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Cassava yield loss in farmer fields was mainly caused by low soil fertility and suboptimal management practices in two provinces of the Democratic Republic of Congo

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ABSTRACT

A better understanding of the factors that contribute to low cassava yields in farmers' fields is required to guide the formulation of cassava intensification programs. Using a boundary line approach, we analysed the contribution of soil fertility, pest and disease infestation and farmers' cultivation practices to the cassava yield gap in Kongo Central (KC) and Tshopo (TSH) provinces of the Democratic Republic of Congo. Data were obtained by monitoring 42 and 37 farmer-managed cassava fields during two cropping cycles in KC and one cropping cycle in TSH, respectively. Each field was visited three times over the cassava growing period for the observations. Logistic model was fitted against the observed maximum cassava root yields and used to calculate the achievable yield per field and for individual factor. At field level, the factor that led to the lowest achievable yield ($Y_{up(i)1}$) was considered as the dominant yield constraint. Cassava yield loss per field was expressed as the increase in the maximal root yield observed per province (Y_{att}- attainable yield) compared to $Y_{up(i)1}$. Y_{att} was 21 and 24 t ha^{-1} in TSH and KC, respectively. With the cassava varieties that farmers are growing in the study areas, pests and diseases played a sparse role in the yield losses. Cassava mosaic was the only visible disease we observed and it was the dominant yield constraint in 3% and 12% of the fields in KC and TSH, respectively. The frequent yield constraints were suboptimal field management and low soil fertility. Cultivation practices and soil parameters led to $Y_{up(i)1}$ in 47% and 50% of the fields in KC, and in 47% and 41% of those in TSH, respectively. Individual soil parameters were the yield constraint in few fields, suggesting that large-scale programs in terms of lime application or recommendation of the blanket fertilisers would result in sparse efficacy. In KC, yield losses caused by low soil fertility averaged 6.2 t ha^{-1} and were higher than those caused by suboptimal field management (5.5 t ha^{-1}); almost nil for cassava mosaic disease (CMD). In TSH, yield losses caused by low soil fertility (4.5 t ha^{-1}) were lower than those caused by suboptimal field management (6.5 t ha^{-1}) and CMD (6.1 t ha^{-1}). Irrespective of the constraint type, yield loss per field was up to 48% and 64% of the Y_{att} in KC and TSH, respectively. Scenario analysis indicated that the yield losses would remain at about two third of these levels while the dominant constraint was only overcome. We concluded that integrated and site-specific management practices are needed to close the cassava yield gap and maximize the efficacy of cassava intensification programs.

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1. Introduction

Despite several efforts, mainly in terms of dissemination of improved genotypes and integrated pest and disease management, cassava productivity in African smallholder's farming systems is below the optimal level, although some increases in yields have been observed (Rusike et al., 2010; Zinga et al., 2013). Average cassava fresh root yield increased in Africa from 6 to 10 t ha^{-1} over the last 50 years but it is still much lower than the current average yields of 22 t ha^{-1} in Asia (FAOStat, 2015). In sub-Saharan Africa (SSA), cassava yields under research management fields are most often larger than those under smallholder farmer management fields. In East Africa for instance, Obiero (2004), Ntawuruhunga et al. (2006) and Legg et al. (2006) recorded cassava fresh root yields of 60 t ha^{-1} under experimental conditions, while Fermont et al. (2010) observed 6–17 t ha^{-1} of cassava fresh root yields in Kenyan and Ugandan farmer fields. In the Democratic Republic of Congo (DRC), the yields of cassava genotypes in research-managed systems are at least twice as those in farmer-managed systems (Unpublished data). In this context, reducing the gaps between cassava yields under research- and farmer-managed systems is a crucial concern in Africa, especially as cassava is moving from a subsistence crop to one of the major commercialized crops and appears to be one of the promising crops to mitigate drought resulting from climate change. To reduce the yield gap, a better understanding of the factors contributing to low cassava yields is needed, as this can help to design intensification programs and prioritize the interventions in the context of limited available resources. While there is agreement on low cassava productivity because of poor crop management (e.g., late weed control and cassava planting at low density) and pest and disease infestation (Albuquerque et al., 2014), opinions differ on the response of cassava to inherent soil fertility. Compared with many other crops, cassava is generally perceived as tolerant of low soil fertility (Howeler, 2002). Most farmers believe that cassava can restore the fertility of degraded soils and it does not need external nutrient inputs to soils (Leihner, 2002). This explains why many farmers grow cassava on marginal land or land that is about to be abandoned to natural regeneration (Hillocks, 2002; Saïdou et al., 2004; Adjei-Nsiah et al., 2007). In almost all cases where soil fertility was cited among the limiting factors of cassava productivity, the authors emphasized on soil exchangeable K as cassava removes more K than other crops (Howeler et al., 1987; Howeler et al., 1991; Carsky and Toukourou, 2005). Other soil fertility related constraints, such as imbalanced nutrient contents and high content of undesirable nutrients (e.g., zinc and aluminium) may also reduce cassava productivity (Cassman et al., 2002; Ezui et al., 2016).

Boundary line analysis has been used to assess the relative contribution of individual factors to yield gaps of cereals, banana, coffee

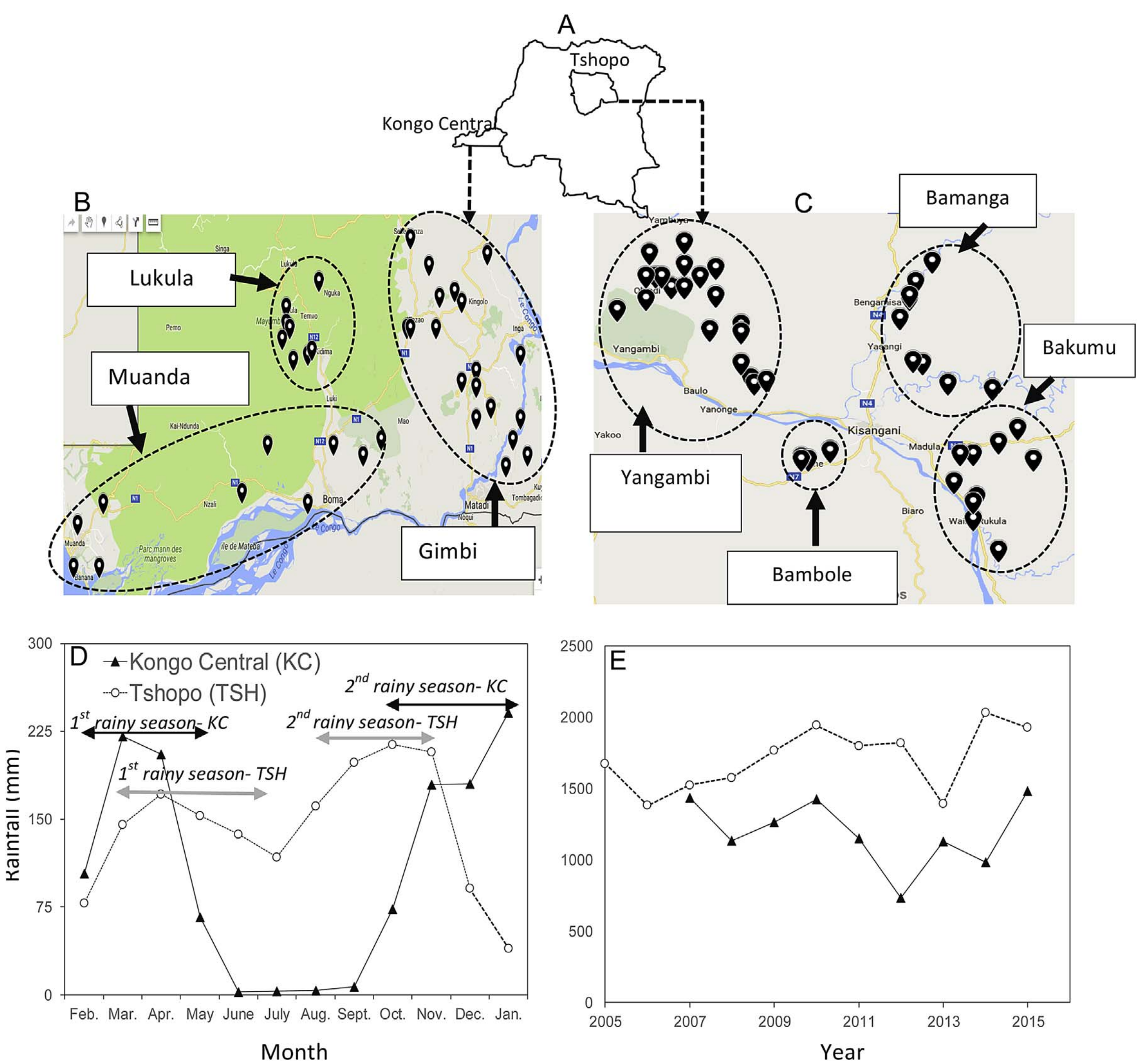

Fig. 1. Study provinces (A) and global positioning system (GPS) of the monitored farmer fields in Kongo Central (B) and Tshopo (C). Monthly (D) and annually (E) rainfalls in Central Kongo and Tshopo as respectively illustrated by data collected from 2007 to 2015 at Gimbi and average of those collected at Litoy and Yangambi from 2005 to 2015 of unexplained yield gaps.

Table 1
Used variables to capture field management (A), soil fertility (B), pest and disease infestation (C) and cassava productivity (D).

Variable	Expression method
A- Field size and management	
Field size (ha)	Given by GPS after walking around field limits
Land preparation	Soil tillage or not.
Type of tillage	Manual or mechanic
Weeding time	Number of days/month between consecutive weed controls (include land preparation) was calculated from the recorded dates per operation.
Weeding number	Number of weed control conducted before cassava harvest
Weeding method	Manual or herbicide use.
Type of association	Cassava was sole- or inter-cropped with other crops.
Fertilizer inputs	Applied or not. Type of fertilizer (organic or inorganic) if applied. Rate if known
Planting time	Number of months between cassava planting and when rains started (March for Tshopo; February and October for 1st and 2nd cropping seasons in Kongo Central, respectively).
Plant density (plant ha^{-1})	Calculated from number of cassava plants counted per square
B-Soil fertility	
Total soil C	C content (g kg^{-1}) in the sampled soil was obtained by spectrophotometric analysis after chromic acid digestion (Heanes, 1984).
Total soil N	N content (g kg^{-1}) in the sampled soil was obtained by colorimetric analysis after wet acid digestion (Buondonno et al., 1995; Anderson and Ingram, 1993).
Exchangeable cations and available P	Exchangeable K^+, Ca^{2+} and Mg^{2+} (Cmol+ kg^{-1}) and available P (mg kg^{-1}) were extracted from the sampled soil using the Mehlich-3 method (Murphy and Riley, 1962).
Soil acidity	Soil pH was obtained in soil: water solution (1:2.5) and exchangeable Al^{3+} by titration after extraction with 1 M KCl.
Particle size	Three fractions (sand, silt and clay) were obtained using hydrometer method.
C/N ratio	Calculated from carbon and nitrogen contents determined in soil samples
Exchangeable cation ratios	Calculated from the concentration of exchangeable cations determined in soil samples
C— Pest and disease infestation	
Cassava mosaic disease (CMD)	Visual observation of the cassava plants in the established squares, using scoring rate ranged from 1 (no infestation) to 5 (highest infestation)
Cassava Brown Streak Disease (CBSD) and others	Visual observation of cassava plants and roots in the established squares, using scoring rate ranged from 1 (no infestation) to 5 (highest infestation)
D-Cassava productivity	
Fresh root yield (t ha^{-1})	Cassava root yield was calculated from production weighed per square.

and cassava (Casanova et al., 1999; Shatar and McBratney, 2004; Fermont et al., 2009; Wairegi et al., 2010; Wang et al., 2015). Boundary line analysis consists to properly describing the maximum yields versus each production factor and then use the calibrated versions of the model to simulate at the plot level and for each factor the upper boundary yields. The factor that leads to the lowest upper boundary yield at plot level is considered as the most yield limiting factor in that plot, according to one of the Liebig Laws. In the case of cassava, Fermont et al. (2009) identified at the plot level only the most limiting factor of cassava yield gap in farmers' fields in Kenya and Uganda. The identified limiting factors varied strongly among sites and years, suggesting that cassava yield limiting factors cannot be generalized across a larger area or over time. For factors changing slowly over time (e.g. soil pH, carbon and nutrient contents) it is useful to identify at the plot level several limiting factors and classify them by their severity (i.e. dominant and latent). This makes sense for two main reasons: (i) a factor that does not change dramatically over time but is the dominant limiting factor during a cropping season was certainly latent limiting factor during the past cropping seasons (no spontaneity phenomena) and (ii) as soon as the dominant limiting factor is overcome another factor (previously latent) will become most limiting.

The objective of this study was to analyse the contribution of soil fertility, pest and disease infestation and field management to the cassava yield gap in two provinces of the Democratic Republic of Congo (DRC) (Kongo Central and Tshopo).

2. Materials and methods

2.1. Study area

The study was conducted in Kongo Central and Tshopo provinces of the DR Congo (Fig. 1A). Rainfall is bimodal in the two provinces, allowing two planting seasons a year (Fig. 1D). In Kongo Central, the 1st rainy season is from mid-February to May while the 2nd rainy season starts in mid-October and ends in mid-January. The 1st rainy season is followed by about 5 months of dry season (June to mid-October) and is less suitable for cropping than the 2nd rainy season, which is followed by about 1 month of dry season (mid-January to Mid-February). In Tshopo, rains are suitable for planting from March to November, with some days/weeks of dry season in July or August (Fig. 1D). The 1st and 2nd planting seasons start in March and September, respectively. In Tshopo, the 1st rainy season is more suitable for cropping as it is followed by the shorter dry season. Furthermore, during the 2nd season in Tshopo rains may be excessive from September to November. On average, 36% of the total annual rainfall occurs during these months (Fig. 1D). Total annual rainfall is lower in Kongo Central than in Tshopo (Fig. 1E). In Kongo Central, vegetation, rainfall and soil fertility are decreasing from the north to the south.

2.2. Data collection

Data were collected by monitoring 42 and 37 cassava fields of small households during two cropping cycles in Kongo Central and one cropping cycle in Tshopo, respectively (Fig. 1B and C). Households were randomly selected with the aim of having at least three representative fields per agro-ecological area. Based on the presence of a research station and visual observation on the gradient of rainfall, vegetation and soil fertility, we considered in Kongo Central three agro-ecological areas: Gimbi (research station nearby) were 23 farmer fields were monitored, and Lukula and Muanda (far from the research stations) where 11 and 8 farmer fields were respectively monitored (Fig. 1B). Cassava fields monitored in Tshopo were selected around Yangambi (research station) and in three other areas far from the research station: Bambole, Bamanga and Bakumu (Fig. 1C). The monitored cassava fields in Tshopo (15, 4, 8 and 10 at Yangambi, Bambole, Bamanga and Bakumu, respectively) were planted during the 1st rainy season in 2014. In Central Kongo, the fields monitored at Lukula and Muanda were planted during the 1st rainy season in 2014, while those monitored around the Gimbi research station were planted during the 2nd rainy season in 2015.

We interviewed the household head and recorded his/her socio-economic characteristics (e.g., age, gender, educational backgrounds, land tenure and income sources). One of the cassava fields that the household had early planted during the concerned season was visited three times over the growing period for the observations as listed in Table 1. The 1st, 2nd and 3rd visits were conducted between 1 and 2, 4 and 5 and around 12 months after cassava planting, respectively. Periods of field visit were chosen with the aim of: *(i)* avoiding that farmers forget some of the conducted activities, *(ii)* sampling soils before eventual fertiliser applications and *(iii)* coinciding the observation with the periods when major pest and diseases prevail and can be easily observed in the study area (beginning of rainy season and medium cassava growth stage for CMD, towards cassava maturity for Brown Steak). During the 1st visit, the household's socio-economic characteristics and the initial cultivation practices in the selected cassava field (e.g., land preparation, field size, type of association, planting date and mode, eventual fertilizer application, weeding periods and methods, etc.) were recorded. Cultivation practices that could be directly observed (e.g., planting density, patterns and intercrops) were recorded in the field. Those that could not be directly observed (e.g., planting date, eventual fertilizer application or cassava leaf harvest, weeding dates, harvesting of the associated crops) were recorded by interviewing the farmer. During the first visit, 3 squares (5 m × 5 m) were randomly delimited in the cassava field, in which we sampled soil and recorded pest and disease infestation. Soils were randomly taken in five places per square at 0–30 cm depth and mixed into one composite sample per field/household. Pest and disease infestation was scored on all plants of each square, using scoring rate ranged from 1 (no infestation) to 5 (highest infestation). During each of the following visits, all crop management practices that the farmer had conducted since the last visit were recorded. Pest and disease infestation was again scored. At the last field visit, cassava was harvested in the squares and the roots were weighed to calculate the yield.

2.3. Data analysis

In the present study, we analysed data on cassava yield, soil fertility, cultivation practices and pest and disease infestation. Data on the household's socio-economic characteristics were not analysed as they do not relate directly to yield gap.

2.3.1. Yield gap estimates

The contribution of soil fertility, farmers' cultivation practices and pest and disease infestation to the cassava yield gap was analysed using three levels of cassava root yields: the attainable root yield (Y_{att}), actual root yield (Y_{obs}) and the upper boundary yields ($Y_{up(i)}$). We considered Y_{att} as the highest cassava fresh root obtained in the monitored fields within each province (Waddington et al., 2010; Wang et al., 2015). Tittonell and Giller (2013) defined Y_{att} as the maximum yield achieved by implementing the results of local research or the combination of best practices as determined from local research. Therefore, the Y_{att} used in the present study should be lower than that Tittonell and Giller (2013) defined, as it would be rare to have the farmers who apply all the best practices. Actual cassava root yield (Y_{obs}) of an individual field was the average of cassava root yields measured in the three sampling squares per field. Y_{obs} is lower than or at the most equal to Y_{att}. The way we estimated the upper boundary yield for a factor "*i*" ($Y_{up(i)}$) depended on whether the factor is categorical (e.g., tillage and no tillage for land preparation) or continuous (e.g., soil C content or plant population). For categorical factor, $Y_{up(i)}$ for each field that received or benefited from a given level of the factor was the highest yield obtained in any field that received or benefited from that specific factor level within the province. $Y_{up(i)}$ corresponds theoretically to the cassava root that the field could have been yielded if the production would only have been limited by the factor "*i*". For each continuous factor, $Y_{up(i)}$ were calculated by calibrating a boundary curve along the maximum yields obtained by a series of factor values. Boundary curves were calibrated by fitting these maximum yields against continuous values of the factor, using the general logistic model as formulated by Kintché et al. (2015a) (Eq. (1)):

$$Y_{up(i)} = \frac{A}{B + C^{*}\exp(k^{*}x)} \tag{1}$$

where $Y_{up(i)}$ are the model values; x are the factor values, and *A, B, C* and *k* the model constants. *A, B* and *C* are positive values while "*k*" can be positive (if actual root yields and factor values are negatively correlated) or negative (if they are positively correlated). Per factor, the best boundary curve was obtained by fitting the maximal model value (A/B) to the attainable yield (Y_{att}) observed per province, and then *C* and *K* values were determined by adjustment to minimize the bias between the maximum yields and model-predicted values. The bias between the maximum yields and model-predicted values was measured using the root mean square error (RMSE). Further information on model calibration process are available in Wang et al. (2015). Number of $Y_{up(i)}$-values per field is equal to the number of candidate factors explaining the yield gap (each factor leads to one $Y_{up(i)}$-value). The candidate factors for yield gap explanation were selected by calculating the correlation coefficient (r) between the actual yields and values of each factor. Factors for which, the correlation coefficient was almost nil were not considered. While some factors were highly correlated (absolute r value > 0.5), only one of them was used in the boundary line analysis and considered as the proxy of the other factors with whom it is correlated.

2.3.2. Identification of the yield limiting factors and calculation of the explained and unexplained yield gaps

For each field, $Y_{up(i)}$ of different factors were arranged in ascending order as in the following list: $\{Y_{up(i)1}, Y_{up(i)2}, Y_{up(i)3}, \ldots, Y_{up(i)n}\}$; where $Y_{up(i)1}$ is the lowest $Y_{up(i)}$ and $Y_{up(i)n}$ the highest. According to Liebig's Law, the factors that led to $Y_{up(i)1}$ and $Y_{up(i)2}$ were respectively considered as the dominant and first latent limiting factor of cassava root productivity at the concerned field. We stopped the iteration at two levels of factor severity because $Y_{up(i)3}$ were significantly higher than $Y_{up(i)2}$ ($Y_{up(i)1}$ and $Y_{up(i)2}$ were not significantly different; $p < 5\%$). At the provincial level, we calculated the percentage of fields where each factor was the limiting factor and then estimated the distribution of limiting factors across the area.

The explained yield gap per field (Y_{G1}) was estimated as the increase in the attainable yield (Y_{att}) compared to the lowest upper boundary yield of the concerned field ($Y_{up(i)1}$); i.e. the gap due to the dominant limiting factor. Y_{G1} was interpreted as the yield loss caused by the dominant limiting factor in the concerned field (Wang et al., 2015). We compared Y_{G1} of the fields where soil parameters, farmers' cultivation practices and pest and disease infestation were the dominant yield-constraint and then measured the magnitude of yield loss attributable to constraint types. The unexplained yield gap (Y_{G2}) was estimated as the increase in $Y_{up(i)1}$ compared to Y_{obs}. High value of Y_{G2} means that there are other important limiting factors that were not considered in the analysis and/or the model did not perform well in the concerned field as it does not address factor interactions (Shatar and McBratney, 2004).

3. Results

3.1. Cassava field size and cultivation practices

The size of the monitored cassava fields ranged between 0.1 and 0.98 ha in Kongo Central, and between 0.2 and 4.4 ha in Tshopo. About 33% of the fields in Tshopo had a size larger than the maximal size recorded in Kongo Central. Cassava fields monitored during the 1st

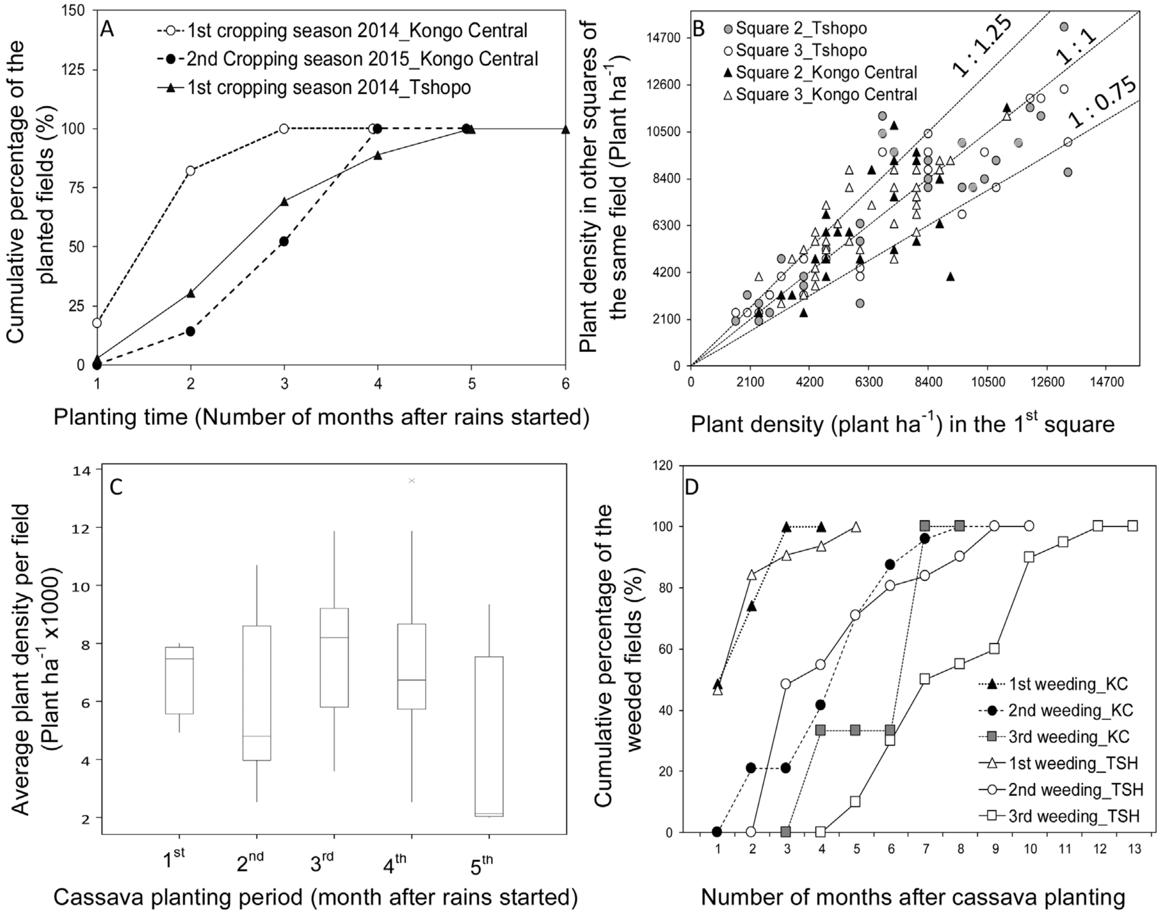

Fig. 2. Progression over rainy seasons of the proportion of the planted cassava fields (A), variability of cassava density within a field (B), relationship between cassava plant density and the planting period (C) and weeding period of the monitored cassava fields (D). In figures A and C, first month after rains started corresponds to March for Tshopo, February and October for the 1st and 2nd cropping cycles in Kongo Central respectively. In figure B, plant density of one of the three squares established per field was plotted against those of the two other squares. Reference lines were plotted for propose illustration. In Figure C, the bottom of the vertical line below the box corresponds to the minimal value of the observations, while the top of the vertical line above the box corresponds to the maximal value. Lower, medium and upper horizontal lines of the box correspond to the highest values for 25%, 50% and 75% of the observations. In the legend of figure D, KC and TSH stand for Kongo Central and Tshopo, respectively.

cropping cycle-2014 in Kongo Central were planted during the first three months of the rainy season (February-April), with 60% of the fields planted in March (Fig. 2A). Early plantings ocurred mainly at Muanda while the latest plantings were more pronounced at Lukula (Table 2A). During the 2nd cropping cycle-2015 in Kongo Central and the 1st planting cycle-2014 in Tshopo, cassava planting started from the 2nd month of the rainy season and was completed after 4 and 5 months in Kongo Central and Tshopo, respectively (Fig. 2A). The latest plantings occurred at Bakumu and Yangambi (Table 2A).

Irrespective of the area, cassava plant density varied widely within and among fields (Fig. 2B). Compared to the first sampled square, cassava plant density in the two other squares of the field was more than 25% higher or more than 25% lower, indicating high density heterogeneity within the field (Fig. 2B). Average plant density varied between 2000 and 15,200 plants ha^{-1} among the fields in Tshopo, and between 2400 and 11,600 plants ha^{-1} among those in Kongo Central. Cassava plant density was at a lesser extent related to the planting period (Fig. 2C). Half of the fields planted during the 3rd month of the rainy seasons had plant density higher than that of 70% and 80% of the fields planted during the 2nd and 4th months of the rainy seasons, respectively.

Improved cassava varieties were more widely cultivated in Kongo Central than in Tshopo (Table 2B). About 60% of the households in Tshopo cultivated exclusively local cassava varieties, compared to less than 10% of the households in Kongo Central. In both Tshopo and Kongo Central, none of the interviewed households cultivated exclusively improved cassava varieties. Among households cultivating both local and improved varieties (40% and 90% in Tshopo and Kongo Central respectively), those in Kongo Central allocated large areas to improved varieties (Table 2C). About 40% of the households cultivating both local and improved cassava varieties in Kongo Central allocated more than 75% of the cultivated area to improved varieties, and this was more pronounced around the Gimbi research station (65% vs. 10–17% for the other areas). In Tshopo, all households cropping both local and improved cassava varieties allocated less than 75% of the cultivated area to improved varieties. In that province, the cultivation of local cassava varieties and the allocation of small areas to improved varieties were more pronounced around the Yangambi research station than at Bamanga and Bambole.

Both in Kongo Central and Tshopo, the monitored cassava fields were weeded one, two or three times. In Tshopo, 69% of the fields were weeded three times compared to 20% in Kongo Central (Table 2D). In Tshopo, three weed controls over the cassava growing period was conducted in 89% of the fields around the Yangambi research station, compared to 29–67% of the fields in other areas within the province. One weed control over the growing period was exclusively conducted at Bamanga. In Kongo Central, the proportions of the fields weeded three times did not differ clearly among the agro-ecological areas, but large proportion of the fields around the Gimbi research station were weeded twice (Table 2D). Although a smaller proportion of the fields in Kongo Central were weeded three times,

Table 2
Proportion of the fields (%) where a variant of cultivation practice was conducted.

Cultivation practice	Kongo Central				Tshopo				
	Lukula	Muanda	Gimbi	Overal	Bamanga	Bakumu	Bambole	Yangambi	Overal
A) Planting time (Number of month since rains started)									
One*	8	29	0	8	0	0	0	0	0
Two	58	57	16	37	75	50	25	15	31
Three	34	14	42	29	25	13	50	50	39
Four	–	–	42	26	0	13	25	25	19
Five	–	–	–	–	0	24	0	10	11
B) Utilization of the improved and local cassava varieties									
Local only	8	14	5	9	0	57	40	75	60
Local + improved	92	86	95	91	100	43	60	25	40
C) Area allocated to the improved varieties when household is cropping both improved and local varieties (% of total area cultivated)									
< 25%	36	50	6	23	25	33	0	50	29
25 to 50%	27	33	12	19	0	67	33	50	36
50 to 75%	27	0	18	17	75	0	67	0	35
> 75%	10	17	65	41	0	0	0	0	0
D) Total number of weed control									
One	40	50	17	29	50	0	0	0	6
Two	40	33	63	51	0	71	33	11	25
Three	20	17	21	20	50	29	67	89	69
E) Period of first weed control (Month after planting)									
1st	50	33	53	49	0	43	80	47	47
2nd	20	17	32	26	67	29	20	41	37
3rd	30	50	15	25	0	14	0	6	6
4th	0	0	0	0	33	0	0	6	10
F) Fertilizers									
Used	0	0	11	3	0	12	0	0	5
No used	100	100	89	97	100	88	100	100	95
G) Soil tillage									
Tilled	25	71	0	21	25	0	20	5	8
No tilled	75	29	100	79	75	100	80	95	92

*February for Lukula and Muanda (1st planting season 2014 in Kongo Central), October for Gimbi (2nd planting season 2015 in Kongo Central) and March for Tshopo (1st planting season 2014).

some fields were weeded early as compared to the fields in Tshopo (Fig. 2D). All fields in Kongo Central were weeded for the first time before the 3rd month after planting (MAP) ended. Within the same period in Tshopo, about 10% of the fields (33% and 6% at Bamanga and Yangambi, respectively) were not yet weeded; they were weeded for the first time during the 4th MAP (Table 2E and Fig. 2D). By the end of the 2nd MAP, about 20% of the fields in Kongo Central were weeded for the second time, while within the same duration in Tshopo none of the fields was weeded for the second time (Fig. 2D). In Tshopo, the second weed control was conducted in 40% of the fields during the 3rd MAP and was delayed until 9th MAP in some fields, compared to Kongo Central where all fields were weeded for the second time before the 7th MAP ended. The third weed control was conducted between 4th and 7th MAP in Kongo Central, compared to Tshopo where it was conducted between 5th and 12th MAP (Fig. 2D).

Cultivation practices, such as manual weed control, low or no fertilizer application in cassava fields, cassava intercrops, biomass burned before cassava planting, etc., were common practices both in Tshopo and Kongo Central. Weeds were manually controlled in all monitored fields. Biomass was burned before cassava planting in all fields in Tshopo and in 90% of those in Kongo Central. Both in Kongo Central and Tshopo, cassava was intercropped in more than 90% of the fields and planted with no pattern in about 80% of the fields. Farmers applied manure in 12% of the fields at Bakumu (Tshopo) and 11% of those at Gimbi (Kongo Central) (Table 2F), without being able to estimate the applied amounts. In Kongo Central, soil was not tilled in all fields at Gimbi but it was tilled in 25% and 71% of the fields at Lukula and Muanda, respectively. In Tshopo, all fields at Bakumu were not tilled while 5–25% of the fields in other areas were tilled (Table 2G).

3.2. Biophysical characteristics of the monitored cassava fields

3.2.1. Altitude and soil fertility indicators

The cassava fields monitored in Kongo Central were between 15 and 203 m above sea level (masl), thus at lower altitude than those in Tshopo (362–1522 masl). Contrary to the four study areas in Tshopo, soil fertility indicators varied widely among the agro-ecological areas in Kongo Central (Fig. 3). In Kongo Central, except for the silt rate and exchangeable K content, soil parameters differed significantly across the agro-ecological areas. The worst soil fertility indicators were observed at Muanda, except for soil available P that was high but widely variable within the fields. Fields at Muanda had the *i)* lowest organic C and total N contents, *ii)* the highest sand rates, and *iii)* were among the fields that had low pH and exchangeable cation contents. Compared to Lukula, fields at Gimbi were more acidic (low pH and high Al content) but they had the highest C and N contents and the lowest sand rates. For the areas in Tshopo, only soil organic C, exchangeable K and C/N ratio were significantly different (Fig. 3B, E and H). Exchangeable Al in half of the fields at Bambole was higher than 2 Cmol[+] kg^{-1}, while all fields in the other areas had Al content lower than that value (Fig. 3J).

3.2.2. Pest and disease infestation

Cassava mosaic disease(CMD) was the main disease observed in the monitored fields. Cassava Brown Streak Disease (CBSD) was only observed in 3 of the 37 fields in Tshopo, with severity scores < 3. CMD infestation was more severe in Tshopo than in Kongo Central. All fields in Tshopo were infested by CMD during the early (1–2 MAP) and medium (4–5 MAP) cassava growth stages. The severity scores ranged between 2 and 4 at early stages, and between 2 and 5 at the medium stages. In Kongo Central, CMD was found in about half of the fields with

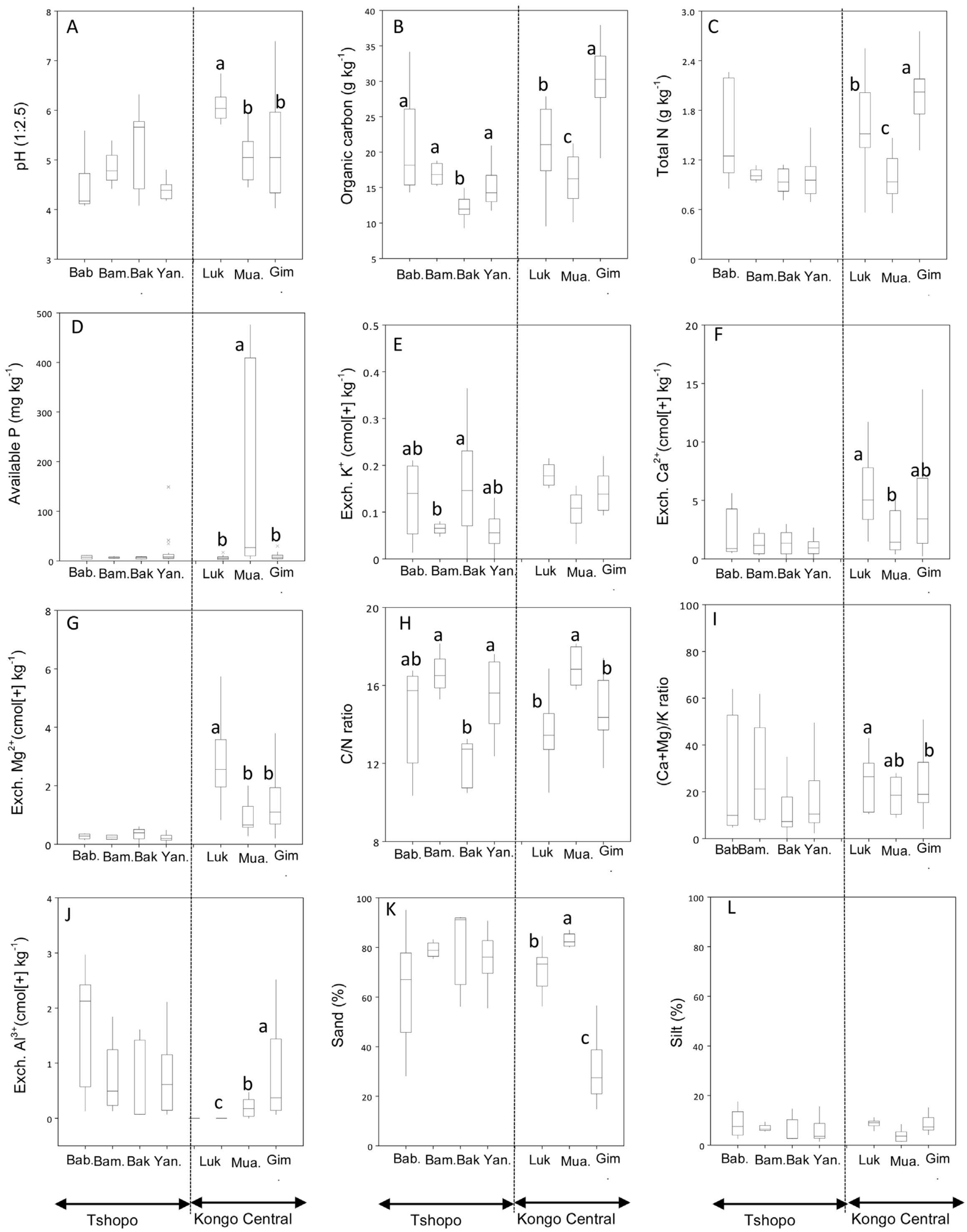

Fig. 3. Variability of soil fertility indicators: pH (A), organic carbon (B), total N (C), available P (D), exchangeable K^+ (E), Ca^{2+} (F), Mg^{2+} (G), C/N (H), cation ratio (I), Al^{3+} (J), sand (K) and silt (L)). *Bab., Bam., Bak. and Yan.* stand respectively for Bambole, Bamanga, Bakumu and Yangambi in Tshopo, and *Luk., Mua. and Gim.* for Lukula, Muanda and Gimbi in Kongo Central. Per soil parameter and at province level, average values were significantly different for the boxplots marked with different letters ($p < 0.05$). No mention if there was no significant difference.

severity scores < 3 both at the early and medium growth stages.

In Tshopo, CMD severity depended on the agro-ecological areas and the planting period (Fig. 4). At the early growth stages, CMD severity scores did not exceed 3 in the fields at Yangambi and Bambole, but it was 4 in 25% and 63% of the fields at Bamanga and Bakumu, respectively (Fig. 4A). The same occurred during the medium growth stages (4–5 MAP), where the severity scores ranged between 2 and 4 at Yangambi and Bambole but between 3 and 5 at Bamanga and Bakumu (Fig. 4B). Cassava fields planted during the 3rd month of the rainy season (May) were less infested by cassava mosaic virus than the fields planted before (April) or after (June/July) this period (Fig. 4C and D). At the early growth stages, CMD severity was at the lowest level (score 2) in 86% of the fields planted in May compared to 9–29% for the fields planted before or after this period (Fig. 4C). At the medium growth stages, similar contrasts in CMD infestation and severity were observed between the fields planted in May versus those planted earlier or later (Fig. 4D).

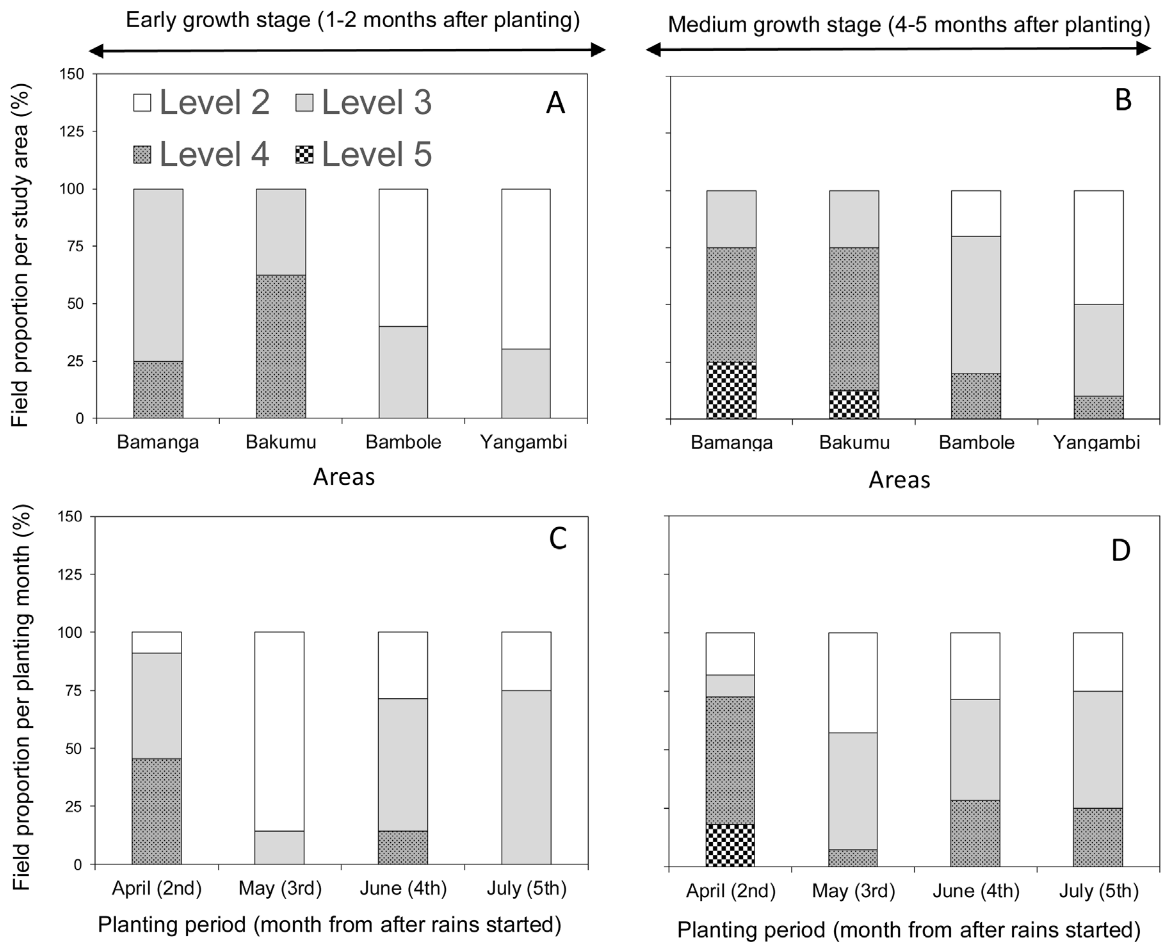

Fig. 4. Cassava mosaic severity within the areas (A and B) and the relationship between cassava mosaic severity and planting time (C and D) in Tshopo.

3.2.3. Attainable and actual cassava root yields

The attainable cassava root yield (Y_{att}) was 21 and 24 t ha^{-1} in Tshopo and Kongo Central respectively. The actual root yields (Y_{obs}) averaged 13 and 14 t ha^{-1} in Tshopo and Kongo Central respectively and varied widely among the agro-ecological areas within the province (Fig. 5). In Tshopo, the lowest Y_{obs} were obtained at Bambole where the maximum yield was 9 t ha^{-1} (Fig. 5A). At Bamanga, Bakumu and Yangambi all fields yielded at least 9 t ha^{-1}. Average actual yield at Yangambi (15 t ha^{-1}) was statistically similar to that at Bakumu (13 t ha^{-1}) but significantly higher than that at Bamanga (11 t ha^{-1}) and Bambole (7 t ha^{-1}). In Kongo Central, Y_{obs} varied from 7 to 15 t ha^{-1} at Lukula, 8 to 22 t ha^{-1} at Muanda and from 5 to 24 t ha^{-1} at Gimbi (Fig. 5B). The average actual yields at Gimbi (15 t ha^{-1}) and Muanda (14 t ha^{-1}) were statistically similar, but significantly higher than that at Lukula (11 t ha^{-1}). Cassava root yield varied widely within the field (Data not shown). Root yield measured in some squares was almost twice of that measured in other squares of the same field.

3.3. Relationship between cassava root productivity and the biotic/abiotic factors

3.3.1. Cultivation practices

Cassava root yield depended on the number of weed control conducted over the growing period and the time between consecutive weed controls (Fig. 6). Fields weeded only once produced significantly lower yields (average of 12 t ha^{-1}) than the fields weeded two or three times (16 t ha^{-1}) (Fig. 6A) in both provinces. On average, fields weeded thrice did not yield more than those weeded twice. Cassava root yield depended also on the number of weed controls conducted at a given period of the crop cycle. In Kongo Central, fields in which the first weed control was conducted before the end of the 1st MAP yielded significantly higher (15 t ha^{-1}) than those fields where the first weed control was conducted after this period (13 t ha^{-1}) (Fig. 6B). In Tshopo (Data not shown), fields where the first weed control was conducted during the 1st MAP yielded on average significantly higher than fields weeded for the first time during the 2nd MAP (15 vs. 13 t ha^{-1}). Similar contrasts among the cassava root yields were observed for two or three weed controls over the crop cycle. In Tshopo for instance, fields that were weeded thrice before the end of the 6th MAP, yielded on average higher than the fields weeded twice at this moment, although the average yields of the three-time weeded fields did not differ from that of the two-time weeded fields when the weeding period is not considered (Fig. 6A).There were satisfactory relationships between the cassava upper boundary yields ($Y_{up(i)}$) and the time that separated planting date from the first or last weed control (Fig. 6C and D). Both in Kongo Central and Tshopo, $Y_{up(i)}$ values were lower than the attainable yield (Y_{att}) in all fields where the first weed control had been conducted after the 2nd MAP (Fig. 6C). Yet, in some fields where the first weed control had been conducted before the 2nd MAP, $Y_{up(i)}$ values were equal or similar to Y_{att}. Because of the effect of other factors on cassava root yield, most fields yielded lower than the Y_{att} although they had been weeded before the 2nd MAP. $Y_{up(i)}$ values were lower than Y_{att} in all fields where weed control was stopped before the end of the 5th and 6th MAP in Kongo Central and in Tshopo respectively. Some fields weeded after these periods yielded however equal or similar to Y_{att} (Fig. 6D).

Cassava root yield depended on the planting period, mainly in Tshopo (Fig. 7A). The average yields in fields planted in May (16 t ha^{-1}) was significantly higher than the average yields obtained in fields planted in April (11 t ha^{-1}) and June/July (14 t ha^{-1}). In Kongo Central, yields did not differ among the fields planted at different times

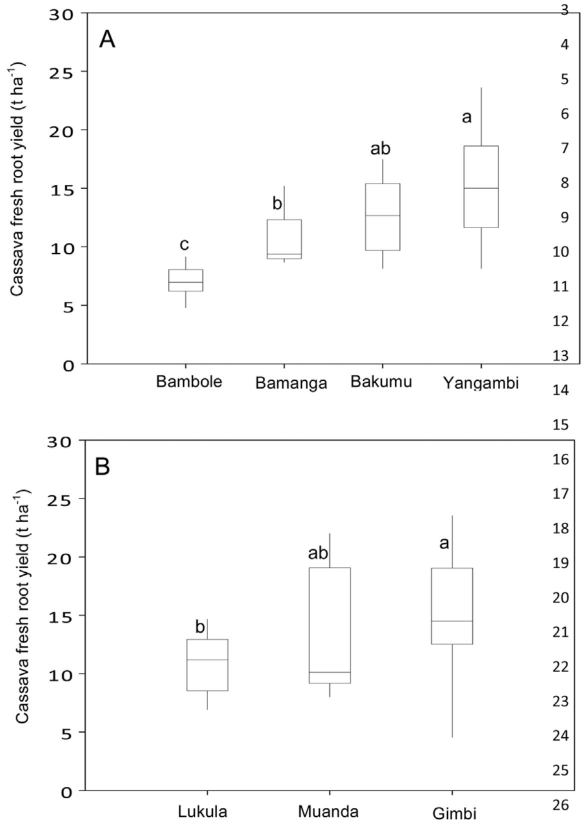

Fig. 5. Variability of cassava fresh root yield within the study areas in Tshopo (A) and Kongo Central (B). At a province level, average yields were significantly different for the boxplots marked with different letters ($p < 0.05$).

within a season. However, average cassava root yield in the fields planted during the 2nd rainy season-2015 at Gimbi (15 t ha^{-1}) was significantly higher than that in the fields planted during the 1st rainy season-2014 at Muanda and Lukula (13 t ha^{-1}).

The cassava root upper boundary yields within individual squares were related to the plant density (Fig. 7B). The highest cassava root yield per square was about 26 t ha^{-1} in Tshopo and Kongo Central, and was obtained in some fields with plant density higher than 5000 plants ha^{-1}. All squares with plant density less than 5000 plants ha^{-1} yielded lower than the maximal yield. Nonetheless, there were many other squares which yielded lower than the maximal yield, although they had plant density higher than 5000 plants ha^{-1} as other factors affected the yield.

Cassava root yields were affected by soil tillage and to a lesser extent by the presence of intercrops (Fig. 7C). In Tshopo, the tilled fields yielded on average significantly lower (8 t ha^{-1}) than the no-tilled fields (13 t ha^{-1}). In Kongo Central, average yields did not differ significantly when the soil was tilled or not. In a few sole cassava fields, average yields were slightly higher than those of the intercropped fields (14 vs. 13 t ha^{-1} in Tshopo and 16 vs. 14 t ha^{-1} in Kongo Central).

3.3.2. *Cassava mosaic virus infestation*

In Tshopo, the infestation of cassava mosaic virus during the early growth stages reduced cassava root yield (Fig. 8A). The fields that were infested by CMD with severity scores of 3 or 4 during the first two MAP yielded significantly lower (11–13 t ha^{-1}) than those where the severity score was 2 during this stage (15 t ha^{-1}). Conversely, CMD infestation during the medium growth stages in Tshopo and during the early and medium growth stages in Kongo Central did not have clear effect on root yields (Fig. 8A and B). In Tshopo, yields were not significantly different between severity levels at 4–5 MAP. The same was true in Kongo Central during all growth stages.

3.3.3. *Soil fertility*

Individual soil parameters were poorly correlated with the actual yields (Y_{obs}). Ratio of the sum of exchangeable Ca and Mg per exchangeable K ((Ca + Mg)/K) had the strongest correlation with Y_{obs} ($r = -0.20$), followed by exchangeable Al ($r = -0.13$) and C/N ratio ($r = 0.11$). Y_{obs} were correlated with soil available P, exchangeable K and pH with a coefficient of 0.09, 0.03 and 0.006, respectively. Correlation coefficient was 0.05 for soil C or total N and almost nil for the other soil parameters (silt, exchangeable Ca and Mg). The upper boundary yields ($Y_{up(i)}$) increased with increasing contents of C, available P, exchangeable K, C/N ratio and pH but decreased with increasing exchangeable Al and the (Ca + Mg)/K ratio (Fig. 9). Both in Kongo Central and Tshopo, the $Y_{up(i)}$ values were lower than the Y_{att} in all fields with a soil C content lower than about 14 g kg^{-1} (Fig. 9A). Y_{att} was reached in some fields with a soil C content higher than 14 g kg^{-1}. However, because of the effect of other factors (field management, pest and disease and other soil parameters) on cassava root yield, many fields yielded lower than the attainable yield although soil C content was higher than 14 g kg^{-1}. This result indicates that the critical soil C contents (i.e. soil C contents with which the attainable yield could not be achieved) were lower than 14 g kg^{-1} in Kongo Central and Tshopo. The critical values were < 4.6 for soil pH, < 1 g kg^{-1} for total soil N and < 5 mg kg^{-1} for available P and they did not differ between the provinces (Fig. 9B, C and D). The critical values of exchangeable K and C/N ratio were slightly lower in the fields in Tshopo than those in Kongo Central (0.08 vs. 0.14 cmol[+] kg^{-1} for exchangeable K and 12 vs. 14 for C/N ratio) (Fig. 9E and F). In Kongo Central, $Y_{up(i)}$ values were lower than Y_{att} in all fields with exchangeable Al higher than 1.8 cmol[+] kg^{-1}(Fig. 9G), indicating that the critical levels of exchangeable Al were the contents higher than 1.8 cmol[+] kg^{-1}. In Tshopo, the boundary line did not reveal critical levels for exchangeable Al, but regular decrease in the upper boundary yields with the increasing soil Al contents (Fig. 9G). In Tshopo, $Y_{up(i)}$ values were lower than Y_{att} in all fields with (Ca + Mg)/K ratio higher than 30, indicating critical levels ≥ 30. In Kongo central, the critical levels of (Ca + Mg)/K were the values ≥ 40 (Fig. 9H).

3.4. *Factors that limited cassava root yield*

Both suboptimal field management, low soil fertility and cassava mosaic virus infestation limited cassava root productivity. Cultivation practices, soil parameters and CMD infestation led to the lowest upper boundary yields ($Y_{up(i)1}$) in 47%, 41% and 12% of the fields in Tshopo and in 47%, 50% and 3% of those in Kongo Central, respectively. This result indicates that suboptimal field management and low soil fertility were the dominant yield-limiting factors with similar frequencies across the fields. They were more frequent than the CMD infestation. In Tshopo, among the cultivation practices that were the dominant yield-limiting factors, late or early cassava planting over the rainy seasons was the most widespread (21% of the fields) (Figs. 10 A and 7 A). It was followed by more than two months between the first weed control and cassava planting and soil tillage (9% of the fields for each practice) (Figs. 10 A, 6 C and 7 C). In that province, no single soil parameter was the dominant and widespread yield-limiting factor: 9% of the fields for low soil pH and less than 6% for each of other soil parameters (Figs. 10 A and 9 B). In Kongo Central, the cultivation practices that were the dominant and widespread yield-limiting factors are: *(i)* more than two months between the first weed control and cassava planting (16%), *(ii)* less than two weed controls over the growing period (13%) and (iii) no weeding after the 5th month of the cassava cycle (11%) (Figs. 10 B and 6 A–D). Among soil parameters, low C/N ratio was the only one that limited cassava root yield in a large proportion of the fields (21%) (Figs. 10 B and 9 F). In Kongo Central, suboptimal field management was the latent yield-limiting factor in 61% of the fields compared to 37% for low soil fertility. The reverse occurred in Tshopo, where suboptimal field management was the latent yield-limiting factor in 32% of the fields compared to 68% for low soil fertility.

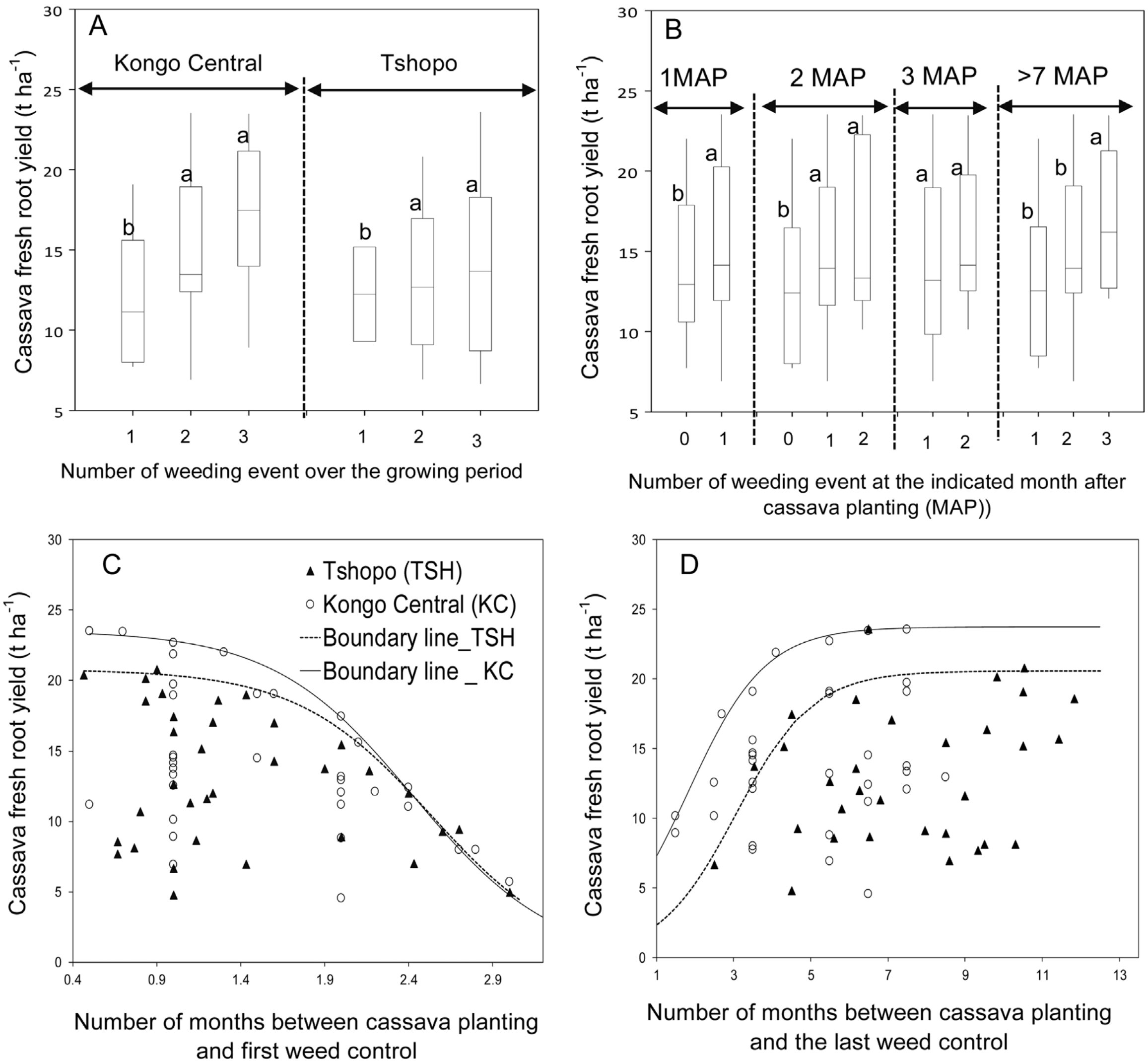

Fig. 6. Cassava root yield as related to: A) total number of weed controls conducted over the growing period, B) increasing number of weed control at a given period of cassava cycle (case of Kongo Central), C) the time between cassava planting and the first weed control, and D) the time between cassava planting and the last weed control. Per province (Fig. A) or period (Fig. B), average cassava root yields were significantly different for the boxplots marked with different letters ($p < 0.05$). No mention when there was no significant difference. Boundary lines (Fig. C and D) were obtained by fitting the logistic model against the maximum yields.

Contrary to suboptimal field management and low soil fertility, CMD infestation limited cassava root yield only in some areas within a province (Table 3). In Kongo Central, CMD was the yield-limiting factor only at Muanda, while suboptimal field management and low soil fertility were the yield-limiting factors in all areas. In Tshopo, CMD was the yield-limiting factor at Bakumu and to a lesser extent at Yangambi but suboptimal field management was the yield-limiting factor in all areas and low soil fertility in three of the four areas. The type of the cultivation practices and soil parameters that limited cassava root yield differed also among and within the provinces (Table 3). In Kongo Central, the ratios of C/N and (Ca + Mg)/K were respectively the dominant limiting factor in 42% and 8% of the fields at Lukula but in none of those at Muanda. Soil C or N content was the dominant limiting factor in 14% of the fields at Muanda but in none of those at Lukula and Gimbi. Soil acidity (low pH or high exchangeable Al) was the dominant yield-limiting factor at Gimbi only. Similar contrasts were observed within the study areas in Tshopo both for the dominant and latent limiting factors (Table 3).

3.5. Yield gaps and the related causes

The explained yield gaps differed among the types of the limiting factors. In the fields where cultivation practices were the dominant liming factors in Kongo Central, the maximum explained yield gap was 9 t ha^{-1} (Fig. 10D). The explained yield gap was higher than 9 t ha^{-1} in about 13% of the fields where soil parameters were the dominant liming factors. This indicates that, in Kongo Central, the yield losses caused by low soil fertility in some fields was higher than that caused by suboptimal field management. Yield losses averaged 6.2 and 5.5 t ha^{-1} in the fields where low soil fertility and suboptimal field management were the dominant limiting factors, respectively (almost nil in few fields where CMD was the dominant limiting factor). In Tshopo, yield losses averaged 6.5, 6.1 and 4.5 t ha^{-1} in the fields where suboptimal field management, CMD infestation and low soil fertility were the dominant limiting factors, respectively (Fig. 10C). Irrespective of the limiting factor type, the gaps between the attainable yield (Y_{att}) and the lowest upper boundary yields ($Y_{up(i)1}$), were up to 48% and 64% of Y_{att} (averages of 22% and 25%) in Kongo Central and Tshopo respectively (Fig. 10E and F). The gaps between Y_{att} and $Y_{up(i)2}$ (i.e. the obtained lowest upper boundary yield without considering in the iteration the dominant limiting factors), were up to 29% of the Y_{att} with an average of 14% in Kongo Central and up to 35% of the Y_{att} with an average of 16% in Tshopo. The average gaps between Y_{att} and $Y_{up(i)2}$ were about 64% of the average gaps between Y_{att} and $Y_{up(i)1}$. This

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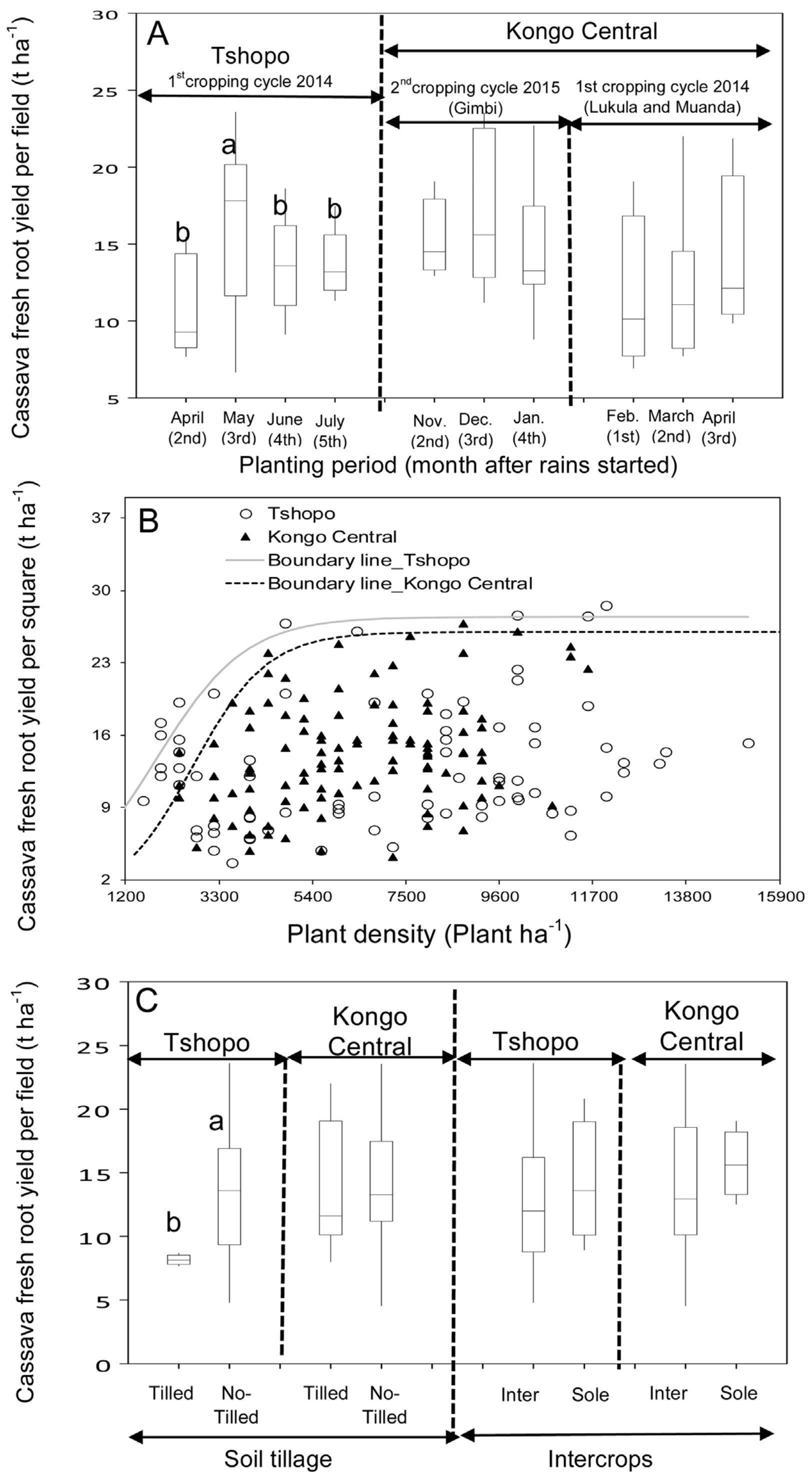

Fig. 7. Cassava root yield as related to: A) planting period, B) plant density and C) soil tillage or intercrops. Per cropping cycle (Fig. A) or cropping practice (Fig. C) averages yields were significantly different for the box-plots marked with different letters ($p < 0.05$); no mention when there was no significant difference. In figure B, planting density of individual square was plotted against the corresponding yield and boundary curves were obtained by fitting the logistic model to the maximum yields.

indicates that, because of the factors that are currently latent, the yield loss would remain at about two third of the current level when only the dominant limiting factor was overcome. Average gaps between Y_{att} and $Y_{up(i)3}$ was about 50% of those between Y_{att} and $Y_{up(i)1}$, indicating that the yield loss would remain at about half of the current level when the dominant and the first latent limiting factors were overcome. Unexplained yield gaps were higher in Kongo Central than in Tshopo (Fig. 10G and H). The unexplained yield gaps averaged 4.3 and 2.8 t ha^{-1} in Kongo central and Tshopo, respectively, and were mainly higher in the fields with low actual yields.

4. Discussion

Our results indicate that suboptimal field management, low soil fertility and CMD infestation constrained cassava root productivity in the study areas (Fig. 10). Contrary to suboptimal field management and low soil fertility that were the dominant yield-limiting factors in almost all the study areas, CMD was the yield-limiting factor only at Bakumu (Tshopo) and Muanda (Kongo Central). During the past years, suboptimal field management and pest and disease infestation were reported as the widespread and severe cassava productivity constraints but only pest and diseases have received attention in the intervention

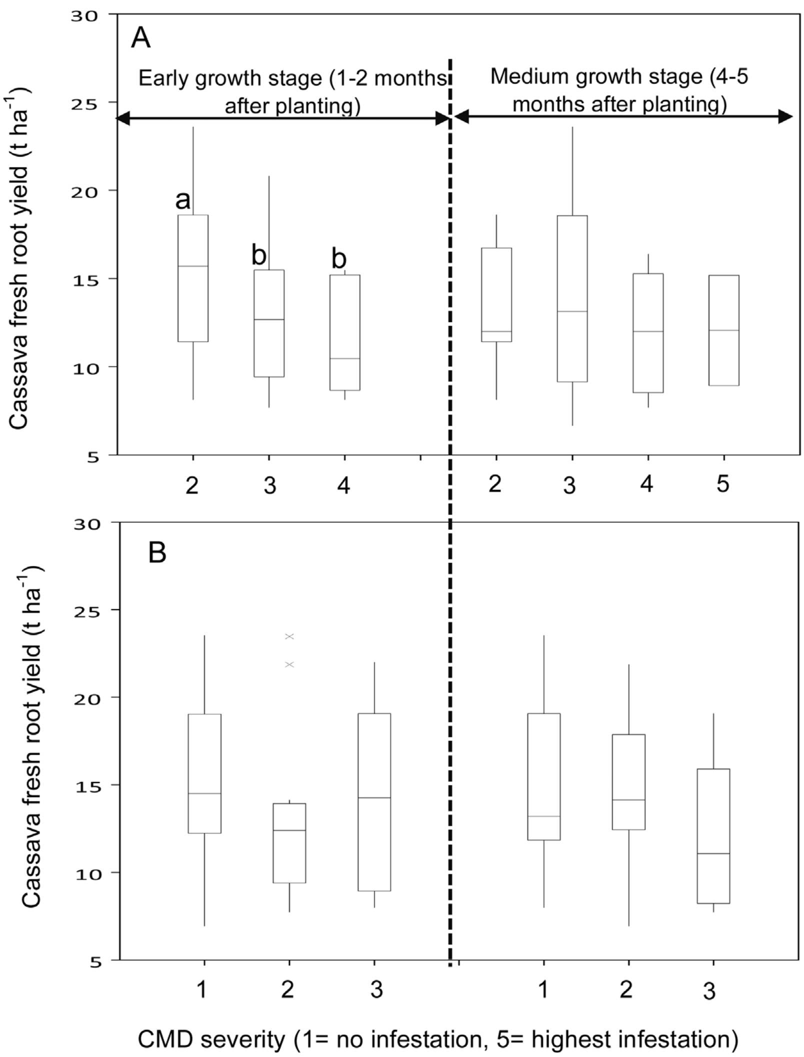

Fig. 8. Relationship between cassava root yield and the severity of cassava mosaic disease (CMD) in Tshopo (A) and Kongo Central (B). Per province and growth stage, averages yields were significantly different for the boxplots marked with different letters ($p < 0.05$); no mention when there was no significant difference.

programs (Briant and Johns, 1940; Fargette and Fauquet, 1988; Chapola, 1981). Suboptimal field management and low soil fertility received little attention since cassava is perceived to be more than other crops tolerant of low soil fertility and erratic rainfall conditions (De Tafur et al., 1997; El-Sharkawy, 2006). The present study indicated that, with the cassava varieties currently growing by farmers in Tshopo and Kongo Central, pests and diseases played a sparse role in the yield losses. The frequent and severe contributors to the yield losses were low soil fertility and suboptimal field management. Fermont et al. (2009) reported similar results in Ugandan and Kenyan farmers' fields. They observed that low soil fertility and weed management constrained more severely the cassava yields than pests and diseases. The cassava root yield losses simulated in the present study were similar with those measured in farmer's fields in DR Congo and elsewhere in Africa (Thresh and Cooter, 2005). Concerning the individual factors, results indicate that late or early planting, and late and sparse field weeding were frequently the yield-limiting factors. This suggests that large-scale programs in terms of cassava planting at the right time and proper weed control may improve cassava productivity in many fields. Conversely, regulating the soil pH by liming may have sparse efficacy since low soil pH constrained cassava root yield in few fields only (Vanlauwe et al., 2010; Vanlauwe et al., 2015). Variable cassava root yield responses to mineral fertilizer have been observed in Africa, China, Indonesia, Philippines and Vietnam (Ogbe et al., 1993; Howeler, 1991; Lema et al., 2004). Similarly, a large-scale recommendation of the blanket fertilizers would have sparse efficacy because the yield-limiting nutrients were field specific. Ezui et al. (2016) have shown an increased nutrient use efficacy and higher cassava yields emanating from balanced nutrition. In the case of cotton in West Africa, the application of blanket fertilizers led to variable yield increases across farmers' fields and were inefficient over time (Kintché et al., 2010; Kintché et al., 2015b). The fact that the yield-limiting factors differed between and within the provinces (Table 4) reinforces the sparse efficacy that may result from large-scale programs. To mitigate cassava productivity constraints, mainly those related to soil, site-specific programs are needed although the approach may be expensive.

Late or early planting was one of the dominant and widespread constraints of cassava root productivity in Tshopo, and this may partially be explained by the relationship observed between planting time and CMD infestation. In Tshopo, cassava fields planted at the onset of the rainy season were more infested by CMD than the fields planted during the third month of the rainy season (Fig. 4C and D). Okogbenin et al. (1998) and Adipala et al. (1998) reported that early planted cassava fields were highly infested by CMD because of the vector abundance (whitefly) at the beginning of the rainy season. The severe CMD infestation observed in the cassava fields planted late (June and July) can be explained by the whitefly moving from the older fields to younger fields due to the whitefly preference for the youngest plants (Leite et al., 2003; Sseruwagi et al., 2003). Although the yield limitation by CMD in Tshopo could be explained by whitefly presence, the common use of contaminated local cassava varieties most likely led to increase CMD incidence. On the other hand, our results indicated that

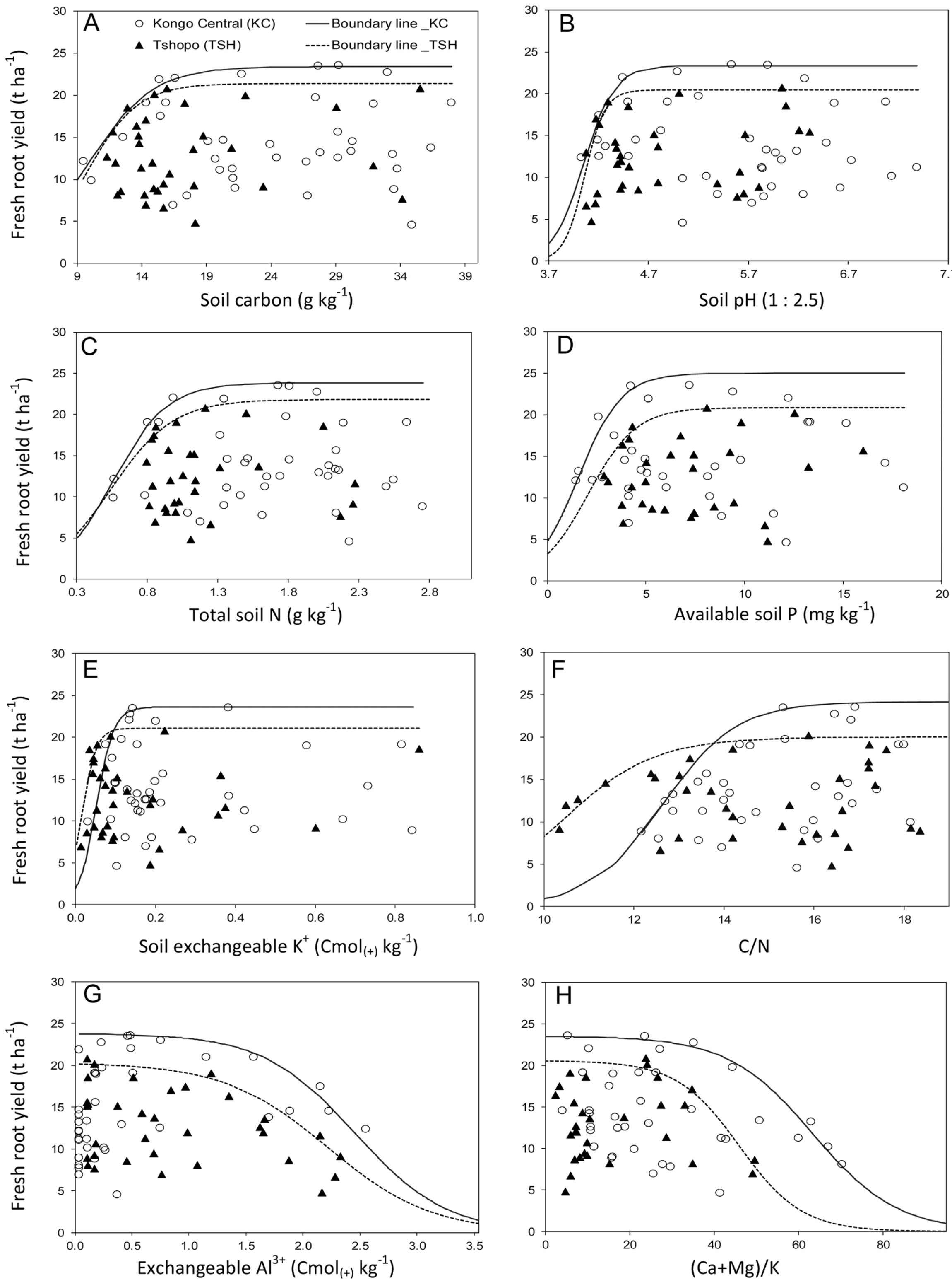

Fig. 9. Relationship between maximum cassava root yields and soil organic carbon (A), pH (B), total N (C), available P (D), exchangeable K^+ (E), C/N ratio (F), exchangeable Al^{3+} (G) and ratio of (Ca + Mg)/K (H). Boundary lines were obtained by fitting the logistic model against the maximum yields.

only CMD infestation during the early growth stages reduced the yield (Fig. 7A). This result is in line with that of Briant and Johns (1940) and Fauquet and Fargette (1990) who reported that early CMD symptoms were infestation from planting material and resulted in more yield losses than the late symptoms caused by whiteflies.

As in the present study, poor weed control is reported as one of the most widespread cassava yield constraints (e.g., Albuquerque et al., 2014; Weerarathne et al., 2016). Our results contrasted however some previous results on the optimal number of weed control. In Kenyan and Ugandan farmer fields, Fermont et al. (2009) reported increasing cassava root yields with weeding events up to 6, while we observed that three weed controls did not increase cassava root productivity compared to two weed controls. Even if an increasing number of weed control can sustain cassava root productivity, two or three weed

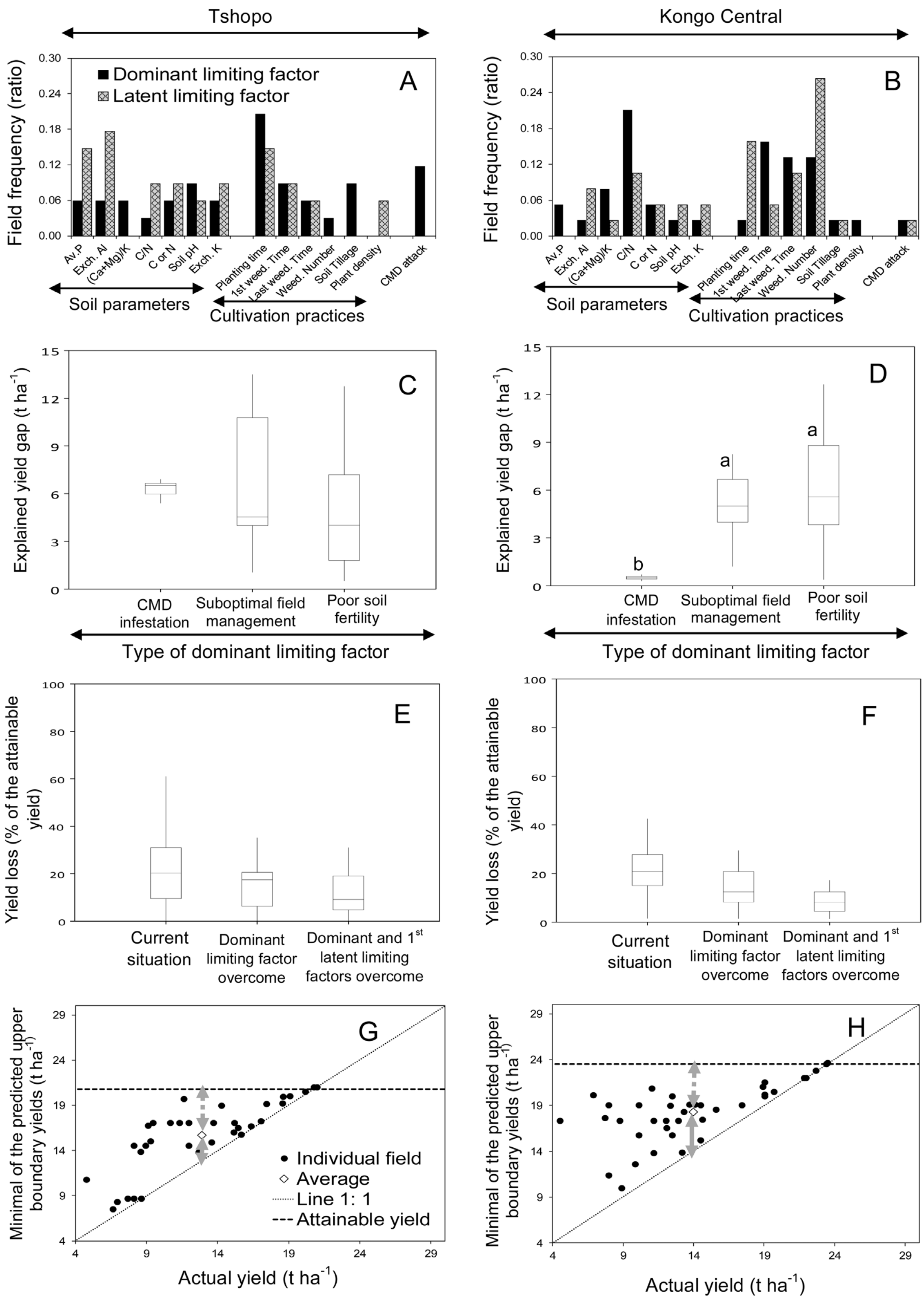

Fig. 10. Distribution across the areas of individual dominant and first latent limiting factors (A and B), magnitude of the explained yield gap as related to the type of the limiting factors (C and D), scenario analysis of the yield losses (E and F) and a comparison of the actual cassava root yield with the predicted minimal upper boundary yield (G and H). In figures G and H, dashed vertical arrows correspond to the average of the explained yield gaps while no dashed arrows correspond to average of unexplained yield gaps.

controls would be sufficient when properly conducted at the right periods. Results indicate that all fields where the first weed control was conducted after the end of the 2nd MAP or where weed control was stopped before the 5–6th MAP, yielded lower than the attainable yield (Fig. 6C and D). This suggests that, when the field is dominated by weeds that grow slowly, one weed control before the end of the 2nd MAP and another one after the 5–6th MAP may be sufficient to sustain the cassava productivity. For the fields dominated by the weeds that

Table 3
Frequency (%) of cassava yield limiting factors across the fields monitored in different agro-ecological area in Tshopo (A) and Kongo Central (B).

Limiting factor	Tshopo (A)					Kongo Central (B)	
	Bamanga	Bakumu	Bambole	Yangambi	Lukula	Muanda	Gimbi
A) Dominant limiting factor [1st level of severity]							
Low pH	8	0	0	17	0	0	5
Low exchangeable K	0	0	0	17	0	0	5
Low available P	0	14	20	0	8	0	5
Low C or N content	5	0	0	11	0	14	0
High exchangeable Al	0	0	20	0	0	0	5
High (Ca + Mg)/K	5	0	20	6	8	0	11
Low C/N	2	0	0	6	42	0	5
Total Soil	***20***	***14***	***60***	***56***	***58***	***14***	***37***
Soil tillage	25	0	20	6	0	0	0
Late or early planting	15	43	0	22	8	14	11
< 2 weed control	25	0	0	0	8	14	16
> 2 months between planting and 1st weeding	15	0	0	11	17	0	26
Weeding stopped before 5–6 MAP	0	0	20	0	0	43	11
Low plant density	0	0	0	0	8	0	0
Total field management	***80***	***43***	***40***	***39***	***42***	***71***	***63***
CMD infestatin	***0***	***43***	***0***	***6***	***0***	***14***	***0***
B) Latent limiting factor [2nd level of severity]							
Low pH	0	0	20	0	0	0	11
Low exchangeable K	0	0	20	6	0	14	5
Low available P	0	14	0	22	0	0	0
Low C or N content	0	14	0	6	0	43	0
High exchangeable Al	50	14	20	17	0	0	11
High (Ca + Mg)/K	0	0	0	0	8	14	5
Low C/N	0	0	0	11	17	0	26
Total Soil	***50***	***43***	***60***	***61***	***25***	***71***	***58***
Soil tillage	0	0	0	6	0	0	5
Late or early planting	25	29	40	6	17	0	11
< 2 weed control	0	0	0	0	25	14	21
> 2 months between planting and 1st weeding	0	14	0	11	8	0	0
Weeding stopped before 5–6 MAP	25	0	0	11	17	14	5
Low plant density	0	14	0	6	0	0	0
Total field management	***50***	***57***	***40***	***39***	***67***	***29***	***42***
CMD infestation	***0***	***0***	***0***	***0***	***8***	***0***	***0***

grow rapidly or when rain excess facilitates weed development during the early cassava ages, one additional weed control between the 2nd and 5th MAP may be required. Field weeding after the 5th or 6th MAP is necessary to sustain cassava productivity in Tshopo and Kongo Central because, irrespective of the planting season, the medium plant stages coincide with another rainy season (Fig. 1D). Low cassava planting density is often considered as one of the causes of low root yield observed in farmer fields. The present study does not support that assertion. Plant density was barely the yield constraint and results indicated that some fields with plant density lower than the research recommended density (10,000 plants ha^{-1}) achieved the attainable yield (Fig. 7B). The attainable yield was not, at all, been achieved when plant density was lower than half of the research-recommended density. Eke-Okoro et al. (2012) reported higher cassava root yields when planted with space of 1 m × 1.5 m (i.e., 6666 plants ha^{-1}) than when planted with the research-recommended density (1 m × 1 m). The effect of soil tillage on cassava root yield differed among the provinces (Fig. 7C). In Kongo Central, cassava root yields in the fields where the soil was tilled were similar to those in the fields where the soil was not tilled. In Tshopo, fields where the soil was tilled produced less cassava root than the fields where the soil was not tilled. Ohiri and Ezumah (1990), Hulugalle et al. (1990), Howeler et al. (1993) and Aiyelari et al. (2002) reported no effect of tillage when growing cassava in sandy loam soils, but Lal and Dinkins (1979), and Ezumah (1983) reported in DR Congo Oxisol low cassava root yields in the tilled soils compared with untilled soils. Our result contrasted however that of Ezumah and Okigbo (1980) who observed that tilled soils produced more cassava root than untilled soils. Tillage effect on cassava root yield depends on soil type, site history and climate conditions during land preparation and cassava planting (Howeler et al., 1993). Moreover, Ofori (1973) and Okigbo (1979) reported that ploughing increased cassava root yield compared to superficial hoeing. This suggests that, since farmer fields we monitored were manually tilled, cassava root development may occur in soil layers deeper than those were reached by hoes, and then led to limited effect on cassava root yield.

The choice of the study areas within the province was guided by the presence of research station, as farmers living nearby may practice (by imitation) the best cultivation technologies. This consideration reflected in the practices conducted by farmers around the Gimbi research station. Compared to Muanda and Lukula, large proportion of farmers at Gimbi cultivated or allocated large areas to the improved varieties. Most of them conducted at least two weed controls and some farmers who applied unknown fertilizer amounts were in that area (Table 2). The presence of research station in Yangambi reflected more on good weed control, rather than on the utilization of the improved varieties. Compared to Bamanga and Bakumu, more farmers in Yangambi weeded 3-time their monitored cassava fields and conducted the first weed control before the end of the 2nd MAP (Table 2). However, most farmers in Yangambi cultivated local varieties and allocated small areas to the improved varieties. Both in Kongo Central and Tshopo, the highest cassava root yields were obtained around the research stations but they remained lower than the yields often reported in research-managed systems, as none of the farmers conducted properly all the cultivation practices that constrained the productivity. The observed cassava root yields in the present study were however higher than the FAO estimates (FAOStat, 2015).

The current study indicated that the attainable yields were obtained in some fields with high soil C/N ratio (Fig. 9F). Fields with high soil C/N were some of the fields recently cleared of fallows or woodlands, and then should be characterized by higher microbial activity because of the no-mineralised organic matter that entered the soil during fallowing period (Kurzatkowski et al., 2004; Six et al., 2004). Although it was not clearly demonstrated in the case of cassava, soils with good microbial activity seem to sustain the productivity of tuber crops. This is well known in the case of yam and explains the empiric position of yam crop at the beginning of crop rotations. Yam is cropped after about 20-year fallowing and one of the elements often used to identify lands suitable for yam productivity is worm excrements (i.e. soils with intensive microbial activity). Studies from areas where land availability was not a production constraint, reported that cassava was preferentially cultivated after fallow or woodland clearing (Silvestre and Arraudeau, 1983; Fresco, 1986), and this is in line with the hypothesis on positive effects of soil microbial activity on cassava root productivity. However, the place of cassava in the rotation varies among areas and changed over time because of the land pressure due to growing population and the general perception on cassava ability to tolerate more than other crops poor soils (Hillocks, 2002; Saïdou et al., 2004; Adjei-Nsiah et al., 2007; Fermont et al., 2008). Soils with high C/N ratios are considered as less sustainable for cropping because of N immobilisation. In the present study, this phenomenon seems having a neglected effect and this is in line with the fact that cassava crop can tolerate more than many other crops N deficiency (Kaweewong et al., 2013). Therefore, soil N content was barely one of the yield constraints in the monitored fields.

Soil exchangeable K constrained cassava root yield, not only because of low contents as often reported (Howeler et al., 1987; Howeler et al., 1991; Carsky and Toukourou, 2005), but also because of imbalanced K versus exchangeable Ca and Mg (Fig. 9 and Table 3). High (Ca + Mg)/K ratio was the yield-limiting factor in 20% and 11% of the fields in Bambole and Gimbi, respectively (Table 3). This suggests that, since cassava removes from the soil more K than Ca and Mg (Putthacharoen et al., 1998), continuous cassava cropping would increase soil (Ca + Mg)/K ratio and then constrain over time the productivity. To sustain long-term cassava root productivity, soil (Ca + Mg)/K ratio should be kept as low as possible and K inputs to the soil is one the realistic alternatives. The critical values of soil exchangeable K and available P observed in the present study were similar with those Howeler (2002) and Fermont et al. (2009) reported. However, the observed critical values of soil pH (< 4.6) and organic carbon ($< 14\ g\ kg^{-1}$) were slightly different from that Fermont et al. (2009) reported (< 5.2 and $< 9\ g\ kg^{-1}$ for soil pH and C, respectively).

The cassava root yield losses were high and scenario analysis indicated that the yield losses would remain high (about two third of the current levels) when only the dominant limiting factor was overcome (Fig. 10E and F). This result suggests that, because of multiple factors that are currently latent, the program aiming to solve only the dominant limiting factor would fail. Even by eliminating the dominant and first limiting factors, yield losses would remain at about half of the current levels and this is in line with low cassava yields usually observed in farmer fields even with improved genotypes. Success in reducing cassava root yield losses would require a combination of the best practices (integrated programs) and they must be site specific. Fermont et al. (2009) reported increasing cassava root yield with increasing combination of the best agronomy practices, but the results varied strongly within sites as the tested management packages were not site specific.

The unexplained yield gaps were higher in Kongo Central than in Tshopo (Fig. 10G and H), indicating that the boundary line analysis performed less in Kongo Central as compared to Tshopo. Wairegi et al. (2010) and Wang et al. (2015) reported high unexplained yield gaps in the case of banana and coffee crops. This result suggests that the study may have excluded some severe cassava yield constraints in Kongo Central. El-Sharkawy (2004) reported that, to achieve maximum yields, cassava requires high solar radiation, high mean day temperature, good rainfall distribution during crop establishment and possibly a dry period before harvesting. Moreover, the fact that a boundary line does not consider the interaction between factors is often pointed out as the artefact of the model (Shatar and McBratney, 2004)

5. Conclusion

The present study aimed to increase understanding of the factors that contribute to low cassava yields in farmers' fields to guide the formulation of cassava intensification programs. A contribution of soil fertility, pest and disease infestation and cultivation practices to cassava yield gaps was analysed in farmer-managed fields in two provinces (Kongo Central and Tshopo) of the Democratic Republic of Congo. We found that, with the cassava varieties currently growing by farmers in the study areas, pests and diseases played a sparse role in the yield losses. The frequent and severe contributors to the yield losses were low soil fertility (pH, Al, nutrient contents and ratios) and suboptimal field management (late/early planting, late/sparse weeding and soil tillage). Cassava root yield constraints varied between fields, suggesting that large-scale programs (as did in the past) mainly in terms of lime application or recommendation of the blanket fertilisers would result in sparse efficacy. Compared to the observed maximal yield, the yield losses were high and scenario analysis revealed that, because of the multiple factors that are currently latent, the yield losses would remain at about two third of the current levels when only the dominant constraint was overcome. We concluded that integrated and site-specific programs are needed to close the cassava yield gap and maximize the efficacy of cassava intensification programs.

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