmer practice) and regime iii (improved crop establishment + improved genotypes) are analysed in more detail to evaluate which factors contributed to the observed yield variability.

3.2 Management regime i: socio-economic diversity, management and cassava yield

The farm surveys showed that socio-economic conditions varied broadly between sites (Table 2); the average amount of arable land per household ranged from 1.2 ha to 4.0 ha ($P<0.01$), average annual household income ranged from US$ 663 to US$ 1,283 ($P<0.001$), while average labour availability ranged from 3.3 to 8.8 adult equivalent per year per household ($P<0.001$) between sites. Farm and crop management also varied strongly between sites; farmers planted on average 0.3 to 0.9 ha of cassava ($P<0.01$), planted an average 0 to 80% of this acreage with improved genotypes ($P<0.001$) and between 38 to 70% as a sole crop ($P<0.01$), while the number of weed operations per field ranged from 3.3 to 5.9 ($P<0.001$) between sites. Farmers rarely applied (in)organic nutrient inputs in cassava fields, but hired labour for cassava varied ($P<0.001$) from 6 to 129 man days per year per farm. These differences were reflected in the average cassava yields as estimated by farmers across sites (Table 1). Yields were significantly larger in Uganda than in Kenya ($P<0.001$).

Average cassava yields of the lower quartile farms were 6.1 and 9.7 t ha^{-1} less than average cassava yields of the upper quartile farms in Kenya and Uganda, respectively ($P<0.001$; Table 3). In both countries, greatest yields were observed on farms with a high annual household income, large amounts of available labour, large acreages of

Table 2: Selected details on socio-economic settings, farm and cassava management in the six farm survey sites in Kenya and Uganda

		Kenya			Uganda			
		Kwang'amor	Mungatsi	Ugunja	Kisiro	Kikooba	Chelekura	SED
Socio-economic								
Arable land	(ha)	2.9 ± 3.4	2.0 ± 1.3	1.2 ± 0.8	4.0 ± 3.5	2.7 ± 1.8	1.8 ± 1.3	0.7
Labour availability[1]	(Adult equivalent year^{-1})	5.1 ± 3.2	4.6 ± 2.2	3.7 ± 1.7	5.4 ± 3.7	3.3 ± 2.8	8.8 ± 6.9	1.2
Household income	(US$ year^{-1})	835 ± 1170	1283 ± 1497	633 ± 703	1266 ± 1120	961 ± 895	868 ± 855	334
Cassava income	(US$ year^{-1})	54 ± 46	24 ± 25	27 ± 23	59 ± 226	313 ± 527	13 ± 25	75
Farm management								
Cassava acreage	(ha)	0.7 ± 0.7	0.3 ± 0.2	0.3 ± 0.2	0.6 ± 0.6	0.9 ± 0.8	0.6 ± 0.6	0.2
Soil fertility score[2]	(-)	2.2 ± 0.4	2.2 ± 0.5	2.2 ± 0.4	2.3 ± 0.3	2.0 ± 0.3	2.4 ± 0.3	0.1
Cassava management								
Improved genotypes[3]	(% Cassava acreage)	44 ± 28	43 ± 31	0 ± 0	46 ± 27	5 ± 12	80 ± 18	7
Sole cropping	(% Cassava acreage)	38 ± 18	51 ± 33	57 ± 32	70 ± 33	70 ± 34	70 ± 32	10
Harvested < 1 year	(% Farms)	33	42	25	61	33	35	-
First weed operation	(Weeks after planting)	3.6 ± 1.4	4.1 ± 1.4	4.0 ± 0.6	3.5 ± 0.6	5.5 ± 2.7	2.9 ± 0.7	0.5
# weed operations	(-)	5.9 ± 1.7	5.2 ± 1.1	3.9 ± 1.0	4.3 ± 0.9	3.3 ± 1.0	4.5 ± 1.1	0.4
Last weed operation	(Months after planting)	8.5 ± 1.1	7.9 ± 1.4	7.5 ± 1.5	7.5 ± 1.9	10.1 ± 3.0	7.7 ± 1.7	0.6
Hired labour	(Man day year^{-1})	19 ± 37	37 ± 62	6 ± 15	53 ± 103	11 ± 29	129 ± 206	31

[1] Labour availability expressed as adult equivalent per year is based on family labour + hired labour.

[2] Farmers scored the soil fertility status of each field from poor (1) to good (3). Using individual field size, a weighted soil fertility score for the farm was calculated.

[3] Mainly Nase 3 and SS4.

Table 3: Comparison of farmer estimates of cassava yield under current farmer management (regime i) and selected details on socio-economic settings and farm and cassava management for the first quartile, second + third quartile and fourth quartile yields in Kenya and Uganda

		Kenya				Uganda			
		1st quartile	2nd + 3rd quartile	4th quartile	*P*	1st quartile	2nd + 3rd quartile	4th quartile	*P*
n		11	31	17		11	27	11	
Cassava yield	($t\ ha^{-1}$)	3.8 ± 0.8	6.4 ± 0.8	9.7 ± 1.5	< 0.001	6.3 ± 1.7	10.2 ± 1.3	16.0 ± 1.9	< 0.001
Socio-economic									
Arable land	(ha)	1.0 ± 0.5	1.7 ± 1.9	3.2 ± 2.9	< 0.001	1.3 ± 0.6	3.5 ± 3.3	2.9 ± 2.0	< 0.05
Labour availability[1]	(Adult equivalent $year^{-1}$)	2.2 ± 1.3	4.0 ± 1.5	6.6 ± 2.7	< 0.001	4.7 ± 4.9	5.5 ± 3.8	9.6 ± 8.5	ns
Household income	(US$ $year^{-1}$)	267 ± 187	907 ± 1108	1289 ± 1517	< 0.001	389 ± 146	1151 ± 1074	1226 ± 956	< 0.1
Cassava income	(US$ $year^{-1}$)	21 ± 23	34 ± 38	50 ± 33	< 0.05	9 ± 14	128 ± 252	105 ± 213	ns
Farm management									
Cassava acreage	(ha)	0.3 ± 0.2	0.4 ± 0.4	0.7 ± 0.7	< 0.01	0.3 ± 0.2	0.7 ± 0.6	1.0 ± 1.0	< 0.1
Soil fertility score[2]	(-)	1.9 ± 0.3	2.2 ± 0.4	2.4 ± 0.3	< 0.01	2.1 ± 0.3	2.3 ± 0.4	2.4 ± 0.3	ns
Cassava management									
Improved genotypes[3]	(% Cassava acreage)	12 ± 23	25 ± 29	49 ± 32	< 0.01	51 ± 31	43 ± 39	53 ± 38	ns
Sole cropping	(% Cassava acreage)	52 ± 27	49 ± 32	46 ± 25	ns	60 ± 36	71 ± 35	73 ± 32	ns
Harvest < 1 year	(% Farms)	82	37	0	< 0.001	55	31	24	ns
First weed operation	(Weeks after planting)	3.7 ± 1.0	3.7 ± 1.0	4.3 ± 1.4	ns	4.4 ± 3.2	3.8 ± 1.5	3.5 ± 1.0	ns
# weed operations	(-)	4.3 ± 1.0	4.6 ± 1.3	6.2 ± 1.7	< 0.01	3.5 ± 1.1	4.0 ± 1.0	4.4 ± 1.2	ns
Last weed operation	(Months after planting)	8.3 ± 1.4	7.8 ± 1.5	8.1 ± 1.3	ns	7.0 ± 2.0	8.6 ± 2.8	9.3 ± 2.2	< 0.1
Hired labour	(Man days $year^{-1}$)	14 ± 31	13 ± 26	37 ± 67	ns	20 ± 46	54 ± 105	168 ± 254	< 0.05

[1] Labour availability expressed as adult equivalent per year is based on family labour + hired labour.

[2] Farmers scored the soil fertility status of each field from poor (1) to good (3). Using individual field size, a weighted soil fertility score for the farm was calculated.

arable land, large acreages of cassava and generally more fertile soils. Yields were positively correlated with these variables ($P<0.05$), but most strongly with labour availability ($P<0.001$; Figure 3a). Household income was positively correlated with availability of labour and arable land ($P<0.01$) in both countries, and with cassava acreage ($P<0.001$) in Uganda. Kenyan farms with high yields more frequently used improved cassava genotypes, never harvested their cassava fields before 12 MAP, and weeded their cassava fields 2.5 times more than farms with low yields. Ugandan farms with high yields hired more labour for cassava activities and weeded their cassava fields one extra time and for 2 months longer than farms with low yields. Household income was positively correlated with hired labour on cassava in both countries ($P<0.01$) and with the use of improved genotypes in Kenya ($P<0.05$). In Kenya, the number of weed operations was positively associated with higher cassava yields up to 6 weedings per crop cycle (Figure 3b). In both countries, late first weeding (> 4 weeks after planting) was associated with small cassava yields as estimated by farmers (Figure 3c). The use of improved genotypes that were available to farmers at the time of the survey (primarily Nase 3 and SS4) was not correlated with yields in Uganda, and only slightly ($R^2 = 0.1$; $P<0.05$) correlated with yields in Kenya (Figure 3d).

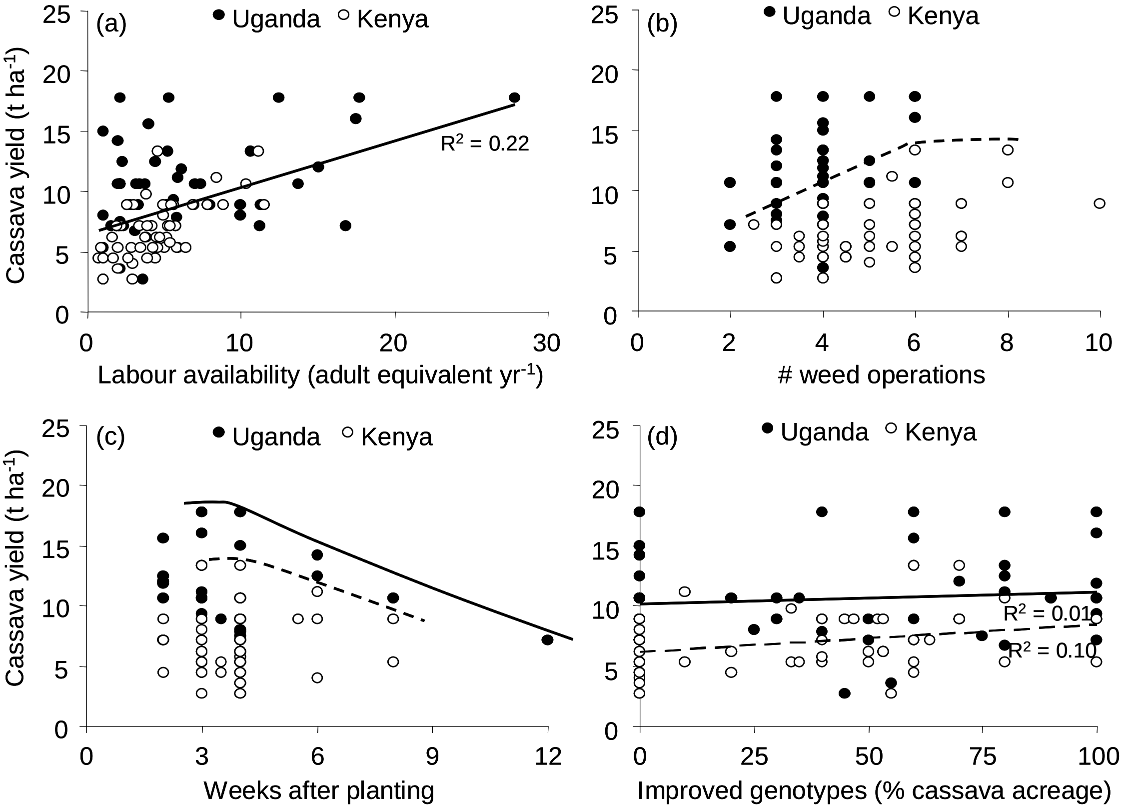

Figure 3: Relationship between cassava yield under management regime i (farmer practice) and (a) labour availability per household; (b) number of weed operations during the growth cycle; (c) timing of first weed operation and; (d) adoption of improved genotypes (primarily Nase 3 and SS4); n = 108.

Table 4. Selected characteristics of the 2004 and 2005 cassava trials at Management regime iii in Kenya (K) and Uganda (U) by site and year

			Soil fertility^{2}					Soil texture		Rainfall^{2}			Management^{2}		Pests & Diseases^{2}		
		Yield	pH	SOC	P	K	∑cat	Sand	Silt	RFtot	RF0_6	#RFd	WM	DH	CBB	CGM	CAD
		(t ha^{-1})	-	(g kg^{-1})	(mg kg^{-1})	(cmol	kg^{-1})	(%)	(%)	(mm)	(mm)	(-)	(-)	(-)	(-)	(-)	(-)
2004																	
Kwang'amor	(K)	11.6	6.0	6.9	4.5	0.33	1.4	76	8	1447	902	127	3.6	339	116	51	26
Mungatsi	(K)	14.0	5.5	11.4	5.8	0.56	3.0	54	18	1781	1054	144	4.4	338	75	36	2
Nambale	(K)	9.4	5.4	10.6	3.8	0.37	2.5	59	14	1830	1076	146	3.1	345	146	55	43
Ugunja	(K)	6.4	5.7	8.7	3.0	0.40	1.9	50	21	1316	675	115	3.4	342	75	21	12
Minani	(U)	19.1	6.2	10.0	5.6	0.78	9.0	67	7	1771	692	93	3.5	398	11	15	0
Kisiro	(U)	15.7	6.5	8.0	12.3	0.46	4.0	76	8	1478	966	107	3.2	384	10	15	0
KARI	(K)	12.4	5.2	14.7	3.1	0.42	7.6	42	21	2200	1001	213	5.0	445	157	10	12
NaCRRI	(U)	17.0	6.2	20.5	7.1	1.32	17.8	54	11	1065	532	154	5.0	375	92	91	1
Average		*12.2*	*5.8*	*10.7*	*5.1*	*0.53*	*5.0*	*60*	*14*	*1644*	*878*	*137*	*3.8*	*369*	*89*	*34*	*14*
2005																	
Kwang'amor	(K)	9.7	5.8	7.2	8.5	0.33	2.6	72	11	2187	1126	164	2.9	390	117	136	3
Mungatsi	(K)	14.7	5.4	9.0	5.3	0.33	1.1	55	19	2377	1306	165	3.6	398	142	129	25
Nambale	(K)	18.7	5.3	8.7	3.4	0.19	1.4	57	15	2460	1107	144	3.2	397	129	149	2
Ugunja	(K)	14.4	5.7	7.8	2.7	0.22	1.5	45	23	1677	801	167	3.6	390	125	46	1
Minani	(U)	14.5	6.1	9.4	2.5	0.55	5.5	67	9	1292	464	90	3.5	370	51	6	0
Kisiro	(U)	14.8	6.3	8.5	4.6	0.32	5.2	74	8	1270	490	88	3.4	370	53	38	0
KARI	(K)	13.0	5.1	16.7	3.1	0.43	8.9	41	20	1853	824	87	5.0	389	172	34	12
NaCRRI	(U)	25.7	6.4	18.9	5.7	0.97	12.4	51	11	1152	538	142	5.0	398	120	42	0
Average		*15.0*	*5.7*	*10.2*	*4.3*	*0.38*	*4.2*	*57*	*15*	*1825*	*850*	*131*	*3.7*	*387*	*114*	*74*	*6*
SED sites		2.1	0.1	0.8	1.1	0.11	0.8	3.0	1.5	11	14	2	0.4	3	13	14	7
SED year		0.9	0.1	0.3	0.5	0.05	0.3	1.3	0.6	5	6	1	0.2	1	6	6	3

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[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMS I92/0067 in Uganda.

[2]

3.3 Management regime iii: (a)biotic and management factors and cassava yields

Abiotic and biotic stresses and management in the 2004 and 2005 trials varied strongly between sites and years (Table 4). Total cumulative rainfall ranged from 1065 to 2460 mm between sites ($P<0.001$) and from 1644 to 1825 mm between years ($P<0.001$). On-farm soil fertility was generally poor, but SOC and exchangeable cations were better at the on-station sites ($P<0.001$). Average soil organic carbon ranged from 6.9 to 20.5 g kg^{-1} ($P<0.001$), average available P from 2.5 to 12.3 mg kg^{-1} (P<0.001) and exchangeable K from 0.19 to 1.32 $cmol_{(+)}$ kg^{-1} ($P<0.001$) between sites and years. The soils in the Kenyan on-farm trials had less exchangeable K and cations and lower pH than the soils in the Ugandan on-farm trials in both years ($P<0.05$). Soil texture ranged from sandy loam to clay loam. Average weed management score per site ranged from 2.9 to 5.0 ($P<0.001$), while days to harvest ranged from 338 to 445 ($P<0.001$). Bacterial blight and green mite pressure was higher in Kenya than in Uganda, and higher in 2005 than in 2004 ($P<0.001$). These differences were reflected in the average yields under management regime iii (improved crop establishment and improved genotypes) that ranged from 6.4 to 25.7 t ha^{-1} between sites and from 12.2 to 15.0 between years (Table 4; $P<0.001$).

3.3.1 Factors explaining yield variability

Of the 58% yield variability explained by the linear model for the entire data set (RMSE = 4.0 t ha^{-1}), approximately one-third of the explained variability was associated with rainfall between the 9th and 12th month of the growth cycle, while variables pertaining to soil fertility (exchangeable Mg, available P and pH), weed management and soil texture variables explained the remaining variability in approximately equal parts (Table 5). Of the 38% yield variability explained by the Kenyan model (RMSE = 5.0 t ha^{-1}), about half was associated with total rainfall, and the rest with weed management and soil pH, while of the 82% yield variability explained by the Ugandan model (RMSE = 2.5 t ha^{-1}), most was associated with crop management variables, notably with weed management, and only a small percentage with soil fertility variables. Exchangeable Mg was strongly correlated with SOC (R^2 = 0.77; $P<0.001$), while rainfall between the 9th and 12th month of the growth cycle was significantly correlated to total rainfall during the growth cycle ($R^2 = 0.28$; $P<0.001$).

3.3.2 Factors contributing to cassava yield gaps

Clear boundary lines were identified in the scatter plots relating soil fertility, soil texture, pest and disease, weed management and selected rainfall variables to cassava

Table 5: Linear regression models of cassava yield under management regime iii[1] in the 2004 and 2005 trials for the entire data set (a) and Ugandan (b) and Kenyan (c) data sets separately

Variable	Regression coefficient	Square of semi partial correlation coefficient	*P*	% variance explained
(a) Entire data set[2] ($R^2 = 0.58$)				
Rainfall 9-12 MAP	0.57	0.20	< 0.001	30.2
Weed management	0.52	0.15	< 0.001	23.6
Silt	-0.43	0.10	< 0.001	14.9
Exchangeable Mg	-0.38	0.07	< 0.001	11.2
Available P	0.36	0.07	< 0.001	10.1
Clay	0.30	0.04	< 0.003	6.2
pH	0.24	0.03	< 0.017	3.8
Constant	-2.66	-	< 0.745	-
(b) Kenya data set[3] ($R^2 = 0.38$)				
Total rainfall	2.44	0.15	< 0.001	48.4
Weed management	0.13	0.10	< 0.003	32.2
pH	2.48	0.05	< 0.034	16.1
Days to harvest	-0.00	0.01	< 0.349	3.2
Constant	-20.1	-	< 0.001	-
(c) Uganda data set[4] ($R^2 = 0.82$)				
Weed management	1.25	0.22	< 0.001	51.2
Days to harvest	0.33	0.19	< 0.001	44.0
Exchangeable Ca	-1.20	0.02	< 0.086	4.7
Rainfall 9-12 MAP	0.04	0.00	< 0.844	0.1
Constant	-111.3	-	< 0.001	-

[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMSI92/0067 in Uganda)

[2] $y = -2.66 + 0.57 \times RF_{9-12} + 0.52 \times WM - 0.43 \times Silt - 0.38 \times Exch.Mg + 0.36 \times P + 0.30 \times Clay + 0.24 \times pH$

[3] $y = -20.1 + 2.44 \times RF_{tot} + 0.13 \times WM + 2.48 \times pH - 0.001 \times Days\_harv$

[4] $y = -111.3 + 1.25 \times WM + 0.33 \times Days\_harv - 1.20 \times Exch.Ca + 0.04 \times RF_{9-12}$

yield under management regime iii (improved crop establishment and improved genotypes) in the 2004 and 2005 trials (e.g. Figures 2a-c; 4a and b). The observed attainable yield (y_{max}) at management regime iii was 27.3 t ha^{-1}. No boundary lines could be identified for amongst others total rainfall, rainfall from 0 to 3 MAP, and days to harvest. Both genotypes responded similarly to all studied variables. Following von Liebig's law of the minimum, predictive multivariate models for cassava yield were developed using the identified boundary lines. This resulted in moderately good estimations for the yields measured in 2004 and 2005 in Uganda ($R^2 = 0.42$ and 0.47; RSME = 4.5 and 5.2 t ha^{-1}) and in 2005 in Kenya ($R^2 = 0.38$; RMSE = 5.5 t ha^{-1}), but in poor estimations in 2004 in Kenya ($R^2 = 0.06$; RMSE = 8.2 t ha^{-1}). In the scatter plots of yield versus weed management and yield versus rainfall during the first six months after planting, the 2004 Kenya data showed a distinctly different pattern from the rest of the data (Figures 4c and d). Developing a separate predictive model for the 2004 Kenya data, whereby the general boundary lines for weed management and

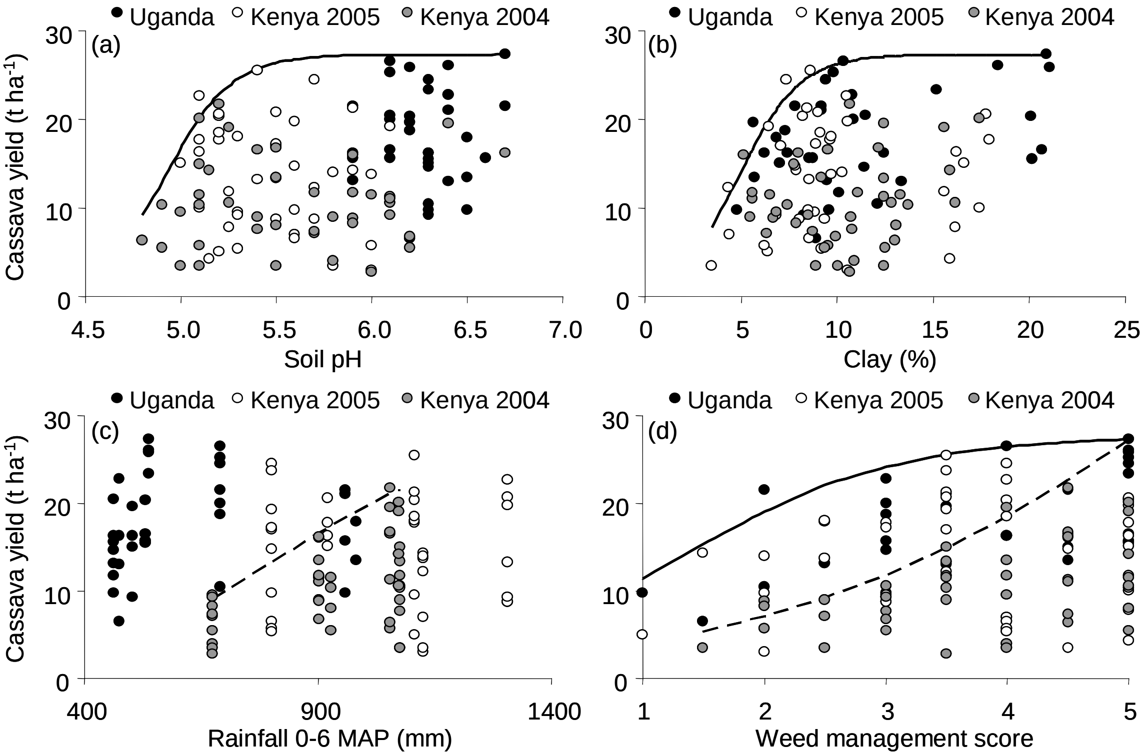


Figure 4: Boundary lines for cassava yield under management regime iii (improved crop establishment and genotypes) in the 2004 and 2005 trials for (a) soil pH; (b) clay content; (c) rainfall from 0 to 6 MAP and; (d) weed management. Black and dotted lines represent boundary lines for the overall and 2004 Kenya data sets, respectively. Weed management was scored from very poor (1) to very good (5).

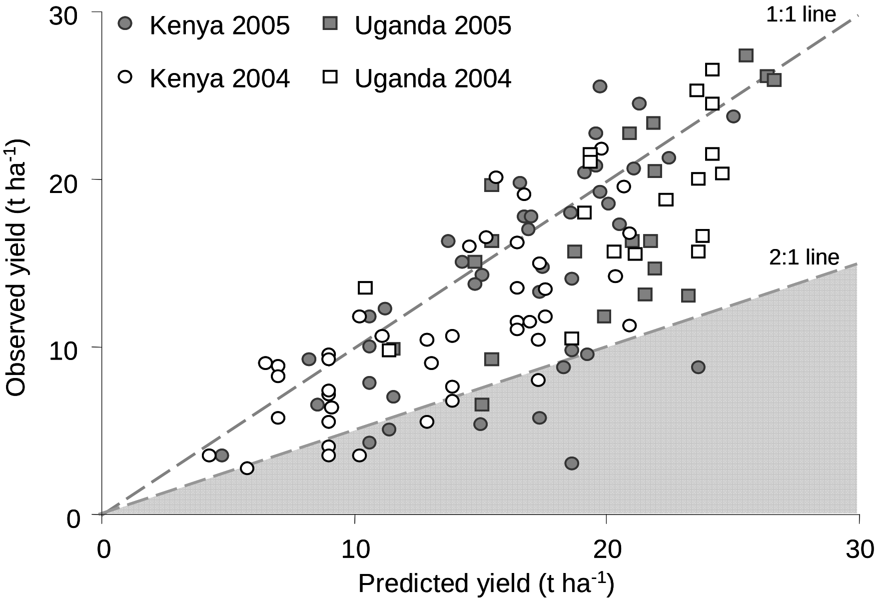
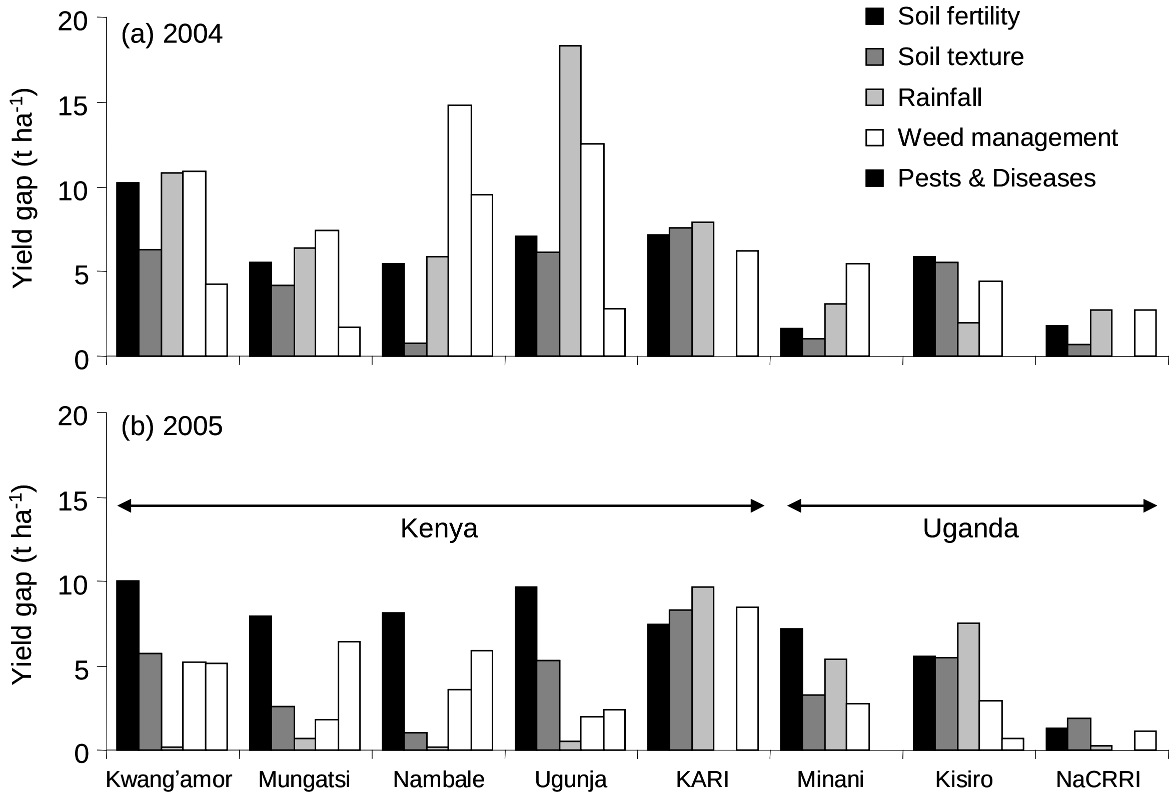


Figure 5: Predicted versus observed cassava yields under management regime iii (improved crop establishment and genotypes) for the 2004 and 2005 trials. Predictions are made using the multivariate boundary line model. Dashed lines represent the 1:1 and 2:1 lines.

rainfall during the first six months after planting were substituted with the boundary lines for the 2004 Kenya data, resulted in good yield estimations for this data set with an R^2 of 0.56 and RMSE of 3.8 t ha^{-1} (Figure 5).

The factors responsible for the identified yield gaps varied strongly between years and sites (Figure 6 and Table 6). Overall, poor soil fertility was the most important constraint and limited yields by an average difference of 6.7 t ha^{-1} with respect to the attainable yield. However, soil fertility limited production more strongly in Kenya (7.9 t ha^{-1} difference) than in Uganda (4.3 t ha^{-1} difference). Available P, total N and SOC limited yields in approximately one third of all fields. Yield limitations due to soil pH, total N, K and the sum of cations were either restricted to, or stronger, in Kenya than in Uganda. Rainfall limited yields by an average difference of 5.4 t ha^{-1} with the attainable yield. Observed yield limitations due to rainfall were associated with too



(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	4.2 ± 3.1	3.0 ± 5.4	0.6 ± 1.3

Figure 6: Identified yield gaps for cassava planted under management regime iii (improved crop establishment and genotypes) in the 2004 and 2005 trials due to soil fertility, soil texture, rainfall, weed management and pest & disease constraints in (a) 2004; (b) 2005 and; (c) average yield gap per constraint per country. Yield gaps are based on the multivariate boundary line model.

Table 6: Percentage of fields in the 2004 and 2005 trials at Management regime iii[1] where cassava production was affected[2] by abiotic and/or biotic stresses and/or weed management in Kenya (K) and Uganda (U) by year and site

			Soil fertility[3]						Soil texture[3]			Rainfall[3]		Mgm[3]	Pests & Diseases[3]		
		n	pH	SOC	N	P	K	Σcat	Sand	Clay	Silt	RF0-6	#RFd	WM	CBB	CGM	CAD
2004																	
Kwang'amor	(K)	9	0	78	67	22	11	67	0	67	0	100	0	100	11	11	44
Mungatsi	(K)	7	43	0	0	0	0	29	14	14	29	100	0	100	0	0	29
Nambale	(K)	9	33	22	0	22	11	33	0	11	0	100	0	100	67	22	100
Ugunja	(K)	9	22	33	11	67	0	44	33	0	44	100	0	100	11	0	33
Minani	(U)	8	0	13	0	0	0	0	0	13	0	0	100	38	0	0	0
Kisiro	(U)	6	0	50	50	0	0	0	0	83	0	0	0	50	0	0	0
KARI	(K)	8	88	0	0	75	0	0	88	0	63	100	0	0	88	0	88
NaCRRI	(U)	4	0	0	0	25	0	0	0	0	0	0	0	0	0	50	25
2005																	
Kwang'amor	(K)	9	0	57	86	14	14	29	0	57	0	0	0	57	14	71	14
Mungatsi	(K)	8	25	25	63	13	25	63	13	13	25	0	0	38	38	75	88
Nambale	(K)	7	44	22	67	33	67	67	0	0	0	0	0	44	33	100	11
Ugunja	(K)	10	0	50	90	70	10	50	70	0	40	0	0	20	10	10	10
Minani	(U)	8	0	25	13	50	25	13	0	25	0	0	100	50	0	0	0
Kisiro	(U)	8	0	63	0	38	13	0	0	63	0	0	100	38	0	25	0
KARI	(K)	8	100	0	0	63	0	0	88	0	50	0	50	0	88	0	63
NaCRRI	(U)	4	0	0	0	25	0	0	25	0	0	0	0	0	0	0	0

[1] Improved crop establishment and improved genotypes (MM96/5280 in Kenya and TMSI92/0067 in Uganda)

[2] $y\_max_{ij} < 90\% \ y_{max}$

[3] SOC = soil organic carbon; N = total N; P = available P; K = Exchangeable K; ∑cat = sum of exchangeable K + Ca + Mg; RF0_6 = rainfall in first six months after; #RFd = number of rain days during growth cycle; WM = Weed management, ranges from very poor (1) to very good (5); CBB = Cassava Bacterial Blight; CGM = Cassava Green Mites; CAD = Cassava Antracnose Disease.

little rainfall during the first six months after planting in 2004 in Kenya and with a too low number of rain days in Uganda during the crop cycle, whereby the number of rain days is positively correlated to cumulative rainfall (mm) during the first six months after planting ($P<0.001$). Weed management caused an average yield gap of 5.0 t ha^{-1} and restricted production most in farmer fields in Kenya in 2004 (yield gap of 11.6 t ha^{-1}), whereas soil texture caused an average yield gap of 4.3 t ha^{-1}. Observed limitations due to soil texture were associated with high silt contents (> 20%) and/or low clay content (<19%). Although 62% of the Kenyan fields in 2005 were affected by green mites, the absolute contribution to the yield gap (3.8 t ha^{-1}) from pests and diseases was the least important of all constraints recorded in this study.

In approximately 14% of the fields, yields predicted by the multivariate model were at least 100% higher than observed yields (Figure 5 – grey triangle). All but one of these fields were located in Kenya and over 25% were located in Ugunja. In all these fields, yields were limited by a multitude of constraints (3-8), but in none of these fields could the observed yield be accurately predicted by the single most limiting constraint.

4. Discussion

4.1 Constraints to cassava production in eastern Africa

Cassava production in most fields in our study was affected by multiple abiotic and biotic constraints that differed strongly between fields, sites and years. Their impact was aggravated by sub-optimal management practices (e.g. Table 3-5; Figures 4 and 6). Consequently, current farmer yields are less than one-fifth of the maximum yields recorded in the same region (Figure 1). Although the full management package (regime iv) more than doubled average yields, maximum yields in our trials were still ca. 14 to 25 t ha^{-1} lower than the maximum recorded yields in Kenya and Uganda (Figure 1). To achieve maximum yields, cassava requires high solar radiation, high mean day temperature, sufficient supply of all required nutrients, good rainfall distribution during crop establishment and possibly a dry period before harvesting (El-Sharkawy, 2004). Evidently, agro-ecological conditions in 2004 and 2005 were not optimal for cassava production.

Within the agro-ecological conditions prevalent during our trials, the farm survey, linear regressions and boundary line analyses all identified poor weed management as an important constraint to cassava production (Tables 3, 5 and 6 and Figure 6). Other studies (Melifonwu, 1994; Doll et al., 1982, quoted in Leihner, 2002) underline the importance of weed management for good cassava production. Uncontrolled weed growth during the first three MAP may reduce yields by 50-65%. Although three weed operations per growing cycle are recommended, farmers in our study weeded their fields on average 3.3 to 5.9 times (Table 2). Nonetheless, yield increases were observed in Kenya when the total number of weed operations increased to 6 per crop cycle (Figure 3b). Interestingly, only 12% of the farmers considered weeds as an important production constraint (Fermont, unpublished).

Poor soil fertility was identified in the boundary line analysis as the most important constraint to cassava production – despite the general perception that cassava is tolerant to poor soil fertility (Howeler, 2002) – and affected the majority of farmers' fields in our study (Figure 6 and Table 6). The importance of poor soil fertility as a major yield limiting factor is well illustrated by the strong response to fertilization, which over-ruled yield differences between sites (Figure 1 and Table 1). This is further reinforced by the fact that 62% of the farmers perceived poor soil fertility as a production constraint, 22% perceived it to be the most important constraint (Fermont, unpublished), and the observation that the smallest yields were found on farms with soils that were perceived as the poorest by farmers (Table 3). Soil fertility constraints in western Kenya were generally more severe than in Uganda (Table 6 and Figure 6) due to lower amounts of cations and pH (Table 4); which is exacerbated by its higher land pressure (Fermont et al., 2008 – Chapter 3).

Low rainfall, either during the first 6 months after planting or during the total crop cycle, was identified as the most important factor explaining yield variability in Kenya in the linear regression analysis, and as the overall second most important constraint in the boundary line analysis (Figure 6 and Table 6). These findings are rather surprising as cassava is considered to be a drought tolerant crop that can produce acceptable yields with as little rainfall as 700 mm year^{-1}, while being able to endure several months of drought (De Tafur et al., 1997b; El-Sharkawy, 2006). In our trials, total rainfall during the growth cycle was 1065 mm or more (Table 4) and drought periods did not exceed 40 consecutive days. The identified rainfall variables may be proxies for insufficient soil water availability during the early growth stages of cassava. Water stress during the first six months after planting is known to reduce storage root initiation and negatively affect root yields (Connor et al., 1981). In medium-high rainfall areas, early water stress may be caused by poor rainfall distribution in combination with sealing and crusting of topsoils in case of high intensity rain storms on bare soils (Hoogmoed and Stroosnijder, 1984). The latter was particularly visible at sites with high silt contents.

Although 68% of the farmers considered pests and diseases to be a production constraint on their farms (Fermont, unpublished) and in some years and sites a single pest or disease could affect up to 100% of the fields (Table 6), green mites, bacterial blight and anthracnose were not identified as important constraints for cassava production (Table 5 and 6 and Figure 6). Due to the adoption of resistant genotypes and farmer selection of tolerant landraces, the cassava mosaic disease epidemic has been largely brought under control in East Africa (Legg et al., 2006). Biological control programmes have successfully reduced the impact of green mites and especially mealy bugs on cassava production, while tolerance to bacterial blight is a key component of all breeding programmes in East Africa. As was also found for banana production in East Africa, farmers may overemphasize the importance of pests and diseases as production constraints because damage by pests and diseases can be more easily observed than most abiotic stresses (van Asten et al., 2009).

4.2 Interactions between production constraints

In the analysis of our trials, we observed interactions between rainfall and weed management for the 2004 Kenya data (Figures 4c and d). Poor rainfall during crop establishment resulted in slower plant development and consequently more labour was required for weeding. This was most obvious in sites with high silt content, where soil crusting hindered infiltration of rainwater. Interactions between factors influencing cassava yields were also observed by Schultness et al. (2004) for pest pressure and crop management and by De Tafur et al. (1997a) for water stress and fertilization during early growth stages.

In the farm survey analysis, we observed interactions between household resource endowment, crop management and soil fertility (Table 3), with less endowed farmers having lower cassava yields, less access to labour (e.g. for weeding) and generally poorer soils than better endowed farmers. Similar links between poverty and low crop yields were found by Zingore et al. (2006) and Tittonell et al. (2007b) for maize and groundnuts, while Tittonell et al. (2007c) showed that soil heterogeneity not only determined water and nutrient limitations, but also influenced farmers' management decisions. It will be more difficult for less endowed than for more endowed households to increase cassava yields because: (i) less endowed households face multiple production constraints and lack the social and economic capital to intensify crop management, while (ii) in a multi-stress environment removing one stress will increase production less than in an environment facing only one or two stresses.

Whereas linear regression models allowed us to identify overall trends for the whole study taking into account variable interactions, the boundary line approach identifies limiting factors for each individual field while ignoring interactions. Both approaches ascribed similar importance to weed management, rainfall and pest and diseases, but indicated different degrees of importance for soil fertility as a yield-determining factor (Table 5 and Figure 6). The importance given to variables in the linear regression or boundary line models depended on whether or not the variables showed significant linear correlations with yield or clear boundary lines. Weed management displayed both a linear correlation with yield and a clear boundary line, while most soil variables only displayed a clear boundary line (Figures 2 and 4). Soil fertility data from farm surveys or farmer trials will generally show a wide scatter when plotted against yield and often exhibit a plateau above which no increase in yield is observed (Shatar and McBratney, 2004). In such cases, the explaining power of a boundary line approach, which identifies the maximum yield at each given level of an independent variable, may be better than the explanatory power of a linear regression analysis. On the other hand, ignoring interactions between variables, as is done in the boundary line approach, is an oversimplification that may result in over prediction of yields (Figure 5 – grey triangle). Both analysis tools performed poorly with the Kenya data set. This could be due to strong interactions between variables and/or omission of major variables affecting yields in Kenya. The performance of the boundary line model was improved by identifying separate boundary lines for the Kenya 2004 data set. This shows that in case variables do not interact strongly, data from various years and sites may be analysed together, but in case of interactions site/year specific boundary lines need to be identified to account for the interactions.

4.3 Closing the cassava yield gap through improved production practices

The identified yield gaps for cassava may be (partially) closed through improved production practices as shows from the doubling of cassava yields when the full technology package (regime iv) was used (Table 1). Nonetheless, even without introducing new genotypes and fertilizer there is scope for yield improvement, as is clear from the large variation in cassava yields under current farmer practice (Table 3). Underlying this variation are differences in financial and human capital between farmers translating into differences in labour availability, particularly for weed management. During the survey, many farmers indicated to first weed cereal and legume fields and weed cassava fields later as cassava is perceived to be more tolerant of weed pressure. The promotion of options to improve early weed control thus seems key to reducing weed constraints in cassava production. Average cassava plant densities on farmers' fields in the region are low (3200 to 6400 plants ha^{-1}; Nweke et al., 1998; 1999). Increasing plant density to the recommended 10,000 plants ha^{-1} on fertile soils and up to 20.000 plants ha^{-1} on poorer soils will result in earlier canopy closure and subsequently less weed pressure. This effect can be reinforced through the use of vigorous early branching genotypes instead of erect genotypes (Leihner, 1980). Cassava breeders will need to find a balance between yield potential and weed control as early branching genotypes generally have less yield potential than erect genotypes. For farmers with sufficient financial means, the use of pre-emergence herbicides is perhaps an option to reduce labour requirements for weed management (Melifonwu, 1994; Leihner, 2002; Nguyen et al., 2008).

To reduce the impact of soil fertility constraints in cassava production, fertilizer is perhaps the easiest, but probably also the most expensive technology. We observed strong responses to NPK fertilizer (Table 1) and cost-benefit analysis indicated that fertilizer use was profitable in the majority of fields (Fermont, unpublished). In Asia, fertilizer use is a key component of many technology packages for cassava production and has been widely adopted by farmers (Howeler, 2008). An added benefit of fertilizer use is a reduction in labour requirements for weed management due to faster canopy closure. Medium/low technologies to (partially) overcome soil fertility constraints could include adaptations of best-best options developed for African cereal systems (Odendo et al., 2006; Okalebo et al., 2006; Ojiem et al., 2007), such as (i) the combined use of inorganic and organic fertilizer; (ii) targeted micro-dosages of fertilizer; and (iii) intercropping and/or crop rotation options with dual-purpose legumes, especially in N-limited areas. Decreasing nutrient removal from cassava fields through the non-removal of stems and the return of ashes from cassava stems when used for fuel may also help to particularly reduce the impact of potassium deficiency (Fermont et al., 2008 – Chapter 3).

Farmers may be able to reduce the impact of drought through avoidance strategies, e.g. early planting at the onset of the rains, and improving rainfall infiltration and reducing evaporation by ensuring a good soil coverage through improved weed control, mulches or conservation tillage (Stroosnijder, 2008). However, most of the above-mentioned practices require additional labour at the onset of the rainy season, a period of peak labour demand. A more practical approach perhaps is the identification and/or breeding of genotypes that are tolerant to early drought stress and subsequent introduction of these genotypes. Although cassava mosaic disease, green mites, bacterial blight and anthracnose were of limited importance in this study, new disease threats that include co-infection of mosaic geminiviruses with DNA satellites, which breaks down the known resistance to mosaic virus, and the brown streak virus (Alicai et al., 2007; Ndunguru et al., 2008) can potentially reduce cassava production substantially and thereby over-rule all other constraints. Hence, despite the findings of this study, development and dissemination of genotypes resistant to new pest and disease threats remains of paramount importance.

5. Conclusions

The comparative analysis of multi-locational on-farm and on-station experiments and farmer surveys clearly demonstrate that there is substantial ‘room to manoeuvre’ to improve cassava production in East Africa, as current cassava yields on smallholder farms are far below attainable yields in the region. The observed yield gaps are caused by a multitude of production constraints. Abiotic constraints and related crop management practices are far more important than perceived by farmers and scientists to date. Efforts to improve productivity should be geared towards combining approaches to identify and overcome the most important constraints simultaneously. This would represent a strong reappraisal of the current agenda of existing research programmes on cassava yield improvement that have tended to focus on single constraints, and particularly on specific pests and diseases (e.g. control of cassava mosaic disease, green mites and mealy bugs). This will require the development and on-farm participatory evaluation of a range of technologies geared towards integrated crop management, resting on four main pillars: (i) improved germplasm; (ii) soil fertility management; (iii) early weed control; and (iv) water capture and use efficiency. Dissemination of improved genotypes will form the back-bone of any new technology package, because the introduction of new genotypes presents the ideal entry point for the promotion of alternative crop management options.