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Original article

The performance of a wide range of plantain cultivars at three contrasting altitude sites in North Kivu, Eastern Democratic Republic of Congo

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Summary

Plantains (*Musa* spp., plantain subgroup in the AAB genome group), an important staple food and income crop for millions of people in Africa and Latin America, grow best at lower elevations (<1,200 m a.s.l.) characterized by high temperatures and humid conditions. In Africa, this includes the Congo basin that has a high diversity of plantains. Plantains are high in pro-vitamin A carotenoid content, and identifying cultivars suitable for mid- to high altitude sites could potentially increase their contribution to reducing the problem of vitamin A deficiency. This study evaluated 52 plantain cultivars sourced from eastern DR Congo (representing the majority of plantain diversity in Eastern DR Congo and less than 50% of the known diversity across the whole of DR Congo) for their interaction and adaptability to different altitudes/temperatures, with the aim of identifying cultivars suited to high/cooler altitudes. The performance of plantains declined with increasing altitude. Highest yields (18–50 tonnes ha^{-1} yr^{-1}) occurred at 1,066 m compared with 11–35 at the mid-altitude (1,815 m), and only 0.6–3.5 tonnes ha^{-1} yr^{-1} at the high altitude (2,172 m) site. Most (65%) of the 52 plantain cultivars performed well at the mid-altitude site. Thus, and in agreement with previous reports on 5 plantains, a broad range of plantains sourced from Eastern DR Congo could be promoted at mid-altitude areas that have traditionally been known to be conducive for only the East African highland bananas (*Musa* AAA-EAH genome group). Studies to evaluate, at mid- to high elevation, a larger portion of the plantain diversity of the whole of DR Congo and even West Africa are warranted.

Keywords
Musa, plant growth, temperature, pro-vitamin A carotenoid, yield

Significance of this study

What is already known on this subject?
- Plantain (*Musa* AAB genome group) cultivars grow best at low elevation sites (<1,200 m a.s.l.) and are known to be rich in pro-vitamin A carotenoid.

What are the new findings?
- Most of the assessed plantain cultivars also performed well at the mid-elevation trial site (1,815 m), while plantain bunches were mostly deformed and inedible at the high elevation site (2,172 m).

What is the expected impact on horticulture?
- Plantain cultivars could be widely promoted at mid-elevation sites to combat vitamin A deficiency. Best performing cultivars at mid- and high elevations offer a good opportunity for breeding towards cold-tolerance.

Introduction

Plantains (*Musa* spp., plantain subgroup in the AAB genome group) are an important staple food and income crop for millions of people in Africa and Latin America (FAOStat, 2016). Plantain fruits are reported to contain high levels of pro-vitamin A carotenoids and could potentially be used for alleviating vitamin A deficiency, especially among children below 5 years and mothers of childbearing age (Englberger *et al.*, 2003; Honfo *et al.*, 2007). Plantains have been reported to grow best at lower elevation sites (<1,200 m) which are characterised by high temperatures and humid conditions (Sebasigari, 1985; Dheda *et al.*, 2011; Ocimati *et al.*, 2013a, b). For example, in Africa this has limited their production to the low-lying regions of West Africa and the Congo basin in central Africa which is also a zone of secondary diversification for this *Musa* group. DR Congo constitutes an exceptional area where the East African highland bananas (*Musa* AAA-EAH genome group) meet the plantains (Karamura *et al.*, 2013; Sivirihauma *et al.*, 2017), with over one hundred plantain cultivars recorded in the Congo basin (Dheda *et al.*, 2011). Production of some plantain cultivars (*e.g.*, 'Musilongo', 'Kotina', and 'Kasilongo') at higher elevation sites along the Albertine rift valley in Eastern DR Congo (at about 1,700 m) has been reported (Ndungo, Vigheri, 2011, pers. commun.; Ocimati *et al.*, 2013a, b; Sivirihauma *et al.*, 2017). In Colombia, plantain cultivation has been reported from sea level to 2,000 m a.s.l. within a temperature range of 17–35°C (Herrera, 1999).

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An extreme case has been the cultivation of 'Vuhembe' in farmers' fields at Ndihira, located at 2,172 m (Charles Sivirihauma, 2014, pers. commun.).

Higher elevation sites (1,000–2,000 m a.s.l.) are more favourable for the East African highland banana types (*Musa* AAA-EAH genome group) (Gold *et al*., 2002; Eledu *et al*., 2004).

Identifying a wider range of plantain cultivars suitable for high altitude sites could potentially increase their contribution to nutrition, food and income security in banana dependent higher altitude regions. Altitude has a profound effect on temperature of a location. Temperature is one of the primary factors that drives banana and plantain development (Fortescue *et al*., 2011). Initial studies (Sikyolo *et al*., 2013; Turner *et al*., 2016; Sivirihauma *et al*., 2016) using a few plantain cultivars ('Vuhembe', 'Vuhindi', 'Kotina', 'Musilongo', and 'Nguma') assessed the effect of altitude on plantain growth, development and yield in North Kivu province of East DR Congo. Sikyolo *et al*. (2013) and Sivirihauma *et al*. (2016) reported significant altitude effects, with high altitude and corresponding lower temperatures increasing suckering per parent plant and crop cycle duration, whereas number of functional leaves, bunch weights and yield were reduced. The plantain 'Vuhembe' had mean bunch weights of 11.2 kg at the high elevation experimental site of 2,172 m (Sikyolo *et al*., 2013) in line with low (4.8 to 6.3 t ha^{-1} yr^{-1}) plantain yields in farmer's fields across the plantain belt in DR Congo (Anonymous, 2016). Turner *et al*. (2016) reported a longer phyllochron and a higher proportion of lateral buds that grew into suckers at the high altitude sites characterized by cooler temperatures whereas the low altitude sites with warm conditions had shorter phyllochrons, and fewer lateral buds that grew into suckers. Turner *et al*. (2016) also reported a cool temperature response in the juvenile phase in four of the five plantain cultivars evaluated. In-depth knowledge on site specific and altitude (mid and possibly high) effects on plantain growth, development and yield is currently lacking for a wider range of plantain cultivars, and this information would be valuable to agronomists, breeders and farmers. We speculated that in a larger plantain germplasm pool there could be cultivars that can withstand cool temperatures and perform better contrary to observations made for five plantain cultivars assessed at 2,172 m by Sikyolo *et al*. (2013), Sivirihauma *et al*. (2016), and Turner *et al*. (2016). Such cultivar(s) would give bunch sizes that are easily marketable and be a potential starting material for breeding towards cold tolerance and improving nutrition and food security at similar high altitudes. The specific objective of this study was to evaluate a wide range of plantain cultivars for their interaction and adaptability to different altitudes/temperatures, with a special focus on the identification of plantain cultivars suited to cooler altitudes.

Materials and methods

This study was conducted in the North Kivu province of Eastern DR Congo. North Kivu consists of different agro-ecologies characterised by a wide range of altitudes and environmental conditions spread over a small location making it ideal for the study. The sites are also located within 1° latitude of the equator, thus limiting the variation in photoperiod.

The effect of altitude on plantain (AAB genome group) growth and yield was determined over two consecutive growth cycles for a total of 52 local plantain cultivars. The experiments were established in September 2010 at three sites of contrasting altitude in North Kivu, Eastern Democratic Republic of Congo (DR Congo), namely, at Mavivi (1,066 m, 00.56902°N, 29.4789°E), the research fields of the Catholic University of Graben (UCG) at Butembo (1,815 m, 00.11786°N, 29.2587°E) and at the INERA-Ndihira research farm (2,172 m, 00.24963°S, 29.2049°E). Soil characteristics and weather data for these locations are presented in Table 1. Soil characteristics were determined through analysis

Table 1. The biophysical characteristics of the three sites. Temperature and rainfall cover the period 2009–2011. Records for temperature were obtained from the ENRA (in Beni), INERA (Institut National pour l'Étude et la Recherche Agronomique, Ndihira) and Rughenda Airport (Butembo) meteorological weather stations. Rainfall data for Butembo and Mavivi were computed from radar images, while rainfall data for Ndihira was obtained from the INERA meteorological station at Ndihira.

Variable (unit)	Location/altitude (m)		
	Mavivi	Butembo	Ndihira
Altitude (m)	1,066	1,815	2,172
Annual temperature (°C)			
Mean minimum (monthly minimum range)	19.4 (18.6–19.9)	13.1 (12.4–14.4)	11.0 (10.4–12.3)
Mean maximum (monthly maximum range)	27.8 (25.4–29.9)	24.8 (23.6–26.2)	21.1 (19.9–21.8)
Average (monthly average range)	23.5 (21.1–24.6)	19.0 (18.2–19.7)	16.1 (15.5–16.9)
Annual rainfall (mm)	1,411	1,038	1,338
Soil characteristics (0–20 cm layer)			
pH	6.7	5.7	5.2
Organic matter (%)	5.0	5.1	5.1
N (%)	0.23	0.26	0.25
P (mg kg^{-1})	2.2	10.6	36.1
Ca (cmol(+) kg $soil^{-1}$)	6.36	6.20	6.13
Mg (cmol(+) kg $soil^{-1}$)	1.85	1.43	1.06
K (cmol(+) kg $soil^{-1}$)	0.83	1.14	0.90
Sand (%)	64.4	32.4	46.4
Clay (%)	16.3	42.3	30.3
Silt (%)	19.3	25.3	23.3
Texture class	Sandy loam	Sandy clay	Sandy clay loam

of composite/bulk soil samples collected at each trial site (0–20 cm soil layer) in February 2009. Soil analysis was carried out at the National Agricultural Research Organization (NARO), Kawanda Soils Laboratory, Uganda.

Plantain germplasm collections had previously been established at UCG-Butembo and Mavivi in the period 2006 till 2010 from which planting material for the three field sites was obtained. Fifty-two plantain cultivars were established at both the UCG-Butembo and Mavivi sites, while a subset of 21 cultivars was established at the INERA-Ndihira site. A total of five plants per cultivar were planted in lines at each field site, each plant acting as a replicate. At each experimen-

TABLE 2. Cultivar name and type, Province of origin and the *ex-situ* germplasm collection from where planting material was obtained.

Cultivar name	Type	Province of origin	*Ex-situ* germplasm collection
Adili I	French	Ituri	Mavivi
Adili II	French	Ituri	Mavivi
Agbindolo	French	Ituri	Butembo
Akange	French	Ituri	Butembo
Akobanzi	French	Ituri	Butembo
Akola nembo	False Horn	Ituri	Butembo and Mavivi
Akongo	False Horn	Ituri	Butembo
Akoto nembo	False Horn	Ituri	Butembo and Mavivi
Akoto nguluwe	False Horn	Ituri	Butembo and Mavivi
Alongo	French	Ituri	Butembo
Ayaya	French	Ituri	Butembo and Mavivi
Bubu	French	Ituri	Mavivi
Buembe	French	North Kivu	Mavivi
Bukubekisi	French	Ituri	Mavivi
Chui	French	Ituri	Butembo
Kasilongo	French	North Kivu	Butembo
Kitotina III ngulo	False Horn	North Kivu	Butembo
Kola	French	Ituri	Butembo
Kothina I	False Horn	North Kivu	Butembo
Kotina IV	False Horn	North Kivu	Butembo
Kototina II ngulo	False Horn	North Kivu	Butembo
Mabilanga	False Horn	Ituri	Mavivi
Makaka	True Horn	Ituri	Mavivi
Makpelekese	False Horn	Ituri	Mavivi
Mamba	False Horn	Ituri	Mavivi
Mangondi	False Horn	Ituri	Mavivi
Manzenzele	French	Ituri	Mavivi
Mayayi	False Horn	Ituri	Mavivi
Monana	False Horn	Ituri	Mavivi
Musilongo	False Horn	North Kivu	Butembo
Ndonge	French	Ituri	Mavivi
Ngobia Mukelekele	False Horn	Ituri	Mavivi
Nguma I	French	North Kivu	Butembo
Nguma II	French	North Kivu	Butembo
Nguma III	French	North Kivu	Butembo
Nguma IV	French	North Kivu	Butembo
Nzirabahimao	French	North Kivu	Butembo
Plantain GF	False Horn	North Kivu	Butembo
Plantain masunga	French	North Kivu	Butembo
Sanza mbili	True Horn	North Kivu	Butembo
Sanza moya	True Horn	North Kivu	Butembo
Sanza moya-Mandumbi	True Horn	North Kivu	Butembo
Sanza tatu	True Horn	North Kivu	Butembo
UCG	French	North Kivu	Butembo
UCG I	False Horn	North Kivu	Butembo
UCG II	False Horn	Ituri	Butembo
UCG III	False Horn	North Kivu	Butembo
UCG IV	French	North Kivu	Butembo
Vuhembe	French	North Kivu	Butembo
Vuhetera	French	North Kivu	Butembo
Vuhindi	French	North Kivu	Butembo
Vulambya	French	North Kivu	Butembo

tal site, plant spacing was 2.5 m between plants and 3 m between lines (giving 1,333 mats ha^{-1}). Cultivar name and type, Province of origin of a cultivar (*i.e.*, field site) and the *ex-situ* germplasm collection from where planting material was obtained were recorded (Table 2).

Plantain growth and yield traits were assessed over two consecutive growth cycles (*i.e.*, plant and first ratoon crop) from September 2010 till June 2015 at all three sites. The following plant growth traits were assessed at flowering: plant height (cm), pseudostem circumference at soil level and 100 cm above soil level (cm), number of functional leaves (*i.e.*, having at least 50% of green leaf lamina) and the number of lateral shoots (*i.e.*, suckers). Yield-related traits included: flowering and harvesting date of both crop cycles and time to flowering and harvesting, bunch weight (kg) (*i.e.*, peduncle and hands, without the male bud), total number of hands and fingers of a bunch, and number of fingers of the second lowest (distal) hand.

The total peduncle length was measured and divided into length of the bunch (*i.e.*, R1 or female inflorescence) and length of the male peduncle, being from the last hand of female fruit to tip of male bud/peduncle extremity (*i.e.*, R2 or male inflorescence). The length of R2 is a measure of availability of assimilates to the male section of the inflorescence. The male inflorescence has been reported as a sink and is often removed to shorten the time to fruit filling and increase bunch size (Daniells *et al.*, 1994; Ocimati *et al.*, 2013b; Balkic *et al.*, 2016).

The ratio R2/R1 was calculated as a likely measure of the partitioning of assimilates between male and female sections.

In addition, at harvest, the weight of the remaining functional green leaves (kg) and, after removing the hands, the female peduncle weight (kg) (*i.e.*, real stem section of a bunch without the male bud and hands) were measured. Since soil P concentration was highly correlated with altitude (Table 1), the likely effect of P on plant performance was evaluated by using an established relationship between bioavailable soil P concentration (mg kg^{-1}) and the P concentration in soil solution (µg L^{-1}) following Hue and Fox (2010), despite the absence of visible leaf symptoms during the trial period. Bioavailable P was measured using the Mehlich 3 solution to extract P. The P in solution associated with these concentrations was calculated from the bioavailable P following the procedure of Hue and Fox (2010) ($r = 0.87$). The relationship between P in soil solution and the relative growth of 'Williams' banana (*Musa* AAA genome group, Cavendish) (Lin and Fox, 1987) was used to calculate a P deficit coefficient, where adequate P supply gives a coefficient of 1.0.

Efforts were made at all trial sites to prevent the entry of Xanthomonas wilt by restricting tool use to trial sites. No infections occurred during the trial period. Black leaf streak occurred at low severity levels at the lowest elevation site. Old and dried-up leaves were regularly removed to prevent black leaf streak build-up/spread.

Data analysis

Data was collated using MS Excel. Plantain yields (t ha^{-1} yr^{-1}) were computed from the bunch weight and the time to harvest. Values of R1 and R2 were used to calculate the ratio of R2/R1, while the proportion of the peduncle weight to the whole bunch weight (*i.e.*, weight of the peduncle and hands) was also assessed to provide an indication of fresh weight allocation across the whole inflorescence. Means, analysis of variance, and mean separations for various plant parameters were computed using the GenStat v. 12 statistical package (VSN International Ltd., 2009). MS Excel was used for making figures. CANOCO 5 software (Šmilauer and Lepš, 2014) was used for carrying out principal component analysis to determine the key environmental and plant growth or yield-related variables that influenced bunch weight and yield. Curves were fitted on plots of yield to bunch weight and time to harvest to explore the relationship between the variables using MS Excel. In addition, the relationship between P and plant variables was assessed using correlation analysis in Excel.

Results

Interaction between plant attributes and environmental variables

A principal component analysis (PCA) of the plant attributes to determine the most important variables associated with bunch weight and yield was conducted with selected environmental components as supplementary variables. Soil characteristics of the sites were dropped in the final PCA and separately explored, either because they did not differ significantly between the sites or had collinearity with the sites. Plant pseudostem circumference at 1 m height was highly correlated with pseudostem circumference at soil level, while time to flowering was highly correlated with the time to bunch harvest, and thus omitted from the final PCA. The first principal component axis accounted for 63% of the variation and including the second axis accounted for 73% of the variation (Table S1). The pseudo-canonical correlation of the environmental variables supplementary to axis 1 was 91.3% (Table S1). The total variance (adjusted R^2) accounted for by the data was 55%.

Mean annual temperature (MAT) and altitude (ALT) not only had the greatest contribution to the variation along PC1 but were equal and contrasting (Figure 1A). The interaction between MAT and ALT can be attributed to the fact that the altitude directly influences the temperature in a location, with high altitudes having cooler temperatures and the lower ones having a warmer temperature. Annual rainfall (MAR) had a negligible influence on either of the axes, suggesting altitude/temperature primarily influenced the variations in the plant attributes (Figure 1A). Increasing altitude (*i.e.*, decreasing temperature) was strongly correlated with time to harvest (TH), number of suckers (NS) and the bunch partitioning ratio (R2/R1), thus contrasting bunch weight (Bwt), yield (Y) and the other plant attributes. Thus, favourable growth and development occurred at the low-altitude site of Mavivi (1,066 m), with the least at Ndihira (2,172 m).

More or less equal loadings were observed for most of the plant attributes except for the number of functional leaves at flowering (FL) and the number of hands on the bunch (NH) (Figure 1A, B), suggesting they had the least impact on bunch weight (Bwt) and overall yield (Y). The number of suckers (NS), time to harvest (TH) and the ratio of the male (R2) to female (R1) inflorescence rachis length (R2/R1) were strongly correlated and contrasted with Bwt, Y, FL, NH, number of fingers on the second lowest hand (FH2), plant height (HT) and the pseudostem circumference at ground level (PC0). This suggests a tradeoff between NS, TH and R2/R1 and the other plant attributes, more especially Bwt and Y. Bunch weight and Y were, in contrast, positively correlated with FH2, PC0, HT, NH, and FL. (Figure 1A, B).

Clear groupings of cultivars into the three sites were observed along PC1 (Figure 1B) mainly explained by temperature differences. Cultivars at the Ndhira site were distinctly grouped from the Mavivi and Butembo sites, whereas a partial overlap was observed for the Mavivi and Butembo sites. A scatter of cultivars was observed within each site along the PC2 axis (Figure 1B), which is mainly explained by HT, PC0, NH, R2/R1, TH, and NS.

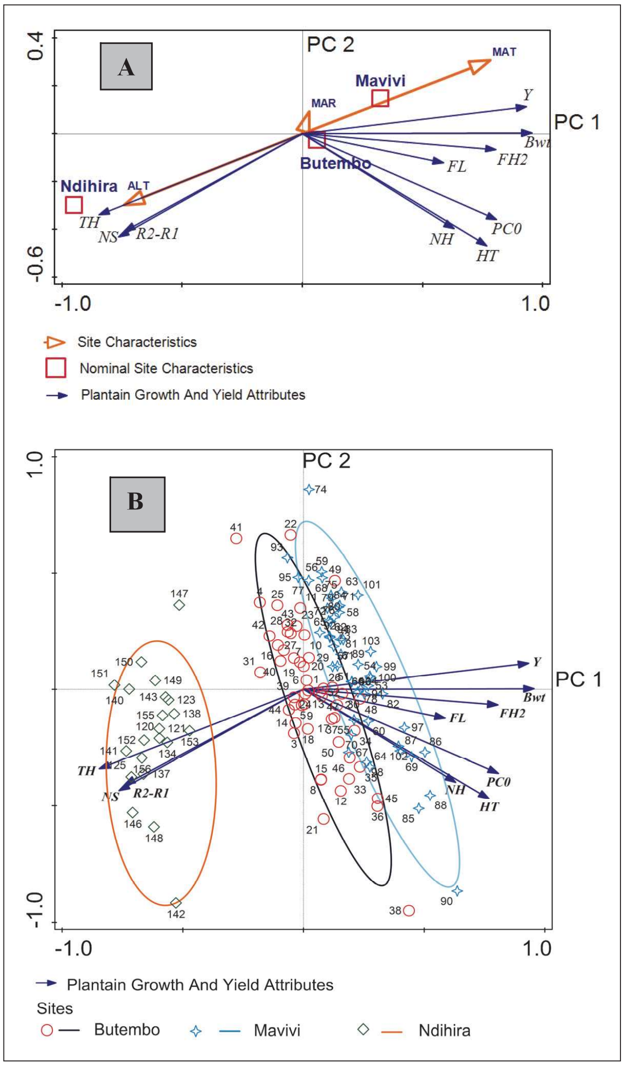

Figure 1. The principal component biplot for A) ten plantain attributes and three supplementary (environmental) variables for 52 plantain cultivars and B) plantain attributes and 52 plantain cultivars grown across three altitudes (1,066, 1,815 and 2,172 m) in Eastern DR Congo. Cultivars 1 to 52 at Butembo are respectively represented as 53–104 at Mavivi and 105–156 at Ndihira.
HT: plant height (cm), PCO: pseudostem circumference at soil level (cm), FL: number of functional leaves (*i.e.*, having at least 50% of green leaf lamina), NS: the number of lateral shoots (*i.e.*, suckers), TH: time to harvest, Bwt: bunch weight (kg) (*i.e.*, peduncle and hands, without the male bud), NH: total number of hands, FH2: number of fingers of the second lowest (distal) hand, MAT: mean annual temperature, MAR: mean annual rainfall, ALT: altitude (m), R1: length of the bunch (*i.e.*, female inflorescence), R2: length of the male peduncle, being from the last hand of female fruit to tip of male bud/peduncle extremity, R2-R1: ratio R2/R1. Supplementary Table S1 provides details of the Principal Component loadings for four axes according to plant attributes. Eigenvalues, explained variation (cumulative) and pseudo-canonical correlation (suppl.) are also presented for the four axes.

Influence of soil chemical properties

The soil chemical properties except for P, did either not significantly vary between the sites or were adequate for banana/plantain production, and as such were anticipated not to significantly influence the variation in the performance of the plantains across the three sites. For example, soil organic matter varied between 5.0 and 5.1%, N between 2.3 and 2.6% and Ca between 6.13 and 6.36 cmolc kg^{-1} across the sites. The soil pH (5.2–6.7), K (0.83–1.14 cmolc kg^{-1}) and Mg (1.06–1.85 cmolc kg^{-1}) across these sites fell within the recommended range for optimal banana production. Soil pH varying between 5 and 6.5 has been reported as the most optimal for banana and plantains, though these crops are tolerant to very acid soils, with good yields reported between a pH range of 4.5 and 8.5, especially if organic matter is adequate (Twyford, 1967; Turner *et al.*, 1989). The K values of 0.83–1.14 cmolc kg^{-1} for the study sites also fell within the wide range of critical K concentration levels (*i.e.*, 0.2–1.5 cmolc kg^{-1}) reported for optimal banana growth and development (Walmsley *et al.*, 1971; Turner *et al.*, 1989; Landon, 1991; Delvaux, 1995; McIntyre *et al.*, 2000). Walmsley *et al.* (1971) reported soil exchangeable Mg levels >1.00 cmolc kg^{-1} as adequate, for banana production. Thus the values of 1.06–1.85 across the sites in this study were accepted as adequate.

In contrast to the above soil nutrients/chemical properties, a large difference in soil P concentration was observed between the three sites. P was 2.2 ppm at Mavivi (1,066 m), 10.6 ppm at Butembo (1,815 m) and 36.1 ppm at Ndihira (2,173 m). According to Twyford (1967), any soil having 15 ppm is deficient in P for bananas, while soils below 25 ppm need attention. P would thus be expected to be deficient at Mavivi and Butembo whereas adequate at the high altitude site of Ndihira. The soil P deficit coefficient calculated using the procedure of Hue and Fox (2010) was 0.68 for Mavivi, 0.78 for Butembo and for Ndihira, 0.93. Given that the coefficient for adequate P is 1.0, all three sites including Ndihira (although only slightly, contrary to Twyford (1967)) were deficient in P.

Plant attributes at flowering

Significant differences ($P<0.001$) were observed between the three altitudes and plantain cultivars for the mean number of suckers per parent plant, the number of functional leaves (FL) at flowering, the time to flowering (TF), plant height (HT) and pseudostem circumference at ground level (PC0). Except for the number of suckers and TF that increased with increasing altitude (Figure 2A, Figure S1), FL, plant height and PC0 in general increased with declining altitude (Figure 2A).

The mean number of suckers varied between 1.2 and 4.5 at the lowest altitude (Mavivi, 1,066 m) compared with 1.7 to 6.1 at Butembo (1,815 m), and 4.9 to 9.4 at Ndihira (2,172 m) (Figure 2). The 2,172 m altitude consistently had the highest number of suckers with the lowest altitude recording the least per parent plant.

A mean of 9.2 FL was recorded at 1,815 m compared with 6.6 leaves at 2,172 m. Some cultivars ('Nzirabahima', 'Bukubekisi', 'Makpelekese', 'Vuhidi', and 'Kotina IV') performed better in terms of FL at the mid altitude site (1,815 m) than the low altitude site (1,066 m). The mean PC0 at ground level at flowering varied between 46 and 62 cm at the highest site (2,172 m), 53 and 99 cm at 1,815 m, and 53 and 103 cm at 1,066 m. Plant height ranged between 224–312 cm at 2,172 m compared with 217–435 cm at 1,815 m and 223–465 cm at 1,066 m. Cultivar 'Mabilanga' that had the shortest

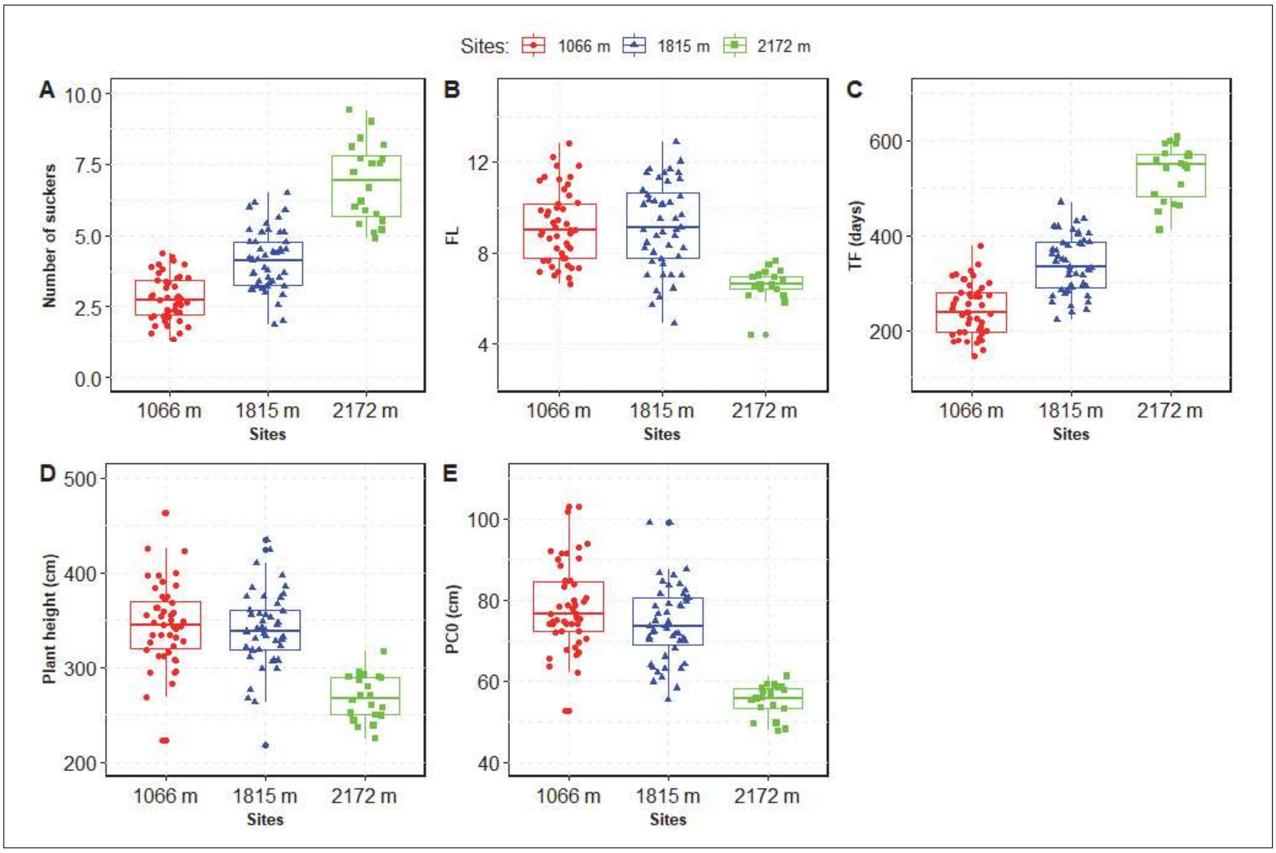

Figure 2. Box plots of the means for: number of suckers per parent plant (A), number of functional leaves, FL (B), time to flowering in days, TF (C), plant height in cm (D), and pseudostem circumference, PC0 in cm (E) for different plantain cultivars averaged over two crop cycles at three sites of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu, Eastern DR Congo, in the period 2010 to 2015. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at the 1,066 and 1,815 m sites. Vertical bars denote quartiles. Detailed values for number of suckers per cultivar and site are presented in Figure S1.

plant height amongst the 52 plantain landraces at both 1,066 and 1,815 m, was not planted at the 2,172 m site.

Plant attributes measured at harvest

Significant differences ($P < 0.001$) in the time to harvest, R2/R1, NH, FH2, fresh peduncle weight, bunch weight and yield were observed across the three sites and between the cultivars. Time to harvest and R2/R1 increased as the altitude increased while NH, FH2, bunch weight and yield declined with increasing altitude (Figure 3). Across the different altitudes, the time to harvest was highest in the plant crop (from planting to bunch harvest) compared with the first ratoon crop (from harvest of the plant crop to harvest of the 1st ratoon). On average, the time to bunch harvests were 379, 662 and 886 days for the plant crop, and 309, 480 and 657 days for the first ratoon crop at 1,066, 1,815 and 2,172 m, respectively (Figure S2).

At 2,172 m, zero male inflorescence length values were recorded for Horn Plantain types that lack a male inflorescence, while French and False Horn plantain cultivars had a tendency to produce an underdeveloped bunch and an abnormally long male inflorescence. In contrast, at 1,066 and 1,815 m well-developed and large female inflorescences were produced, while the male inflorescence section had a normal development for the respective plantain types. The 2,172 m site had significantly higher ($P < 0.001$) male (R2)/female inflorescence length (R1) ratios varying between 1.05 and 6.52. The male:female inflorescence ratio increased with altitude, with values of 0.30–0.99 at 1,066 m and 0.33–1.47 at 1,815 m. Across sites, the regression co-efficient between the male/female inflorescence ratio and bunch weight was negative and relatively strong ($r = -0.32$). Plantain cultivars 'Kothina I' and 'Vuhembe' had the lowest values for male/female inflorescence ratio at 2,172 m.

The mean peduncle fresh biomass weight also varied between 1 and 2 kg at 2,172 m, 0.9 and 2.6 kg at 1,066 m, and 0.9 to 4 kg at 1,815 m. Peduncle fresh weight varied significantly between the cultivars and sites (Figure S3). A significant interaction ($P < 0.05$) was also observed between the sites and the cultivars. A significantly higher proportion of peduncle fresh weight to bunch weight was observed at 2,172 m compared with 1,815 and 1,066 m. A higher variability in the proportion of the peduncle to the entire bunch weight was also observed at 2,172 m (mean 19–74%) compared with 5.1 to 15% at 1,815 m and 5 to 9% at 1,066 m) (Figure S3).

The mean number of hands per bunch was highest at 1,066 m (mean 5.3 hands) compared with 4.6 at 1,815 m and 3.8 at 2,172 m. Variants of 'Nguma', 'Plantain GF', and 'UCG' recorded the largest number of hands. Cultivars 'Vuhembe' and 'Sanza moya-Mandumbi' had the largest mean number of hands at the highest altitude site of 2,172 m, while 'Akongo' had the highest number of hands at 1,815 m. For the remaining cultivars, the mean number of hands was highest at 1,066 m.

The mean number of fingers on the second lowest hand of the bunch were for most of the cultivars higher at 1,815 m,

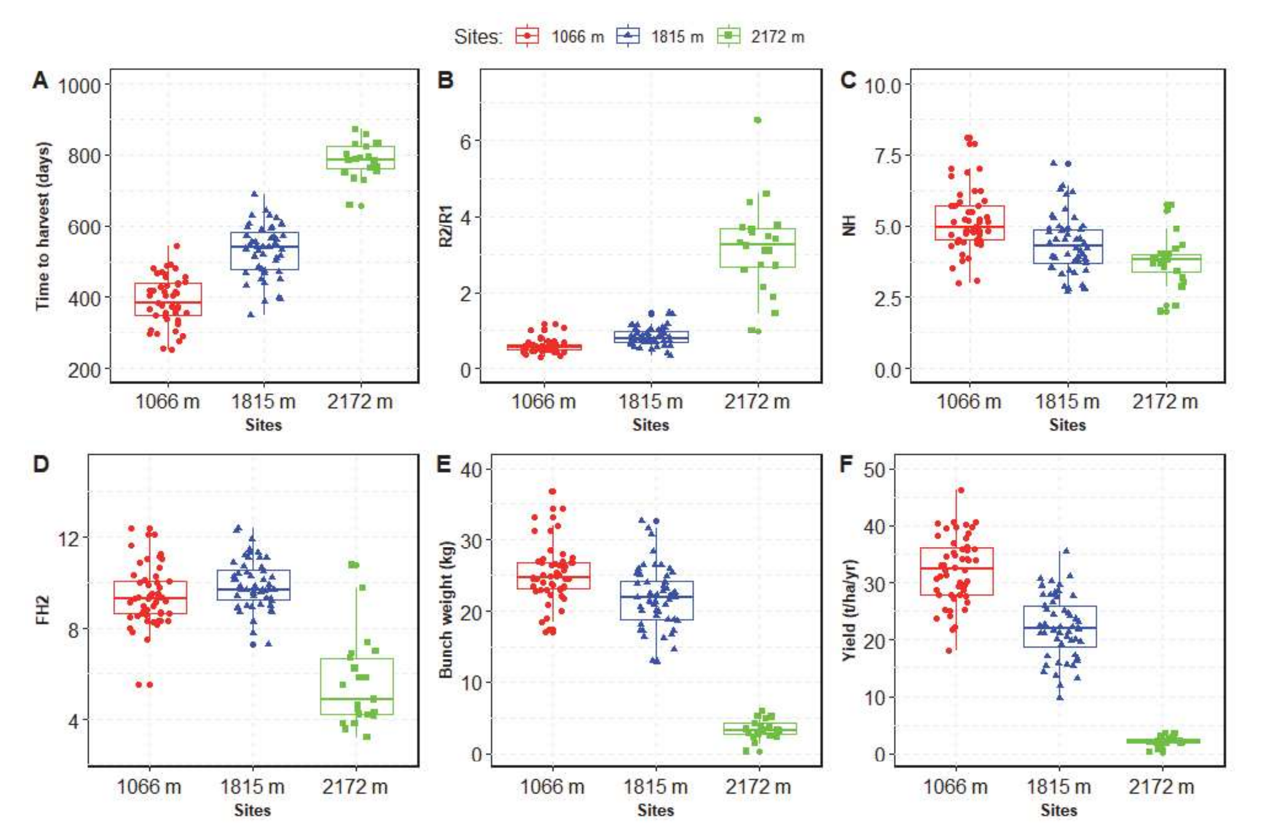

Figure 3. Box plots of the means of two crop cycles for: time to harvest (days), (A); ratio of male to female peduncle length, R2/R1 (B); number of hands on the bunch, NH (C); number of fingers on the second lowest hand on bunch, FH2 (D); bunch weight (kg), (E); and yield (t ha^{-1} yr^{-1}), (F), for different plantain cultivars assessed at three sites with altitudes of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu, Eastern DR Congo, in the period 2010 to 2015. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at the 1,066 and 1,815 m sites. Vertical bars denote the quartiles. Detailed values for mean time to bunch harvest and mean fresh leaf biomass weight at harvest averaged over two crop cycles per cultivar and site are presented in Figures S2 and S4. A box plot showing the proportion of peduncle fresh weight to bunch fresh weight across the three study sites is presented in Figure S3.

varying between 5.5 and 12.4 at 1,066 m (Mavivi), 7.3 to 12.4 at 1,815 m (Butembo) and 3.5 to 11.4 at 2,172 m. (Ndihira). Only the cultivar 'Sanza tatu' had the largest number of fingers on the second lowest hand of the bunch at 2,172 m.

Fresh leaf biomass assessed at harvest varied significantly ($p<0.001$) between the sites. In general, the 1,815 m altitude had the highest leaf biomass at harvest, with the least at the 2,172 m altitude (Figure S4). Mean total fresh leaf biomass per plant varied between 1.9 and 5.8 kg at 1,066 m, 2.2 and 5.8 kg at 1,815 m, and 0.9 and 3.3 kg at 2,172 m. No significant differences occurred between the cultivars ($P=0.386$), and no significant interactions occurred between the cultivars and the sites ($P=0.997$). Fresh leaf biomass at harvest had no strong relationship with bunch weight ($r=0.06$) or the number of functional leaves at flowering ($r=0.02$).

Generally, higher bunch weights and yields were obtained at 1,066 m, declining with increasing altitude (Table 3). Mean bunch weights varying between 17.1 kg (for 'Sanza moya') and 38.1 kg ('UCG I') were observed at the low altitude site (1,066 m) compared with 13.0 kg ('Sanza moya') to 32.7 kg ('Plantain GF') and 1.5 kg ('Sanza tatu') to 6 kg ('Vuhembe') at 1,815 m and 2,172 m, respectively.

At 1,066 m (Mavivi) all the cultivars had marketable bunch weights with only four cultivars giving a mean bunch weight below 20 kg. Six cultivars, 'UCG I', 'Plantain GF', 'Nguma IV', 'Nguma II', 'Nguma I' and 'Nguma III' had large bunch weights exceeding 30 kg (Table 3). At 1,815 m (Butembo), 18 cultivars had mean bunch weights below 20 kg, whereas 'Plantain GF', 'Nguma IV', and 'UCG I' had mean bunch weights above 30 kg, though these values were lower than for the same cultivars at 1,066 m. At 2,172 m, 'Vuhembe', 'Vuhindi', and 'Musilongo' (with mean bunch weights between 5 and 6 kg) were the best cultivars. A large percentage of bunches below 5 kg were deformed and had an abnormally long male peduncle and the fruits were mostly inedible (Table 3, Figure 4). Cultivars that performed well at 1,066 and 1,875 m performed poorly at 2,172 m.

Mean plantain yields (t ha^{-1} yr^{-1}) varied between 49.9 ('UCG I') and 17.9 ('Sanza moya') at 1,066 m, 35.1 (for 'UCG V') and 10.9 ('Sanza moya') at 1,815 m and ranged from 3.5 ('Vuhembe') to 0.64 ('Sanza tatu') at 2,172 m. Yield was determined as a function of bunch weight and the time to harvest of the bunches across the plant and first ratoon crops. Time to harvest for the plant crop covered the time from planting to bunch harvest, while for the ratoon crop time to harvest covered time from plant crop harvest to harvest of the 1st ratoon bunch. As such, cultivars that had heavy bunches across the altitudes did not always result in the best yields due to often longer time periods between subsequent harvests. For example, the cultivar 'Vuhembe' that had a moderate mean bunch weight (25 kg) ranked third (43 t ha^{-1} yr^{-1}) after 'UCG I' (38 kg; 50 t ha^{-1} yr^{-1}) at 1,066 m due to its short time interval

Table 3. Mean bunch weights (kg) and yield (t ha^{-1} yr^{-1}) for plantain cultivars grown at three different altitudes of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu Province, Eastern DR Congo, in the period 2010 to 2015. A dash ('-') denotes that a cultivar was not evaluated at a given site. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at 1,066 and 1,815 m.

Cultivar	Bunch weight (kg)			Yield (t ha^{-1} yr^{-1})		
	Mavivi	Butembo	Ndihira	Mavivi	Butembo	Ndihira
Adili I	26.4±0.6	22.5±0.7	-	35.7±1.1	22.1±1.3	-
Adili II	25.8±0.6	24.0±0.6	-	35.4±1.1	24.4±1.2	-
Agbindolo	22.2±0.7	17.3±0.7	-	27.0±1.2	16.1±1.3	-
Akange	27.8±0.6	17.2±0.6	-	27.4±1.1	14.1±1.1	-
Akobanzi	22.1±0.7	20.5±0.6	-	29.3±1.2	22.0±1.2	-
Akola nembo	24.5±0.7	12.8±0.7	-	30.9±1.2	13.3±1.4	-
Akongo	24.8±0.7	23.8±0.6	-	27.5±1.2	21.1±1.2	-
Akoto nembo	28.4±0.7	26.6±0.7	-	36.6±1.2	26.2±1.3	-
Akoto nguluwe	24.2±0.7	21.9±0.7	-	25.7±1.2	17.8±1.4	-
Alongo	26.8±0.7	22.6±0.6	-	33.5±1.2	21.7±1.1	-
Ayaya	23.6±0.7	21.2±0.7	-	34.1±1.2	24.9±1.3	-
Bubu	25.6±0.7	25.5±0.6	-	30.1±1.2	24.2±1.1	-
Buembe	21.6±0.7	20.1±0.6	-	26.4±1.2	19.4±1.1	-
Bukubekisi	26.7±0.7	17.3±0.7	-	35.5±1.5	17.7±1.5	-
Chui	26.6±0.6	25.2±0.6	-	29.1±1.1	22.3±1.2	-
Kasilongo	23.2±0.6	18.6±0.6	2.9±0.7	32.1±1.0	19.4±1.1	1.9±1.3
Kitotina III	25.0±0.6	19.4±0.6	2.2±0.7	36.4±1.1	21.0±1.1	2.0±1.3
Kola	26.7±0.7	23.5±0.7	-	31.7±1.2	20.4±1.4	-
Kothina I	23.2±0.6	18.1±0.6	3.2±0.7	36.1±1.0	20.9±1.1	1.9±1.4
Kotina IV	25.3±0.6	21.9±0.6	-	37.1±1.2	23.0±1.1	-
Kototina II	22.8±0.6	21.8±0.6	3.1±0.7	32.8±1.1	23.1±1.1	2.3±1.4
Mabilanga	24.9±0.7	25.9±0.6	-	35.1±1.2	29.2±1.2	-
Makaka	18.9±0.7	16.4±0.7	-	24.0±1.5	16.1±1.3	-
Makpelekese	23.4±0.7	20.9±0.6	-	28.3±1.2	19.9±1.2	-
Mamba	20.3±0.7	18.8±0.6	-	25.2±1.2	19.7±1.2	-
Mangondi	26.4±0.6	24.8±0.6	-	32.4±1.1	24.0±1.2	-
Manzenzele	23.2±0.7	21.7±0.7	-	28.8±1.5	23.3±1.3	-
Mayayi	26.9±0.6	22.3±0.6	-	32.6±1.0	21.9±1.1	-
Monana	22.8±0.7	21.1±0.7	-	28.4±1.2	19.0±1.5	-
Musilongo	27.0±0.7	24.0±0.6	5.0±0.6	37.5±1.5	27.6±1.1	3.3±1.2
Ndonge	24.8±0.6	18.9±0.6	-	29.8±1.1	16.5±1.2	-
Ngobia Mukelekele	22.9±0.6	19.9±0.7	-	27.9±1.1	20.0±1.3	-
Nguma I	31.2±0.6	28.3±0.6	3.3±0.7	40.5±1.0	27.4±1.1	1.9±1.3
Nguma II	32.0±0.6	26.5±0.6	4.2±0.6	46.2±1.1	28.3±1.1	2.1±1.1
Nguma III	31.2±0.6	26.5±0.6	-	38.0±1.0	24.9±1.1	-
Nguma IV	33.1±0.6	31.6±0.6	2.4±0.7	40.2±1.1	30.1±1.1	2.2±1.3
Nzirabahima	23.6±0.6	21.9±0.6	3.2±0.8	39.5±1.0	30.5±1.1	2.0±1.5
Plantain masunga	27.3±0.6	22.3±0.6	3.6±0.7	39.0±1.1	25.7±1.1	2.6±1.7
Plantain GF	36.9±0.6	32.8±0.6	4.9±0.9	31.2±1.1	19.9±1.1	3.1±1.5
Sanza mbili	22.8±0.7	14.6±0.6	-	27.7±1.2	13.1±1.1	-
Sanza moya	17.1±0.7	14.2±0.6	-	17.9±1.2	10.9±1.1	-
Sanza moya-Mandumbi	19.9±0.6	13.0±0.6	3.6±0.8	25.0±1.0	11.7±1.1	2.2±1.5
Sanza tatu	18.5±0.6	16.7±0.6	1.1±1.0	25.0±1.1	17.2±1.1	0.6±1.9
UCG	20.8±0.6	16.4±0.6	4.1±1.1	27.7±1.1	16.9±1.1	2.5±2.1
UCG I	38.2±0.6	30.8±0.6	2.9±0.8	49.9±1.1	28.1±1.1	2.1±1.5
UCG II	26.3±0.6	25.1±0.6	3.9±0.8	33.7±1.1	27.6±1.2	2.3±1.5
UCG III	24.4±0.6	21.4±0.6	2.5±0.9	39.6±1.0	26.2±1.1	2.1±1.7
UCG IV	23.9±0.7	22.8±0.6	2.8±0.8	39.5±1.2	35.1±1.1	1.5±1.5
Vuhembe	24.6±0.6	23.1±0.6	6.0±0.6	43.2±1.1	30.9±1.1	3.5±1.1
Vuhetera	25.0±0.6	21.0±0.6	-	34.0±1.0	22.0±1.1	-
Vuhindi	25.0±0.6	20.0±0.6	5.1±0.8	38.8±1.1	22.6±1.1	2.7±1.3
Vulambya	24.1±0.7	19.9±0.6	3.5±0.8	35.6±1.2	29.3±1.1	1.4±1.3
Site mean	25.5±0.1	21.9±0.6	3.5±0.2	33.9±0.2	22.7±0.2	2.2±0.3
Lsd		1.6			2.7	
Cv%		8.6			12.5	
P value (site, site × cultivar)		<.001			<.001	

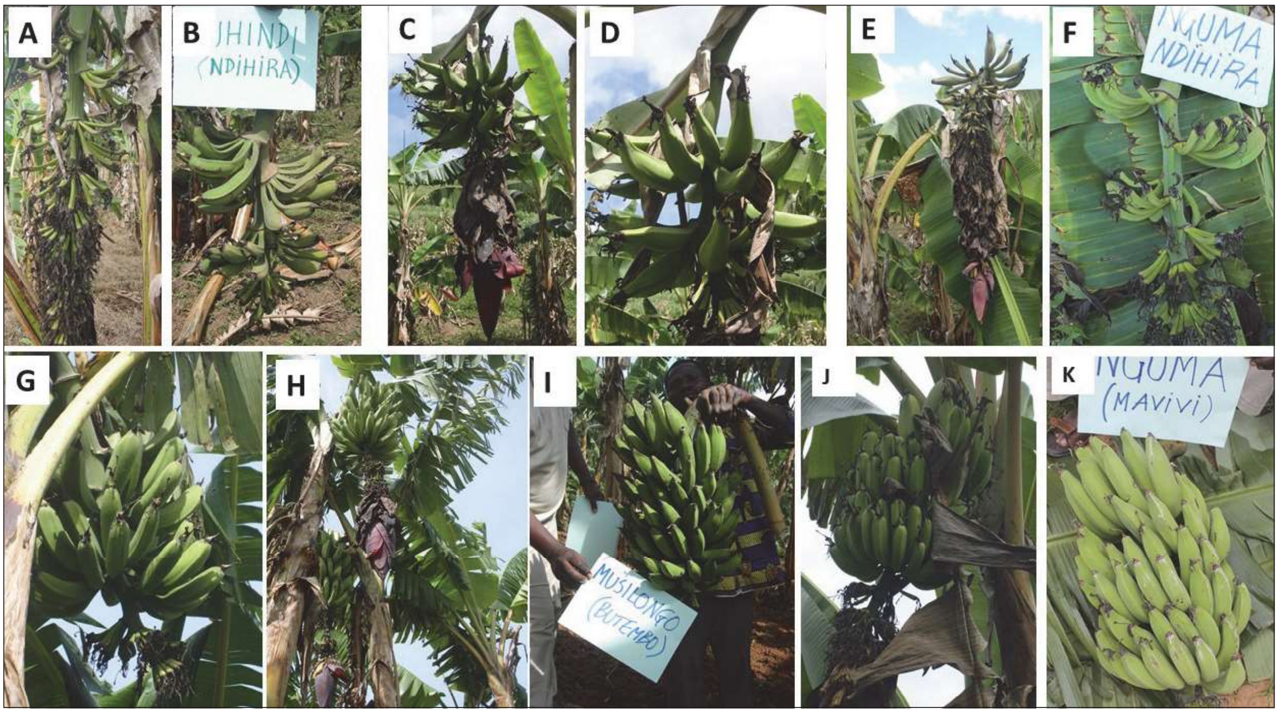

Figure 4. Poorly developed bunches of plantain cultivars 'Vuhindi' (A and B), 'Vuhembe' (C and D), and 'Nguma' (E and F) at Ndihira (2,172 m) and better developed bunches of 'Vuhindi' (G), 'Nguma' (H) and 'Musilongo' (I) at Butembo (1,815 m), and 'Vuhindi' (J) and 'Nguma' (K) at Mavivi (1,066 m).

between subsequent harvests. Similarly, at 1,815 m, 'Vuhembe' (23 kg), 'Nzirabahima' (22 kg), and 'Vulambya' (20 kg), with moderate bunch weights, also came among the top five cultivars in terms of yield (Table 3).

Fitted curves of yield plots showed in general a linear increase with bunch weight, while an exponential decay with increasing time to bunch harvest (Figure 5).

At Ndihira (2,172 m) there are significant correlations between on one hand pseudostem circumference at soil level and on the other hand bunch weight ($r = 0.49$, $p = 0.025$) and number of hands in a bunch ($r = 0.53$, $p = 0.013$). It is assumed that a larger pseudostem can contain heat for longer periods of time, and thus positively influence the development of the inflorescence.

Discussion

This study evaluated 52 plantain cultivars at three altitudes in Eastern DR Congo, with the objective of exploring the interaction of cultivars with the environment and cultivar suitability especially for the high altitude sites that have been reported to be less favourable for plantains.

The PCA shows a differential impact of the environment on the cultivars and a wide variability within plantain cultivars (*cf.* Figure 1A, B). The grouping of Ndhira away from the other two sites is consistent with it being a challenging environment for plantains, while the scatter of cultivars in their respective groupings suggests there is a wide variation in plant growth and performance.

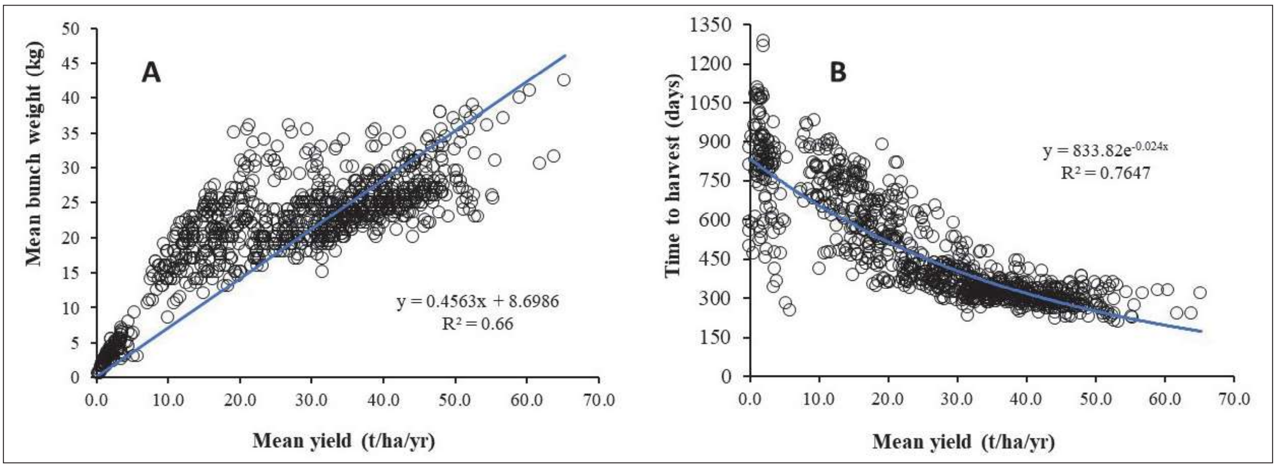

Figure 5. Plot and fitted curves of mean yield (t ha^{-1} yr^{-1}) against the mean of: a) bunch weight (kg) and b) time to harvest (days).

Altitude and plant attributes at flowering

At flowering, the number of functional leaves, number of suckers per parent plant, pseudostem circumference at ground level and plant height were compared across the three altitudes. The number of functional leaves, the pseudostem circumference and plant height were in most cases higher at 1,066 m, and declined with increasing altitude across the 21/52 plantain cultivars evaluated. In contrast, the number of suckers per parent plant increased with an increase in altitude. A longer phyllochron, resulting in a larger number of lateral buds per parent plant developing into new shoots, has been associated with the highest altitude site in this study (Turner *et al*., 2016). This variation across the plant traits is mainly attributed to a drop in temperature with increasing altitude. The rate of most chemical reactions, enzyme activity, the rate of translocation of photosynthates in general increase with an increase in temperature (Bareja, 2011). Temperature, photoperiod and soil water balance have been reported as the primary drivers of banana and plantain development (Fortescue *et al*., 2011). For example, temperatures between 16 and 18 °C significantly slow down plantain growth (Ngo-Samnick, 2011). Earlier studies with five plantain cultivars also showed temperature differences at different sites (current sites inclusive) to affect growth and development in a similar manner to that in the 21/52 plantain cultivars (Sikiyolo *et al*., 2013; Sivirihauma *et al*., 2016; Turner *et al*., 2016).

The average annual temperature at Ndihira is only 16.1 °C, thus clearly below the optimum temperature range for plantains.

Though important for plantain growth, the effect of annual rainfall was small as the rainfall across the sites (> 1,000 mm) was adequate for banana and plantain growth and development.

The trade-off between the number of suckers per parent plant with the number of functional leaves, pseudostem circumference, and plant height as the altitude increases could be attributed to an increased competition for assimilates, underground and aboveground resources or, alternatively, to a change in partitioning of carbohydrates between different parts of the plant under cooler temperatures.

We postulate that suckers draw assimilates and water from the parent plant in the early stages of their development, thus the larger their number, the higher the competition they will exert against the growth and development process in the parent plant. Similarly, when semi or fully independent, they could continue to compete with the parent plant for underground and above ground resources, negatively affecting the growth and development of the parent plant. Experiments are however needed to determine which of the two, *i.e.*, competition or partitioning of carbohydrates best explains the trade-offs associated with suckering. Shading has been reported to reduce root mass in the Cavendish (AAA genome) banana cv. 'Grand Naine' (Lecompte and Pagès, 2007). A higher shade level at 2,172 m arising from a large number of lateral shoots per parent plant potentially could also affect root growth and the overall growth and development of the above ground parts of the parent plant.

Yield attributes

The number of hands on the bunch, the number of fingers on the second lowest hand, bunch weight and yield increased with increasing temperature (declining altitude), while the time to harvest and the ratio of the length of the male (R2) to female (R1) infloreseense (R2/R1) decreased with rise in temperature. The development of floral structures in banana has been reported to be sensitive to temperature conditions and the effect of temperature during this process is reflected in the fruit shape and anatomy (Turner *et al*., 2008). Flower development is particularly sensitive to low temperature during ovary differentiation (Fahn *et al*., 1961), perianth and stamen formation (White, 1928) and differentiation of the megasporangium (Fortescue and Turner, 2005). Low temperatures (< 18 °C) have been reported to cause various effects including deformed or undersized fruits (Fahn *et al*., 1961; Turner *et al*., 2008), a loss or reduced number of locules in the ovaries (Fahn *et al*., 1961) and malformations in the ovule (Fortescue and Turner, 2005; Turner *et al*., 2008). In current sites, earlier studies by Sikiyolo *et al*. (2013) and Sivirihauma *et al*. (2016) reported deformities of the bunch and fruit (choke throat of bunches, abnormal bunch and fruit shapes, reduced fruit size and/or number of fingers and extensive growth of the male inflorescence) at 2,172 m, that is characterised by a low annual mean temperature of 16 °C. Sivirihauma *et al*. (2016) described the bunch deformities to be somewhat similar to the "November dump" phenomenon that occurs in the sub-tropics. 'Pisang awak' (*Musa* ABB genome group) plants grown in a backyard in Addis Ababa, Ethiopia, at 2,300 m have extremely small bunches and long male peduncles (Guy Blomme, 2018, pers. commun.). In the current study of the performance of 52 plantain cultivars, similar observations occurred across the 21 cultivars assessed at the 2,172 m site. Plantains at this site (2,172 m) consistently recorded the least number of hands, fingers on the second lowest hand and smallest bunch weights and yield. In contrast, the lowest altitude site, with a high mean temperature, had good bunch sizes, about a 15-fold increase over those at the high altitude site. Cultivars grown at mid altitudes had marketable bunch weights/yields. This suggests that none of the 21 cultivars is suitable for the Ndihira site at 2,172 m. The cultivar 'Vuhembe' nevertheless had a fair performance at 2,172 m and could be a promising material for future breeding towards cold-tolerance. Further examination of the fruit's ovary and ovule development at this site is recommended for the identification of materials that are more tolerant to cold temperatures and interesting for future breeding work towards cold tolerance.

Low temperatures also led to a longer time duration to harvest at the high altitude sites. Temperature plays an important role in all growth processes. For example, chemical reactions, enzyme activity, the rate of translocation of photosynthates, plant height, leaf area, total plant dry weight and leaf production have been reported to increase with an increase in temperature (Flint *et al*., 1984; Bareja, 2011). In banana, low temperatures have been reported to increase the phyllochron, thus lengthening the time to flowering and harvest (Turner *et al*., 2016). Bunch weight, yield, number of hands on the bunch, the number of fingers on the second lowest hand contrasted with time to harvest, and the ratio of the length of the male (R2) to female (R1) inflorescence (R2/R1).

The male floral part is a sink for assimilates. Removing the male inflorescence has as such been recommended. Though the trade-off between (R2/R1) and the other yield variables under normal growth conditions could be partially attributed to competition for assimilates between the male inflorescence with the female floral part and other parts of the parent plant, the evidence in this study suggests an overriding effect of temperature on both R2 and R1, perhaps from a change in partitioning of carbohydrates, rather than direct competition. However, the effect of male bud removal on bunch formation was not evaluated in this study. In addition, a higher fresh matter allocation to the peduncle relative to the fruits/hands was observed at 2,172 m. This could be attributed to the malformation of the ovules and ovaries, resulting in a reduced ability to store photosynthates in the fruits.

Fresh leaf biomass at harvest per plant had no association with bunch weight and was as such not a good measure for the efficiency of partitioning of assimilates into the banana fruit. This could be due to the fact that the number of functional leaves (varying between 6.6 and 9.2 leaves) observed at flowering at the three sites, were enough for plants to form fully developed and healthy bunches. Krishnamoorthy *et al.* (2004) reported at least 7 leaves at flowering to be adequate for optimum bunch development. This is also consistent with data on bunch formation in Turner and Gibbs (2018), who reported assimilate availability during bunch formation had little effect on number of hands per bunch (number of hands being a component of bunch weight). The management of the remaining leaves at harvest could potentially influence the fertility of the soils. Some farmers return it onto the soils as mulch whereas others export it out of the field as fodder or for other domestic uses such as construction of shelters, and covering/wrapping of vegetables and food.

Conclusions

Plantains have been reported to grow well under lowland and humid conditions. In the current study, most plantain cultivars however also performed well at a mid-elevation site (1,815 m). For example, the following three cultivars 'Plantain GF', 'Nguma IV', and 'UCG I' had mean bunch weights above 30 kg, whereas 'Vuhembe' (23 kg), 'Nzirabahima' (22 kg), and 'Vulambya' (20 kg) with more moderate bunch weights ranked among the top five cultivars in terms of yield due to a relatively short cropping cycle. This suggests that plantains could be promoted in mid-altitude areas that have traditionally been known to be conducive for East African highland bananas (*Musa* AAA-EAH). Given the higher pro-vitamin A carotenoids (pVACs) content of the plantains, this crop could contribute to reducing vitamin A deficiency for people in mid-altitude production zones. A detailed analysis of pVACs content of the 52 plantain landraces included in this study is ongoing. Additional studies on environmental (*e.g.*, temperature) effects on pVACs content would also be warranted. In contrast, the performance of 21 plantains at 2,172 m was extremely poor, with a highest average bunch weight of only 6 kg ('Vuhembe').

This was mainly attributed to the low temperatures, with most bunches being small and deformed. 2,172 m is also considered as the upper limit for East African highland banana growth, hence results in this study for plantains are not surprising. More studies would be warranted for the cultivars that performed well at the cooler mid- and high altitude sites to understand the underlying mechanisms of cold tolerance, which could possibly feed into breeding efforts. Over 100 plantain landraces have been discovered in the larger Congo basin and Eastern DR Congo. The current study only evaluated less than 20% of the plantain diversity at the high elevation site. Studies to evaluate, at mid- to high elevation sites, growth and yield of a larger portion of the plantain diversity is recommended.

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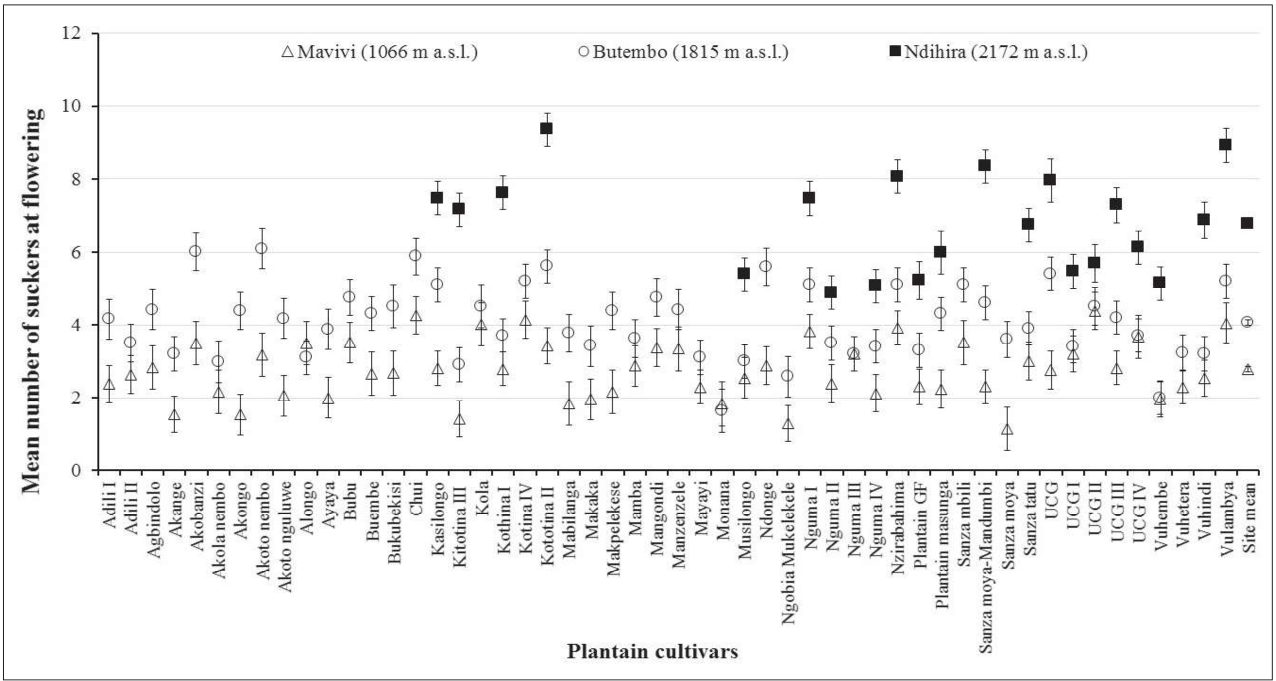
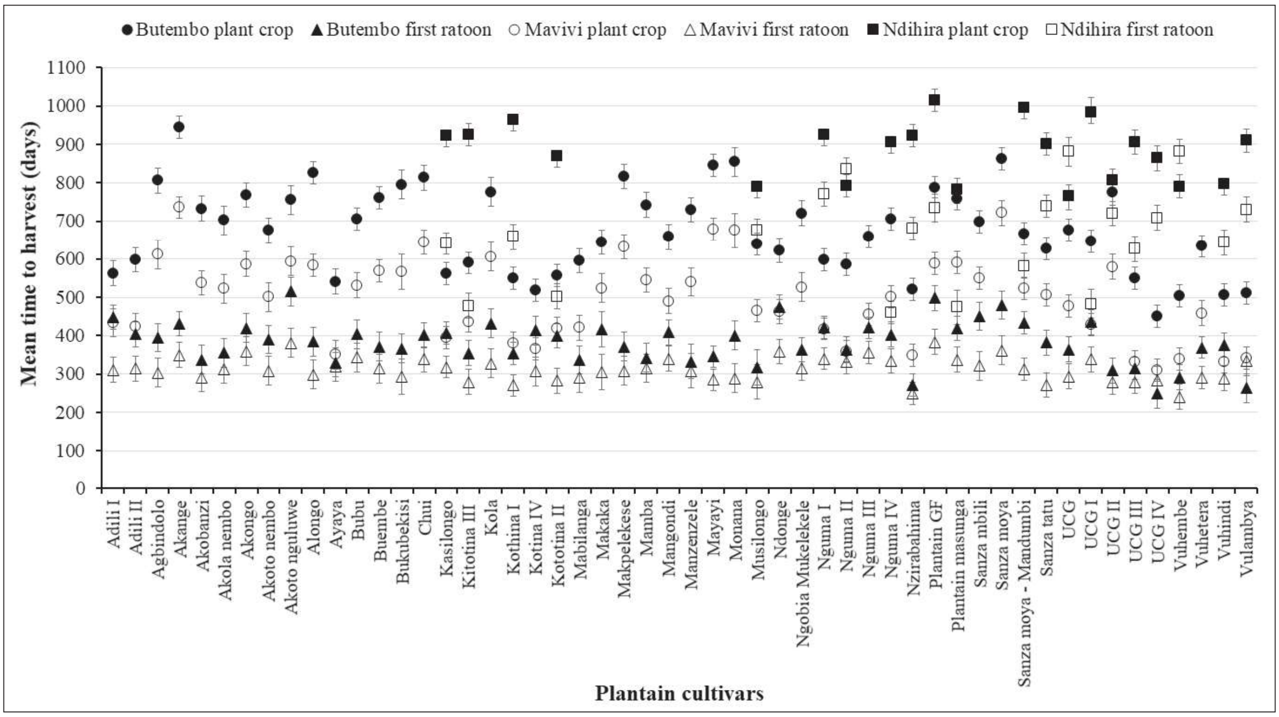
Supplemental Information – Table S1. Principal Component loadings for four axes according to plant attributes. Eigenvalues, explained variation (cumulative) and pseudo-canonical correlation (suppl.) are also presented for the four axes.

	Principal components			
	Axis 1	Axis 2	Axis 3	Axis 4
Number of functional leaves (FL)	-0.5869	0.1231	0.5199	-0.5986
Yield (Y)	-0.9332	-0.1122	-0.1649	-0.0697
Bunch weight (Bwt)	-0.9554	-0.0022	-0.0834	0.0155
Plant height at flowering (HT)	-0.7685	0.4682	0.2008	0.2558
Pseudostem circumference at soil level (PC0)	-0.8076	0.3599	0.2266	0.1969
Number of suckers at flowering (NS)	0.7641	0.4329	0.1005	0.1367
Time to harvest (TH)	0.8462	0.3398	0.1082	0.0504
Number of fingers on the second lowest hand (FH2)	-0.8056	0.0666	-0.0638	0.0944
Number of hands (NH)	-0.6303	0.3978	-0.5886	-0.192
R2/R1#	0.7407	0.4077	-0.2455	-0.3213
Eigenvalues	0.6266	0.1008	0.0829	0.0638
Explained variation (cumulative)	62.66	72.74	81.02	87.4
Pseudo-canonical correlation (suppl.)	0.9128	0.3194	0.3604	0.1754

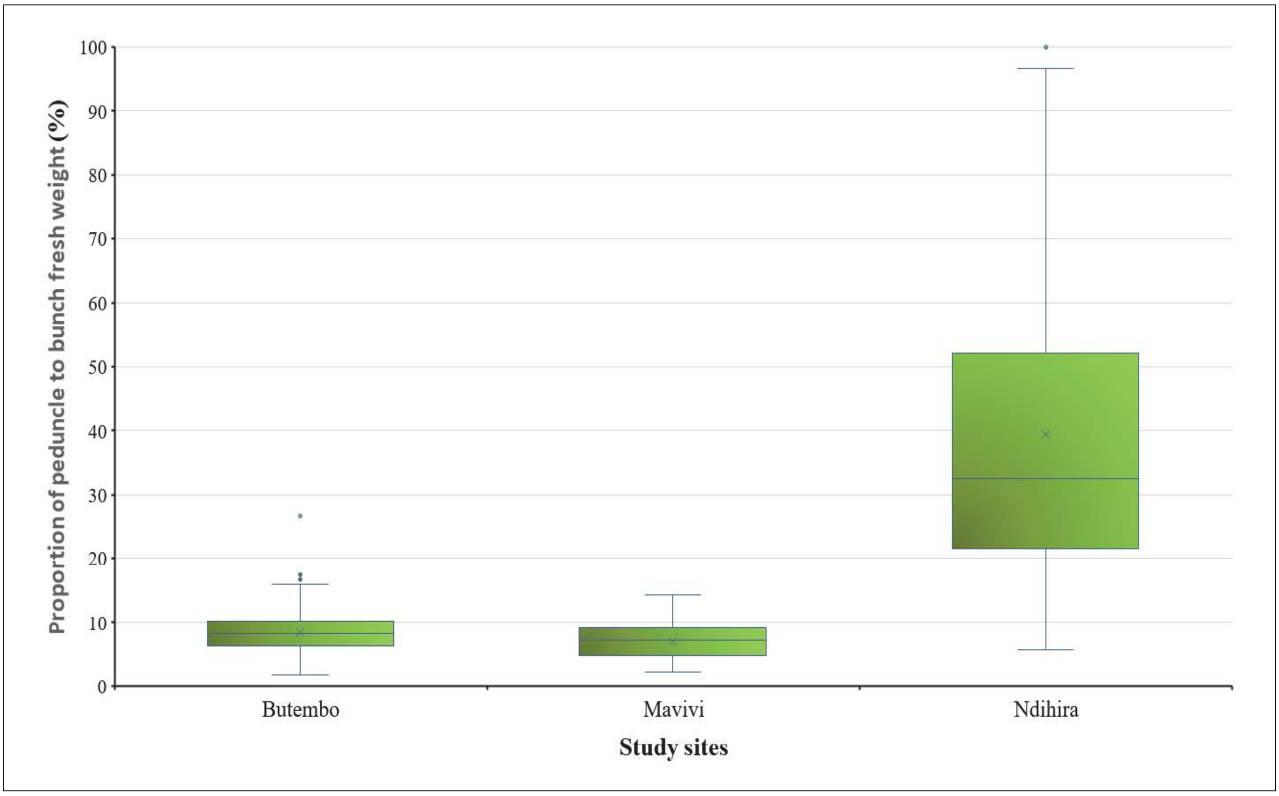
#: R2/R1: with R1 being the length of the bunch (***i.e.***, female inflorescence) and R2 being the length of the male peduncle, being from the last hand of female fruit to tip of male bud/peduncle extremity.



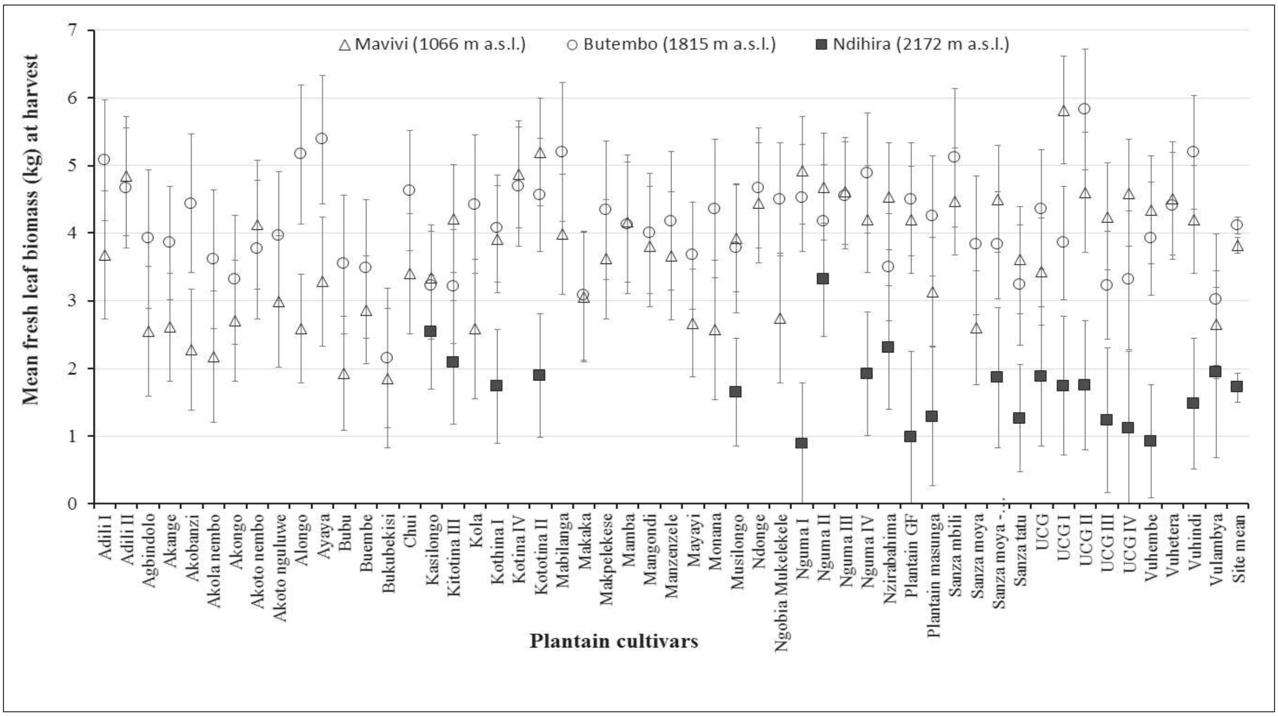
Supplemental Information – Figure S1. The mean number of suckers per parent plant for plantain cultivars averaged over two crop cycles at three different altitudes of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu, Eastern DR Congo, in the period 2010 to 2015. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at the 1,066 and 1,815 m sites. Vertical bars are standard errors (s.e.). (linked to Figure 2).



Supplemental Information – Figure S2. The mean time to bunch harvest of plantain cultivars evaluated at three different altitudes of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu, Eastern DR Congo, in the period 2010 to 2015. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at the 1,066 and 1,815 m sites. Vertical bars are standard errors (s.e.). (linked to Figure 3).



Supplemental Information – Figure S3. A box plot showing the proportion of peduncle fresh weight to bunch fresh weight across the three study sites. Butembo, Mavivi and Ndihira have altitudes of 1,815 m, 1,066 m and 2,172 m, respectively. Vertical bars are the quartiles. (linked to Figure 3).



Supplemental Information – Figure S4. Mean fresh leaf biomass weight at harvest (kg) averaged over two crop cycles in plantain cultivars evaluated at three different altitudes of 1,066 m (Mavivi), 1,815 m (Butembo) and 2,172 m (Ndihira) in North Kivu, Eastern DR Congo, in the period 2010 to 2015. Only 21 cultivars were evaluated at 2,172 m, while a total of 52 cultivars were evaluated at 1,066 and 1,815 m. Vertical bars are standard errors (s.e.). (linked to Figure 3).