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European Journal of Agronomy

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<https://doi.org/10.1016/j.eja.2024.127141>

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What shapes yields of East African Highland banana? An explorative study from farmers' fields

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ARTICLE INFO

Keywords:

Fresh bunch weight
Mat density
Musa acuminata
Banana Xanthomonas Wilt
Yield components

ABSTRACT

Context or problem: East African Highland banana is a main staple and cash crop for millions of people in the Great Lakes region of Africa. Reliable methods for banana yield estimation are lacking and factors underlying yield variability are not well understood.

Objective or research question: We studied the interrelations and relative importance of yield components (yield per mat, mat density, bunch weight, cycle duration and the number of bunches harvested per mat per year or per hectare per year) to on-farm yields. We also explored various methods to estimate yields and tested hypotheses on influence of several biotic and abiotic factors on yields in farmers' fields.

Methods: From July 2019 until June 2021, yields, bunch weights and management practices in 118 fields in West and South-West Uganda were monitored and detailed data on 10 mats per field were collected monthly. This was complemented by a one-off bunch weight survey covering 171 fields.

Results: Median yields in West and South-West Uganda were respectively 31 and 32 ton fresh weight (FW)/ha/year in 2019/2020 and 38 and 36 ton FW/ha/year in 2020/2021. Bunch weights and the number of bunches harvested per hectare were major determinants of yields, while mat density was of minor importance. However, higher mat density was correlated with lighter bunches, longer cycle durations and fewer bunches harvested per mat. Fields that were reportedly manured in the past produced heavier bunches, but the effect of manure applied in 2019/2020 on yields in 2020/2021 was not significant. Higher yields and heavier bunches were associated with mulching, but the underlying causality needs unravelling. Banana Xanthomonas Wilt (BXW) was a major yield-reducing factor. Farmers had to remove diseased suckers in 38% of the monitored fields. Modest amounts of mineral fertilizer had a positive effect on yields and bunch weights, but only in absence of BXW.

Conclusions: Bunch weights and the number of bunches harvested per hectare are major determinants of banana yields. Mineral fertilizer application increases yields within 12 months in the absence of BXW. Manure application seems to need longer duration for effect. On-farm banana yields are higher than reported in literature.

Implications and significance: Yield estimation methods need to be standardized. Future initiatives for improving banana yields should focus on controlling BXW prior to advocating input use. Research should be conducted to unravel the effect of mulch and different combinations and rates of manure and mineral fertilizer on banana yields.

1. Introduction

The East-African highland banana (*Musa* spp. AAA-EA, hereafter referred to as 'banana') plays an essential role in the livelihoods of millions of smallholder farmers in the Great Lakes region (Tripathi et al., 2009). In Uganda, banana is a main staple for over ten million people

and approximately 75% of the farmers grow banana (Promusa, 2022). Attainable yields in Uganda are at least 60–70 ton FW/ha/year (Smithson et al., 2001; Van Asten et al., 2005), but several interlinked socio-economic, abiotic and biotic constraints cause actual yields in farmers' fields to be much lower (Wairegi et al., 2010). Generating reliable data on actual banana yields, their variability and the most

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<https://doi.org/10.1016/j.eja.2024.127141>

Received 9 August 2023; Received in revised form 19 February 2024; Accepted 19 February 2024

1161-0301/© 2024 Published by Elsevier B.V.

important constraints should be a research priority if production is to be improved. Currently, such data are rare in the literature, partly because the estimation of on-farm yields is quite challenging (Hauser and Van Asten, 2010): highly variable cycle durations and plant densities, overlapping growth cycles and year-round harvesting complicate the development of standardized methods for yield estimation in terms of yield/ha/year (Hauser and Van Asten, 2010). To obtain reliable yield estimates and to understand what determines yield, we argue that easy-to-measure yield components should be identified and clear protocols to calculate yields should be available. In addition, investigating the variability and interrelations between yield components enables understanding which yield components are most important in determining yield.

Yield components and yield estimation Yield components are defined as the variables needed to calculate the yield in kg/ha/year (Kozak and Mađry, 2006). Several methods exist to calculate yields, and variables commonly used are bunch weight, plant density, cycle duration and the number of bunches harvested per ha (Hauser and Van Asten, 2010; Ndabamenye et al., 2013a; Meya et al., 2020). Bunch weight is considered a reliable indicator of productivity (Bekunda and Woomer, 1996) and farmers tend to assess the productivity of a field by the size of the bunches, rather than assessing the total annual productivity of the field. Plant density is usually expressed as the number of mats/ha, where a mat is defined as a mother plant (bearing an inflorescence or bunch) and its suckers of younger generations connected through the same rhizome (Ndabamenye et al., 2012). Mat densities (mats/ha) in farmers' fields vary widely (Wairegi et al., 2010; Ndabamenye et al., 2012) and new suckers emerge from the corm year-round and at variable rates (Hauser and Van Asten, 2010). Farmers remove excess suckers to maintain mat vitality, but the number of suckers left on a mat is variable (Kilwinger et al., 2019) and the yield component 'number of suckers/mat', should therefore also be considered in yield calculations. Most agronomic experiments and modelling studies are done using a 'standard' mat spacing of 3 m × 3 m (1111 mats/ha), while maintaining three suckers per mat (e.g. Ssali et al., 2003; Nyombi et al., 2010). This is useful for understanding factors influencing growth under this fixed density, but it doesn't reflect the variation in farmers' fields. Cycle duration is defined as the time between the emergence of a sucker and the harvest of the bunch at horticultural maturity (just before the fingers start ripening). Cycle duration is highly variable and can range between one and three years, depending on the cultivar, stress factors such as drought and nutrient deficiencies (Hauser and Van Asten, 2010) and on the season in which the sucker emerged (Birabwa et al., 2010).

Many of the abovementioned yield components may be correlated to some extent. For instance, a density experiment under low input conditions in multiple agro-ecologies in Rwanda showed that higher densities resulted in prolonged cycle durations and lower bunch weights (Ndabamenye et al., 2013a). This experiment was conducted on a newly established banana plantation, and three suckers per mat were maintained, which may not reflect the conditions in mature farmers' plantations. To date, detailed studies on the variability in yield components, their interrelations and their influence on yield of East-African highland banana under farmers' management have not been conducted.

Yield variability and its causes Banana yield and yield components are affected by biotic and abiotic factors. Field experiments showed that yields and/or bunch weights increased under higher soil potassium (K) levels (Ndabamenye et al., 2013b), and with the application of mulch (Ssali et al., 2003), manure (Meya et al., 2020) and potassium fertilizer (Nyombi et al., 2010). Drought (van Asten et al., 2011), poor soil fertility (Wairegi et al., 2010), Banana Xanthomonas Wilt disease (Tinzaara et al., 2016), banana weevils (*Cosmopolites sordidus*) (Rukazambuga et al., 1998), and weeds (Wairegi et al., 2010) further reduce yields. Catena position may also influence yields as farmers reported that fields in valleys tended to have higher yields than fields on hillslopes and -tops (den Braber et al., 2021). Studies on actual farmers' yields and the factors influencing on-farm yield variability remain exceptional, with

Wairegi et al. (2010) as a rare example. The extent to which the above-mentioned factors have a discernible influence on actual yields in farmers' fields is a major knowledge gap that remains to be addressed.

Aim and hypotheses The objectives of this study were to: 1) identify which yield components are most important in determining yields; 2) assess how these yield components are interrelated; 3) test hypotheses regarding the influence of several biotic and abiotic factors on yields in farmers' fields. We investigated the variability in yield components and assessed the interrelations between yield components. We hypothesized, based on the literature cited above, that banana yield and bunch weights on farmers' fields are positively influenced by the application of manure, fertilizer and mulch, that high rainfall and high soil K content are also positively correlated, and that valley fields have heavier bunches and higher yields than hilltop and hillslope fields. We expected a negative influence of weeds, Banana Xanthomonas Wilt disease and weevils on bunch weight and yields.

2. Methodology

2.1. Study sites and data collection

This study was conducted at two sites. One was in the West and another in the South-West of Uganda. Both sites are located within the major banana-producing regions of Uganda. At each site, two sub counties (Table 1, Fig. 1) were randomly selected for data collection. Two complementary datasets from the selected sub counties were analysed in this study. The first dataset is a detailed *yield monitoring survey*, in which 118 farmer's fields were monitored monthly from July 2019 till June 2021. Second, we used data from a *bunch weight survey* conducted in 2017, in which 171 farmer's fields were visited once. The *yield monitoring survey* enabled us to calculate yields and mean bunch weights per field for two consecutive years, and we collected information on input use, management practices and mat densities. The *bunch weight survey* was a one-off survey in which similar information was collected, but because each field was visited once we could not collect yield data. We used the *bunch weight survey* to complement and compare results from the yield monitoring survey regarding factors influencing bunch weights. The *bunch weight survey* also contained soil nutrient contents of all banana fields. Both surveys were conducted in two sub-counties in West, and two sub-counties in South-West Uganda. Three of the four sub-counties overlapped between the two surveys.

Precipitation is approximately 1200 mm/year in the western region and 900 mm/year in the South-West region, with dry seasons from December to February and from June to August. Soils in the western region are mainly from volcanic origin (Andosols), whereas in south-western region acidic clay loam soils are predominant (Ferralsols). Soil analyses from banana fields included in the bunch weight survey show higher N,P,K and organic matter contents in West Uganda as

Table 1
Number of fields included in the analysis, per subcounty.

Dataset	Type of data collection	Region	Subcounty	Number of fields
Yield monitoring (July 2019-June 2021)	Monthly yield monitoring for 2 years; Mat density; Input use; Household surveys;	South-West	Birere	40
			Rugando	33
		West	Rwimi sub-county	35
			Rwimi town council	22
		Total	118	
Bunch weight survey (2017)	Bunch weights; input use; Mat density; soil nutrients; Household survey;	South-West	Birere	51
			Rugando	65
		West	Rwimi sub-county	37
			Busoro	18
		Total	171	

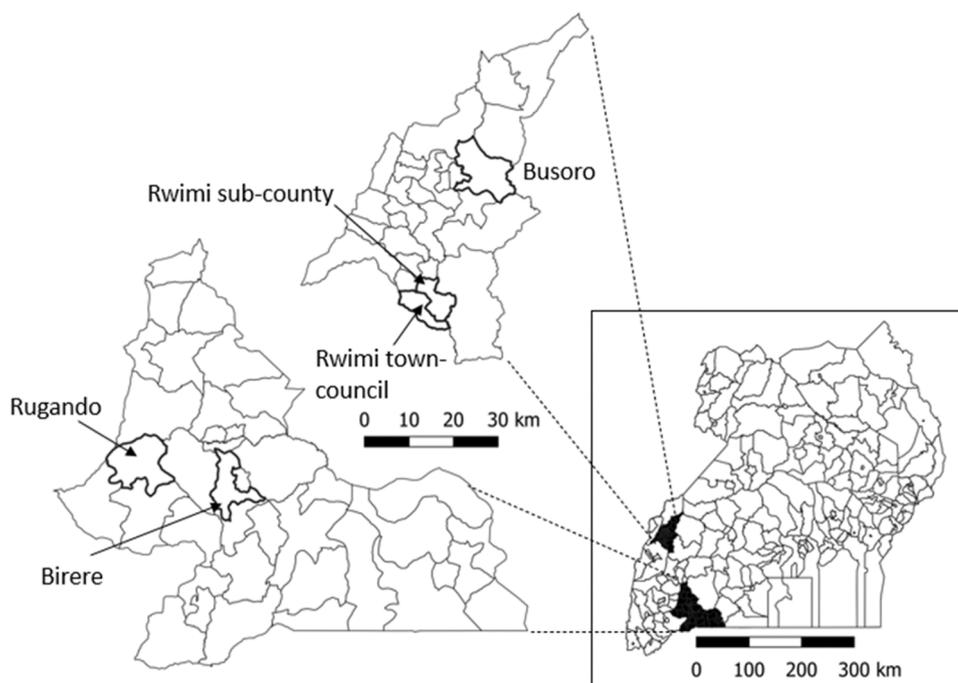


Fig. 1. Overview of the study sites.

compared to South-West Uganda (Table 2).

2.1.1. Yield monitoring

From July 2019 till June 2021, banana growth and yields were monitored in 4 locations, on 45 farms. In total, 118 banana fields were monitored monthly (Table 3). We refer to the period from July 2019 - June 2020 as 'year 1', and to the period from July 2020 - June 2021 as 'year 2' of the yield monitoring. The unit of observation was the banana mat. We selected ten mats per field and aimed to represent the diversity of mats present in the field, while avoiding exceptionally vigorous or stunted mats, or those located at unique spots in the field such as near a rubbish or manure heap. When mats split, (i.e. a group of plants cease sharing a rhizome), we continued monitoring the two mats derived from the original mat. When a mat was terminated by the farmer, or died off, the nearest mat was selected for further monitoring, so that the number of mats monitored per field was at least ten.

The dates of sucker emergence, flowering and harvest were recorded for each mat. At the start of the monitoring period, the emergence dates of the suckers that were already established on the selected mats were estimated based on their size and stage of development. During the monitoring period, emergence dates of all the newly emerging suckers were recorded. We used the date of the first time the sucker became visible in the field. In case suckers did not make it to harvest, the date and the reason of this 'failure' was recorded. This could be due to either natural causes such as toppling, or due to removal by the farmer in an early stage ('desuckering'). When a sucker entered the fruit-filling stage and all hands and fingers in the developing banana bunch became visible, variables for allometric assessment of bunch weight (Wairegi et al., 2009) were recorded.

Four times a year, the distance to the four nearest mats in different

Table 2

Soil characteristics of the study sites in the bunch weight survey. Means are presented and standard deviations are given between brackets.

Region	Sub-county	Soil type	Soil organic matter (%)	Total soil N (%)	Extractable P (mg/kg)	K (mg/kg)
South-West	Birere	Acidic clay loam ferralsols	3.9 (0.65)	0.16 (0.02)	28 (31)	305 (158)
	Rugando		4.1 (0.70)	0.16 (0.02)	38 (58)	340 (233)
West	Rwimi sub-county	Mainly soils of volcanic origin (Andosols)	6.3 (1.17)	0.24 (0.03)	114 (75)	385 (214)
	Busoro		5.2 (0.64)	0.21 (0.02)	93 (56)	482 (268)

Table 3

Number of observations at sucker, mat, field and farm level, per study location in the period July 2019- June 2021.

	Birere	Rugando	Rwimi Sub-county	Rwimi Town Council	Total
Farms monitored	11	12	10	12	45
Fields monitored	39	29	30	20	118
Mats monitored	397	294	312	214	1217
Suckers monitored	2104	1466	2118	1250	6938
Estimated sucker emergences*	873	599	733	428	2633
Observed sucker emergences	1231	867	1385	822	4305
Harvested suckers	1028	671	884	578	3161
Failed suckers	140	103	228	104	575
Still growing suckers	936	692	1006	568	3202
Suckers with estimated cycle duration**	796	546	626	391	2359
Suckers with observed cycle duration**	232	125	258	187	802

* At the start of the yield monitoring, dates for emergence of established suckers were estimated.

** Includes only the suckers that completed their growth cycle during the monitoring period (i.e. the suckers that were harvested (n= 3161).

directions radiating from the reference mat by at least 60° were recorded (Appendix A). The mat area was defined as the region enclosed around the reference mat by connecting the mid-way points between the reference mat and its four nearest neighbouring mats. Weed height and mulch depth in the reference mat area were measured four times a year. Each growing season (twice a year), the area intercropped with annual crops was estimated at field level, and the use of inputs such as manure and fertilizer was quantified and recorded. Field sizes were measured using a hand-held GPS and the position of the field in the landscape was recorded.

At the end of the monitoring period, 3161 suckers had been harvested, 575 suckers had failed, and 3202 suckers had not completed their life cycle yet and were still growing in the field (Table 3). From the 3161 harvested suckers, 2359 were present at the start of the monitoring period, and we had to estimate the emergence dates. We observed the full life cycle of 802 suckers. After the two-year monitoring period, our dataset contained observations on almost 7000 individual suckers and 1217 mats in 118 farmers' fields.

2.1.2. Bunch weight survey

The bunch weight survey was conducted in 2017 with 171 banana-farming households in South-Western and Western Uganda. The structured survey covered household characteristics, crops grown and crop management. The main banana field on each farm was divided into three distance strata: 1) close to the homestead (0–20 m); 2) intermediate distance from the homestead (20–40 m); 3) further away from the homestead (>40 m). Data were collected for determining bunch weights, distance between mats, mulch cover, weed cover, weevil damage and soil nutrients. To assess bunch weights, per field six suckers with recently fully emerged bunches were selected. Two suckers per distance stratum were selected, and variables needed for allometric assessment of bunch weights were taken (Wairegi et al. (2009)). These variables were the number of hands (clusters), the number of fingers in the lower row of the second-last hand, the sucker's girth at 0 cm and at 100 cm. Nine banana mats, three per stratum, were selected to assess intra-mat distances, mulch cover and weed cover. The percentage mulch and weed cover in the area around the mat were visually estimated. Four soil samples were taken per mat, and one composite sample was made for each stratum. Total N was measured after Kjeldahl digestion in concentrated sulphuric acid at 300 °C (Bremner, 1960). Available P and exchangeable K were extracted using the Bray 1 method (Bray and Kurtz, 1945) and ammonium acetate (Doll and Lucas, 1973), respectively. Total N and available P were then determined using colorimetry, while exchangeable K was quantified using a microwave plasma emission spectrophotometer. To assess weevil damage, 6 recently harvested banana corms were identified, and a transverse section was made at the collar region. Weevil damage was assessed based on the percentage damage by weevil larvae tunnelling through the corm tissue, as described by Gold et al. (1994).

2.2. Data analysis

All data processing, data analysis and statistical analyses were performed in R, version 4.2.1.

2.2.1. Bunch weight and plant density estimation

For both datasets, bunch weights and mat densities were calculated. Bunch weights were estimated using the allometric function described by Wairegi et al. (2009). Mat densities (number of mats/ha) estimated from the squared mean inter-mat spacing (Ndabamenye et al., 2013a) were found to be systematically greater than the observed values. The estimated initial densities were therefore adjusted using an empirical function (Eq. 2) established through linear regression of observed and predicted densities from 30 banana fields in West and South-West Uganda (Appendix B). The adjusted mat density was used as a variable in our analyses and is henceforth referred to as mat density.

$$\text{Mat density (mats/ha)} = \frac{10000}{(\text{mean distance to nearest mat}(m))^2} \quad (1)$$

$$\text{Adjusted Mat density (mats/ha)} = 390.105 + (\text{mat density} * 0.498) \quad (2)$$

In addition, plant density in bananas can be expressed by calculating sucker density (suckers/ha):

$$\text{Sucker density (suckers/ha)} = \text{mat density (mats/ha)} \times \text{suckers/mat} \quad (3)$$

We used both mat density and sucker density to calculate yields in different ways as explained below.

2.2.2. Yield calculation

Throughout this paper, whenever we refer to yields, we mean yield in ton FW/ha/year, unless stated otherwise. Because a standard protocol for assessing yields in farmers' fields is lacking, several yield calculation methods, referred to as M1 to M4, were compared (Appendix C). This comparison enabled us to choose the most reliable method, based on how the four methods compared to each other, and based on their practical applicability in farmers' fields. The fresh weights of all bunches harvested from a mat in a certain year were summed. Then, the average yield of all mats (kg FW/mat/year) was calculated for each monitored field. Yield (kg FW/ha/year) was then calculated using Eq. 4:

$$\text{M1: Yield} = \text{mat yield} * \text{mat density} \quad (4)$$

2.2.2.1. Precipitation data and analysis. Daily precipitation for the four yield monitoring study sites for the period July 2018 – July 2021 were downloaded at a 0.05° resolution (pprox. 5.5*5.5 km) from the CHIRPS dataset (Funk et al., 2015). We coupled this data to the yield monitoring dataset by calculating the cumulative precipitation in 12 months prior to harvest for each sucker that yielded a bunch. Since suckers emerge and are harvested on different dates, individual suckers had unique values for the variable cumulative precipitation.

2.3. Statistical analysis

2.3.1. Yield component interrelations

Yield component interrelations were investigated using the yield monitoring dataset. We considered the following yield components: annual yield per mat (kg FW/mat/year), mat density (mats/ha), bunch weight (kg FW), cycle duration (days), number of suckers per mat, number of bunches/mat/year, number of bunches/ha/year (Fig. 2).

For each pair of yield components, we inspected scatter plots and calculated the Kendall rank correlation coefficient, a rank-based measure of association. Values of this coefficient can range between –1 and 1, with negative values denoting a negative correlation. Values closer to –1 or 1 denote stronger correlations. In our description of the results, we only considered correlations of medium (0.3 – 0.5) and large (>0.5) strength.

2.3.2. Variability in yields and bunch weights

2.3.2.1. General approach to modelling and variable selection. We used linear mixed models to test our hypotheses regarding the factors influencing variability in yield and bunch weight (Table 4). The selection of explanatory variables in the models was based on the hypotheses in the introduction. In addition, we included interactions between explanatory variables when we expected these: fertilizer × BXW, manure × BXW and manure × fertilizer. Fertilizer and BXW were expected to interact because an experimental study by (Ochola et al., 2014) suggested that BXW overrides the effect of fertilizer. We expected a similar interaction

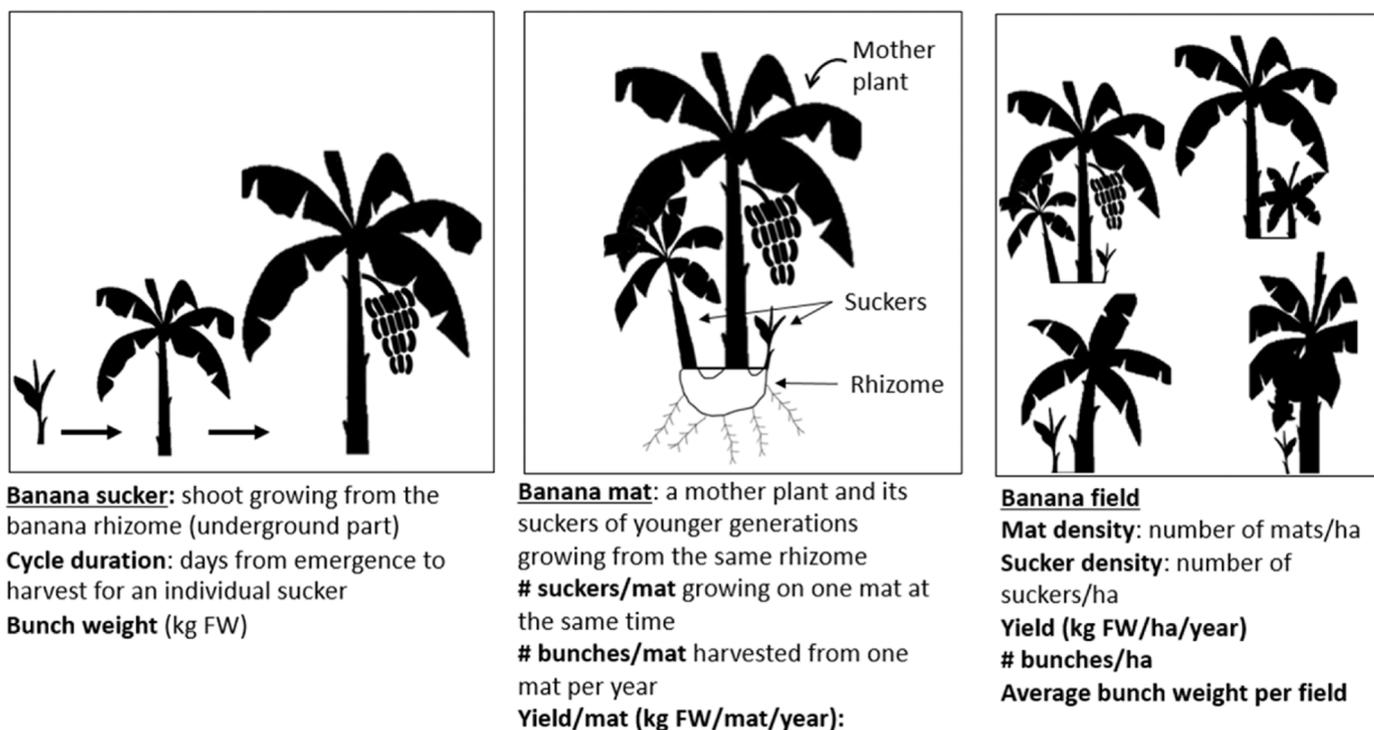


Fig. 2. Illustration of banana growth and definitions of banana yield components.

between BXW and manure. We tested for an interaction between manure and fertilizer because experiments in Tanzania showed that the combination of manure and fertilizer resulted in higher banana yields than the use of sole manure or sole fertilizer (Meya et al., 2020). We did not expect that manure and fertilizer applied in year 1 of the yield monitoring could influence yields in the same year, given the perennial nature of bananas and because many suckers were close to maturity when yield monitoring started. Therefore, we investigated the effect of manure and fertilizer applied in year 1 on the yields and bunch weights in year 2. For the analysis of bunch weights, the co-variate ‘mat density’ was included because we expected a strong influence of mat density on bunch weights, with higher mat densities resulting in lower bunch weights (Ndabamenye et al., 2012). To control for variation caused by differences between sub-counties, ‘sub-county’ was added as a co-variate in all models. In addition, all main effects were tested for interactions with sub-county and significant interactions were retained in the final model. Sub-county could not be included in the random term because this variable had only four levels. We included nested random factors to control for variation caused by differences between villages and between farmers managing multiple fields.

All explanatory variables were scaled and centred to put these variables in the scale of their observed variation. This enables to compare the influence of explanatory variables measured at different scales (e.g., variation in mulch depth can be expected to range between 0 and 10 cm, while variation in manure application could range between 0 and 3000 kg DW/ha/year). For each model, collinearity between variables was investigated by checking the variance inflation factors and the distribution of residuals were inspected for signs of deviation from normality and constant variance. To inspect the behaviour of model predictions in the presence of interactions we used the ‘predict’ function in the R package ‘stats’ to produce plots of the dependent variable as a function of the two interacting variables, while keeping the remaining explanatory variables at mean values.

2.3.2.2. Assessment of yield and bunch weight variability. To assess factors influencing yield variability we used the yield monitoring dataset, and we fitted the following linear mixed model:

Model 1: $Yield = sub\text{-}county \times (mulch\ depth + weed\ height + manure + fertilizer + BXW + catena\ position + (manure \times fertilizer) + (manure \times BXW) + (fertilizer \times BXW)) + (village/farm) + \epsilon$.

Yield is expressed in kg FW/ha/year, and ϵ is the residual error.

To test our hypotheses regarding the main factors that influence bunch weights we used both the yield monitoring dataset and the bunch weight survey. We used the yield monitoring dataset to fit a model similar to model 1, but the dependent variable was the average bunch weight per field (kg FW) and ‘mat density’ was included as a co-variable:

Model 2: $Bunch\ weight = sub\text{-}county \times (mulch\ depth + weed\ height + manure + fertilizer + BXW + catena\ position + mat\ density + (manure \times fertilizer) + (manure \times BXW) + (fertilizer \times BXW)) + (village/farm) + \epsilon$.

Not all variables in the two datasets were the same, and methods to determine variables were slightly different in some cases. The bunch weight survey contained the variables ‘soil K content’ and ‘weevil damage’, while the variables ‘BXW’, ‘fertilizer’ and ‘catena position’ were not present. In the bunch weight survey, mulch cover, weed cover and the use of manure in the past were assessed as binary variables (yes/no), while in the yield monitoring survey, mulch depth and weed height were assessed, while manure application was a continuous variable (Table 4). We therefore used the bunch weight survey to fit the following model:

Model 3: $Bunch\ weight = sub\text{-}county \times (mulch\ cover + weed\ cover + manure\ use + soil\ K + weevil\ damage + mat\ density) + (village/farm) + \epsilon$.

Bunch weight is expressed as kg FW/bunch, and ϵ is the residual error. The random term was similar to the random term of model 1. The main difference with model 1 is the absence of interaction terms with manure, BXW and fertilizer because data on BXW and fertilizer were absent in the bunch weight survey dataset.

We collected data on black sigatoka disease damage using the youngest leaf spotted index in the one-time farm visit. However, it was consistently on old leaves with low variability across enumerated fields, in line with observations reported by Wairegi et al. (2010), who eliminated it from further analysis. Furthermore, farmers objected to excavation of roots for nematode damage evaluation because this is believed to not only reduce fresh bunch weights but also reduce plantation longevity. Therefore, the effect of black sigatoka and nematode damage

Table 4

Variables included in the statistical models to investigate variability in yields and bunch weight. 'Effect' refers to the hypothesized effect of the explanatory variables.

	Yield monitoring survey	Bunch weight survey	Effect
Dependent variables			
Yield	kg FW/ha/year	Not present in dataset	NA
Bunch weight	kg FW, field average	kg FW, field average	NA
Explanatory variables			
Mulch	Field average mulch depth (cm)	Field average mulch cover (%)	+
Weed	Field average weed height (cm)	Field average weed cover (%)	-
Manure	kg dm/ha/year, in year 1	Applied manure in the past (Y/N)	+
Fertilizer	kg/ha/year, in year 1, mostly MOP, some NPK and some Urea	Not present in dataset	+
Catena position	Valley, hillslope, hilltop	Not present in dataset	See introduction
BXW	% of suckers that were removed because of infection	Not present in dataset	+
Banana weevils	Not present in dataset	% of cross sectional area of corm tissue affected by weevils	-
Soil K	Not present in dataset	In mg/kg soil	+
Precipitation	Cumulative precipitation (mm) in 12 months before harvest	Not present. Calculating cumulative precipitation from one-off survey is not insightful	+
Covariates			
Sub-county	For checking interactions with sub-county and explanatory variables		
Mat density	Mats/ha, only included in models with bunch weight as dependent variable		
Random effects			
Village	Controlling for variation caused by differences between villages		
Farm	Controlling for variation caused by farmers managing multiple fields (nested in village)		
Field/mat	Controlling for variation in bunch weight caused by suckers growing on the same mat, and in the same field. This random term was only included in model 4		

Where significant effects of Sub-county were observed, we included it in the model for checking interactions with the explanatory variables.

were not included in this study.

2.3.2.3. In-depth analysis of rainfall effects on bunch weight. The models for investigating variability in yield and bunch weights described above were based on field averages. However, using field averages does not allow for an analysis of the effect of precipitation because suckers in a field bear fruit at different moments. Cumulative precipitation in the 12 months prior to harvest was calculated for each individual sucker that was harvested during the yield monitoring period. We fitted a linear mixed model to assess the influence of cumulative precipitation on bunch weights, and we added key interactions with sub-county, mulch and mat density. These interactions were added because previous research showed that the relationship between bunch mass and mat density could be different in different agroecological zones, and that rainfall plays an important role in this relationship (Ndabamenye et al., 2013a). The interaction with mulch was included because the use of mulch in banana can improve water infiltration and water uptake (McIntyre et al., 2000). A nested random effect of village, farm, field and mat was included in the model.

Model 4: $Bunch\ weight = sub\text{-}county \times (cumulative\ rain + mat\ density + mulch\ depth + (cumulative\ rain \times mulch\ depth) + (cumulative\ rain \times mat\ density)) + (village/farm/field/mat) + \epsilon$.

3. Results

3.1. Yield estimates and yield components

Median yields in West and South-West Uganda were respectively 31 and 32 ton/ha/year in year 1 and 38 and 36 ton/ha/year in year 2 (Fig. 3A). Across years and sites, the 95th percentile yield was 66 ton/ha/year. Yield variation within sub-counties was larger than variation between sub-counties and between years. Median annual yields per mat varied between 20 and 45 kg/year (Fig. 3B), while on average, one or two bunches were harvested per mat (Fig. 3G). Median bunch weights ranged from 20 to 30 kg, with large variation within sub-counties (Fig. 3C). Bunch weights and annual yield per mat were highest in Birere, and lowest in Rugando. Median mat density ranged from roughly 850 mats/ha in the two sub counties in Rwimi to almost 1300 mats/ha in Rugando (Fig. 3D). Median sucker densities ranged from roughly 2500 in Birere to 3000–3500 in Rugando and Rwimi sub-county (Fig. 3E). Rwimi sub-county had low mat densities but high sucker densities because farmers maintained three or more suckers per mat, which was more than in the other sub-counties, on average 2.5–3.0 (Fig. 3F). Median cycle durations were between 530 and 600 days, with shorter cycle durations in West Uganda as compared to South-West Uganda (Fig. 3H). Cycle durations in year 1 of the yield monitoring were not displayed because we deemed the estimates in year 1 not reliable (Appendix D).

In the period prior and during yield monitoring, yearly precipitation ranged between 900 and 1300 mm/year (Table 5). Birere sub-county was much drier than the other sub-counties and Rwimi sub-county received most rainfall. Annual rainfall fluctuation was largest in South-Western sites (Birere and Rugando).

3.2. Yield component interrelations

Yields were strongly and positively correlated with the annual yield per mat and with average bunch weights, and positive associations of medium strength existed between yields and the number of bunches per mat and per ha (Fig. 4). Hence, the number of bunches plays a less important role in determining the yield than the weight of the bunches. Surprisingly, neither of the two density variables (mat density and sucker density) were strongly associated with yield, even though mat density was one of the main variables in the yield calculation formulas Eq. C.1 to C.5.

Annual yields per mat showed medium negative correlations with mat density and with cycle duration, which means that higher annual yields per mat are associated with lower mat densities and with short cycle durations. Mat density was negatively associated with bunch weights and with the number of bunches harvested per mat, while there was a positive correlation with cycle duration. This means that at high mat densities, suckers had longer cycle durations and lighter bunches per mat.

Further inspection of the association between yield and the two density variables (mat density and sucker density) per sub-county further confirmed that there was no strong correlation between density and yield (Appendix E). This can be explained by the relations between the following four sets of yield components: 1) the inverse relation between mat density and bunch weights (correlation coefficient: -0.38); 2) the inverse relation between mat density and cycle duration (correlation co-efficient: -0.41); 3) the inverse relation between mat density and the number of bunches per mat per year (correlation co-efficient: -0.41) 4) the positive relation between mat density and the number of bunches per ha per year (correlation coefficient 0.25). These relations imply that at low mat densities, bunches tend to be heavier, cycle durations tend to be shorter and the number of bunches harvested per mat per year tend to be higher. However, the number of bunches harvested per ha per year is relatively low because of the low density. In contrast, at high mat densities bunches are lighter but more bunches are harvested per ha per year.

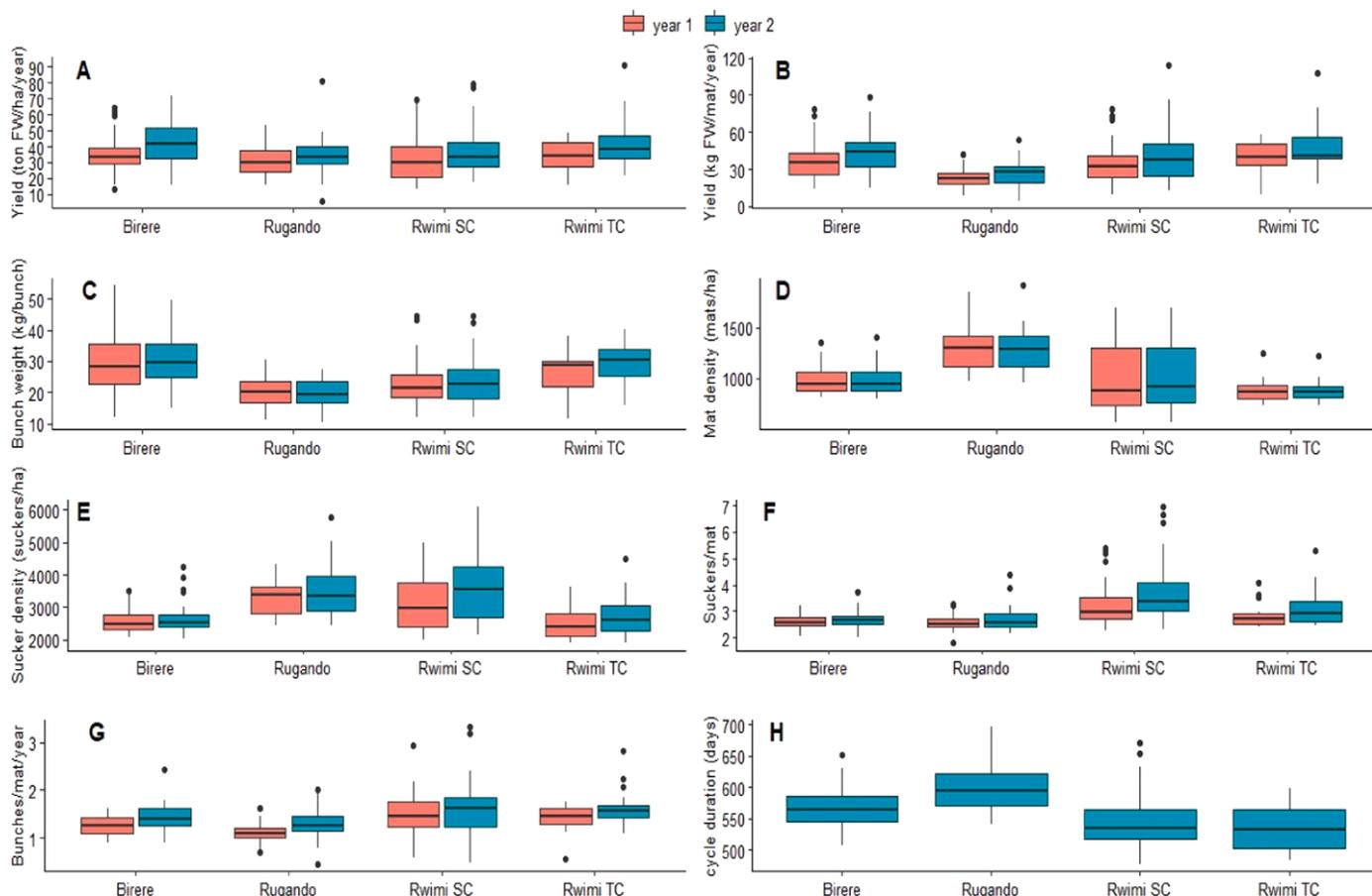


Fig. 3. Yield estimates and yield components in farmers’ fields in south-west and west Uganda. Year 1 refers to the period July 2019 – June 2020 and year 2 refers to July 2020 – June 2021. A: Yield (ton FW /ha/year). B: Per field, average yield per mat (kg FW/mat/year). C: Per field, average bunch weight (kg FW/bunch). D: Number of mats per hectare. E: Number of suckers/ha. F: Number of suckers/mat. G: Number of bunches harvested/mat/year. H: Cycle duration: days from emergence to harvest.

Table 5

Yearly precipitation in the four study sites in the period July 2018 – June 2021. Year 0 is the year prior to the start of the yield monitoring, while in year 1 and 2, yield monitoring took place.

Sub-county	year 0 Jul '18 – Jun '19	year 1 Jul '19 – Jun '20	year 2 Jul '20 – Jun '21	Average
Birere	897	995	1002	965
Rugando	1247	1098	1266	1204
Rwimi sub-county	1279	1274	1295	1283
Rwimi town council	1167	1172	1201	1180

3.3. Yield variability

Yields in farmers’ fields increased with increasing depth of mulch cover and reduced with increasing BXW incidence. However, fertilizer application influenced the yield reduction with BXW infestation (Table 6). None of the explanatory variables showed a significant interaction with sub-county. Average mulch depth per field, over a two-year monitoring period, ranged between 0 and almost 2.5 cm, and more than half of the fields had an average mulch depth of more than 1 cm. Self-mulch (i.e. banana crop residue) was the dominant source of mulch on our study fields, while approximately 20% of the fields had at least 10% mulch from external sources. We did not find evidence that the use of external mulch had benefits over self-mulch although fields where

external mulch was applied had deeper mulch layers. BXW was present in at least 38% of the fields, and in the most severely infected fields, more than 10% of the monitored suckers were removed by farmers due to BXW. Fertilizers of various types, and in various doses, were applied on 25% of the fields. NPK blends were most often used, followed by MOP (Muriate of Potash, a potassium fertilizer), while some farmers combined these two types of fertilizer. The median application rate of fields where fertilizer was applied was 64 kg fertilizer/ha/year. The weak interaction ($P = 0.0561$) between BXW and fertilizer was negative. At high levels of BXW infestation, the effect of fertilizer was overruled by the disease pressure and adding fertilizer resulted in weaker responses as compared to a situation with low BXW infestation levels (Fig. 5 A). In fields where fertilizer was used and no BXW was recorded, median yield was 47 ton/ha/year, while in fields where fertilizer was applied but BXW was present, median yield was 37 ton/ha/year (Fig. 5B). This overruling effect was further confirmed when we analysed a subset of the original dataset ($n=73$), containing only fields that were free of BXW. In the full dataset, containing all fields, the effect of fertilizer was weak ($P = 0.0591$), while in the subset, the effect of fertilizer was much stronger ($P = 0.010$) (Appendix F).

3.4. Bunch weight variability

In the yield monitoring survey, bunch weight variability was influenced by mulch, BXW, fertilizer and the co-variate mat density (Table 7). Analysis of the bunch weight survey confirmed the significant influence of mulch and mat density, and also showed that manure applications in the past and weed cover influenced bunch weights

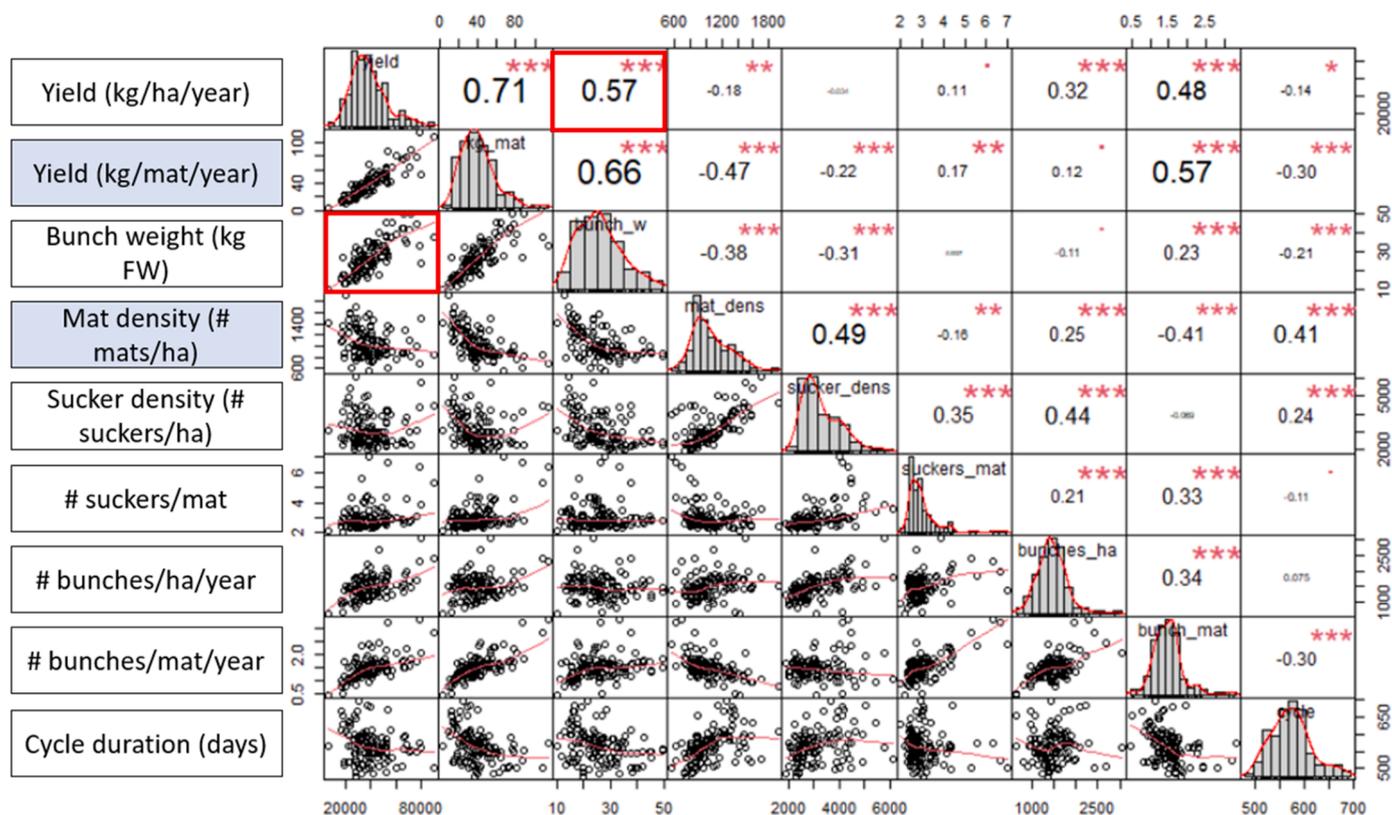


Fig. 4. Correlation matrix of yield components. The distribution of each variable is shown in the diagonal. Below the diagonal, bivariate scatter plots with a fitted line are shown. Above the diagonal, the value of Kendall rank correlation coefficients are shown for each pair of variables. Values range between -1 and 1 , with negative values denoting a negative correlation. Values closer to -1 or 1 denote stronger correlations. The X axes of scatter plots are alternately at the left and right of the figure, and the Y-axes are alternately at the top and bottom of the figure. For instance, see the red-framed plots for the relation between yield and bunch weight. For this relation, the scatter plots' Y-axis is on the right of the figure, and the scatter plots' X-axis is displayed under the figure. Symbols for significant correlations are displayed as *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$. The blue shaded boxes indicate the variables that were included in the formula to calculate yields.

Table 6

ANOVA table of a linear mixed model with yield (kg/ha/year) as dependent variable. Based on dataset yield monitoring. 'Num. DF' refers to the numerator degrees of freedom and 'Den. DF' to the approximate denominator degrees of freedom for the F-test. P values below 0.05 are shown in bold.

Variable	Effect pos (+) or neg (-)	Mean Sq.	Num. DF	Den. DF	F value	Pr(>F)
Sub-county		31739774	3	2	0.1963	0.8917
Mulch depth	+	1008633021	1	82	6.237	0.0145
Weed height	-	2667908	1	95	0.0165	0.8981
Manure	+	15920497	1	85	0.0984	0.7545
Fertilizer	+	590076584	1	95	3.6488	0.0591
BXW	-	810632460	1	95	5.0127	0.0275
Catena position		433809928	2	91	2.6825	0.0738
Manure × fertilizer	-	168914351	1	83	1.0445	0.3097
Manure × BXW	-	10142253	1	86	0.0627	0.8029
Fertilizer × BXW	-	604919917	1	96	3.7406	0.0561

significantly (Table 8). At the level of individual suckers, cumulative rainfall interacted with mulch and mat density in influencing bunch weights.

In both datasets, mulch, mat density and the interaction between mat density and sub-county had significant effects on bunch weights (Tables 7,8). Mat density was negatively correlated with bunch weights,

indicating that competition between mats at high densities resulted in lower bunch weights. Higher values for mulch depth (Table 7, Fig. 6 A) and mulch cover (Table 8) were associated with heavier bunches.

In the yield monitoring dataset, fertilizer application had a positive effect on bunch weights (Table 7), but there was an interaction with manure. When no or very small amounts of manure were added, the response to fertilizer was stronger than when medium or large amounts of manure were added (Fig. 6B). In the bunch weight survey, we found that bunches were significantly heavier in fields where manure was applied in the past (Table 8). Median bunch weights were 14.5 kg FW in fields where no manure had been applied in the past, while in fields with manure applications median bunch weights were 20.1 kg FW. Bunch weights were not significantly influenced by soil K.

In the bunch weight survey, bunch weights were negatively affected by weed cover (Table 8). At low weed cover, mean bunch weights ranged from low to high (i.e., 10–40 kg), but in fields with more than 30% weed cover, bunches were always (much) less than 30 kg (Fig. 7B). In the yield monitoring dataset however, the negative effect of weed height was not significant (Table 6). BXW had a negative effect on bunch weights but there was a similar interaction ($P = 0.057$) between fertilizer and BXW (Table 7) as we found in our analyses of yields (Table 6). The effect of weevils was not significant.

At the level of individual suckers, we found three-way interactions between sub-county × rainfall × mat density and between sub-county × rainfall × mulch (Table 9, Appendix G). Even though these complex interactions are hard to interpret, it is clear that the predicted response to increasing rainfall was stronger in the driest sub-county (Birere) as compared to the wettest sub-county (Rwimi sub-county). In addition, the relation between mat density and bunch weight was different

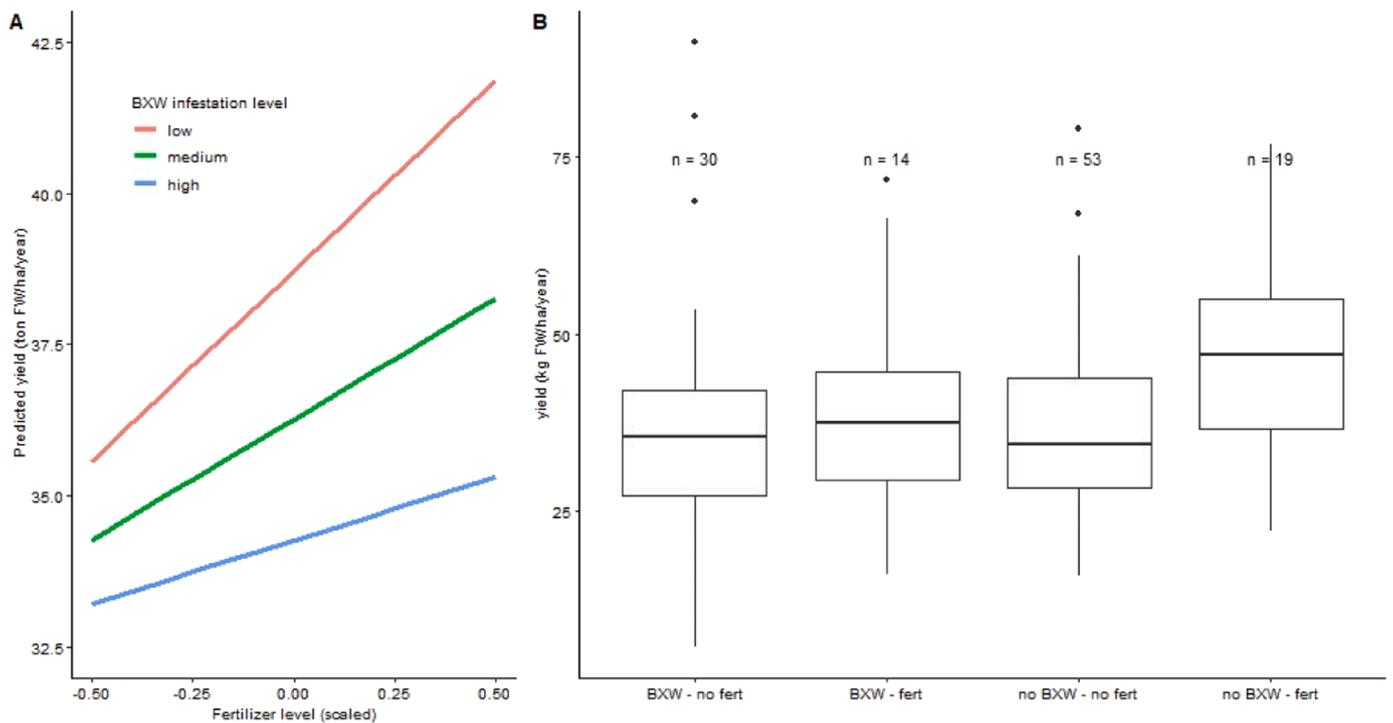


Fig. 5. A) Interaction between BXW infestation and fertilizer. Predicted yields are derived from the linear mixed model, under different fertilizer levels, and at different levels of BXW infestation, while keeping the remaining variables at average values. The x-axis displays the scaled fertilizer data. The high, medium and low levels for BXW infestation are respectively 3rd quartile, average and 1st quartiles values for this variable. B) Yields under various combinations of BXW and fertilizer. ‘Fert’ refers to fertilizer.

Table 7

ANOVA table of a linear mixed model with average bunch weight (kg) per field as dependent variable. Based on yield monitoring dataset. ‘Num. DF’ refers to the numerator degrees of freedom and ‘Den. DF’ to the approximate denominator degrees of freedom for the F-test. P values below 0.05 are shown in bold.

Variable	Effect pos (+) or neg (-)	Mean Sq	Num. DF	Den. DF	F value	Pr (>F)
Sub-county		49	3	64	1.85	0.147
Mulch depth	+	473	1	86	17.87	0.000
Weed height	-	0	1	82	0.00	0.949
Catena position		42	2	80	1.58	0.212
Manure	-	13	1	79	0.47	0.493
Fertilizer	+	366	1	86	13.82	0.000
BXW	-	145	1	84	5.47	0.022
Mat density	-	616	1	82	23.26	0.000
Manure × fertilizer	-	166	1	76	6.29	0.014
Manure × BXW	-	67	1	81	2.52	0.116
fertilizer × BXW	-	99	1	86	3.74	0.057
Sub-county × catena position	-	83	6	80	3.12	0.009
Sub-county × mat density		115	3	80	4.35	0.007

between sub-counties, confirming the results at field level (Tables 7, 8). In all sub-counties except the wettest sub-county (Rwimi sub-county), increasing cumulative rainfall and lower mat densities resulted in heavier bunch weights (Fig. 8).

Table 8

ANOVA table of a linear mixed model with average bunch weight (kg) per field as dependent variable. Based on dataset bunch weight survey. ‘Num. DF’ refers to the numerator degrees of freedom and ‘Den. DF’ to the approximate denominator degrees of freedom for the F-test. P values below 0.05 are shown in bold.

Variable	Effect pos (+) or neg (-)	Mean Sq.	Num. DF	Den. DF	F value	Pr (>F)
Sub-county		33	3	13	1.625	0.234
Mulch cover	+	143	1	120	7.111	0.009
Weed cover	-	102	1	120	5.101	0.026
Manure	+	105	1	122	5.230	0.024
Soil K (mg/kg)	+	11	1	120	0.569	0.452
Weevil damage	+	33	1	118	1.664	0.200
Mat density	-	189	1	123	9.420	0.003
Subcounty × mat density		146	3	120	7.298	0.000

4. Discussion

4.1. Yield estimations

Median yields in West and South-West Uganda were respectively 31 and 32 ton/ha/year in year 1 and 38 and 36 ton/ha/year in year 2. Yield differences between years were most likely caused by differences in rainfall as the year prior to yield monitoring (year 0) was relatively dry. Year 0 was especially dry in Birere and the yield difference between year 1 and year 2 was largest in this study site. The 95th percentile of yields, taken over the four study locations and the two years of yield monitoring, was 66 ton/ha/year, showing that some farmers came very close to the suggested maximum attainable yields of 70 ton/ha/year (Smithson et al., 2001; Van Asten et al., 2005).

Our yield estimates are relatively high compared with findings by Wairegi et al. (2010), who estimated mean yields of 22 ton/ha/year in

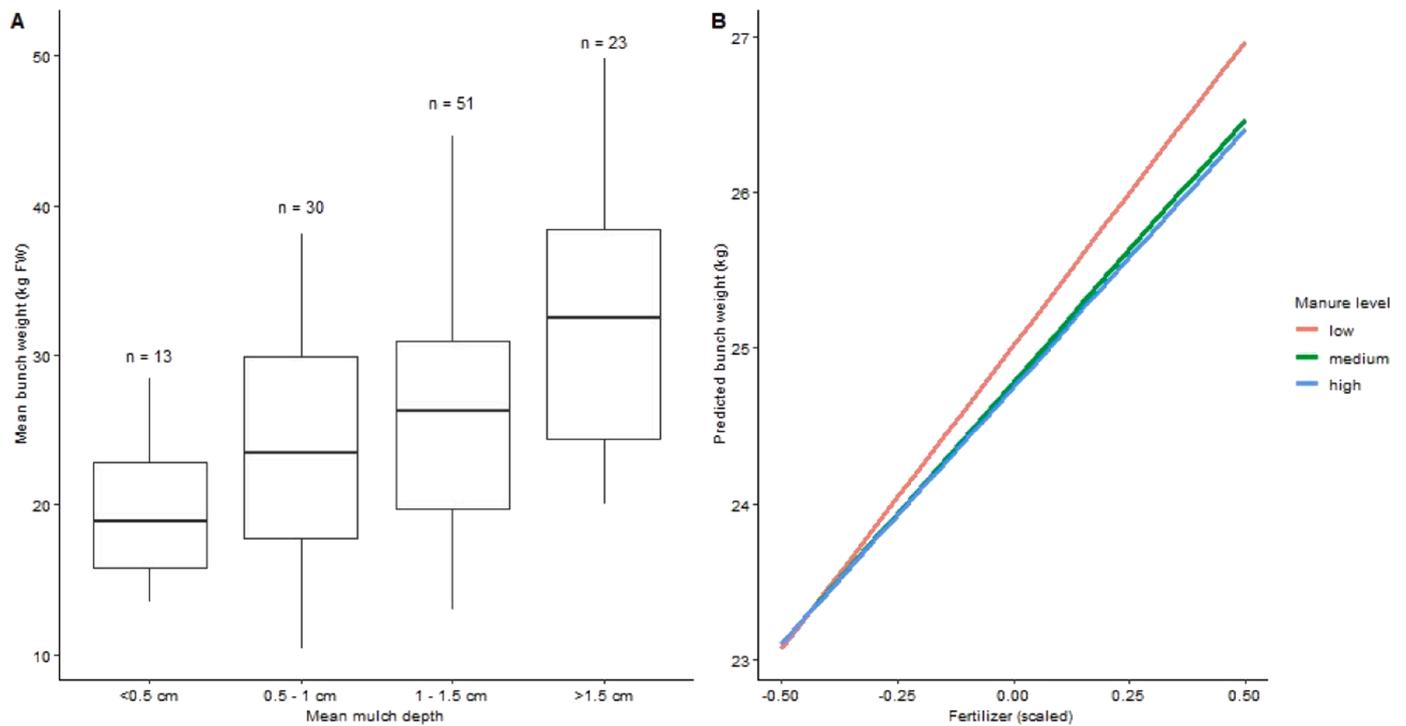


Fig. 6. Significant effects found in the analysis of the yield monitoring dataset. A) Mean bunch weights in fields with different mean mulch depths. B) Interaction between fertilizer and manure. Predicted bunch weights are derived from the linear mixed model, under different fertilizer levels, and at different levels of manure application, while keeping the remaining variables at average values. The x-axis displays the scaled fertilizer data. The high, medium and low levels for manure application are respectively 3rd quartile, average and 1st quartiles values for this variable.

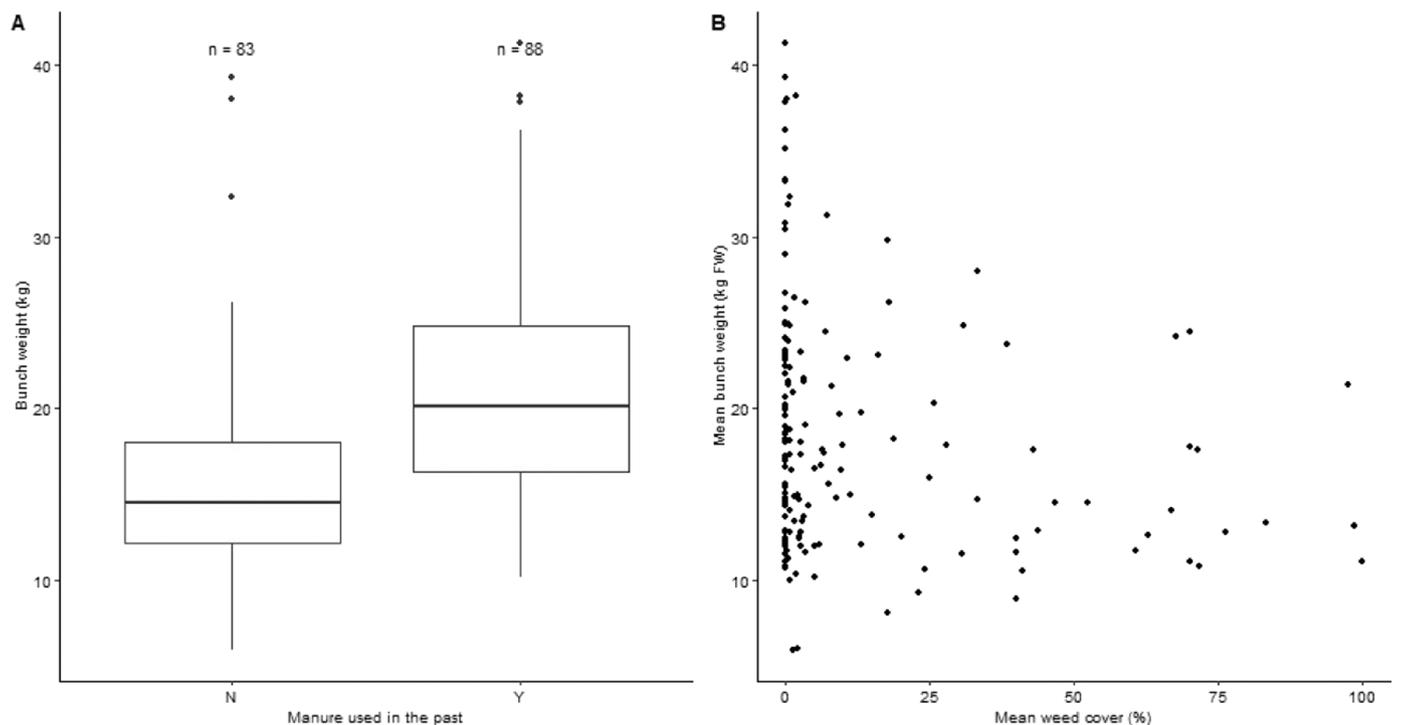


Fig. 7. Significant effects found in the analysis of the bunch weight survey dataset. A) Mean bunch weights in fields where past manure was applied and in fields where manure was not applied in the past. B) Relation between mean weed cover and mean bunch weights.

South-West Uganda. A possible explanation for this difference is that in the study by Wairegi et al. (2010), farmers were trained to record bunch weights, and researchers visited the fields every 3–5 months to monitor the state of the fields and their recent past management. Recording

bunch weights by trained farmers is not ideal for reasons explained by (Wairegi et al., 2009), while the minimum interval to visit fields for data collection and monitoring purposes was 75 days (Wairegi et al., 2009). Hence, the Wairegi et al. (2010) method could have resulted in

Table 9

ANOVA table of linear mixed model with bunch weight (kg) as dependent variable. Analysis was performed at level of suckers. Based on dataset yield monitoring, coupled with precipitation data. 'Num. DF' refers to the numerator degrees of freedom and 'Den. DF' to the approximate denominator degrees of freedom for the F-test. P values below 0.05 are shown in bold.

Effect pos (+) or neg (-)	Mean Sq.	NumDF	DenDF	F value	Pr (>F)
Sub-county	75	3	2	2.650	0.252
Cumulative rain	2	1	2168	0.081	0.777
Mat density	11	1	2166	0.396	0.529
Mulch depth	451	1	1888	15.944	0.000
Cumulative rain × mat density	48	1	2278	1.681	0.195
Cumulative rain × mulch depth	308	1	2140	10.885	0.001
Sub-county × cumulative rain	528	3	2161	18.636	0.000
Sub-county × mat density	157	3	2006	5.529	0.001
Sub-county × mulch depth	96	3	1630	3.383	0.018
Sub-county × cumulative rain × mat density	327	3	2282	11.555	0.000
Sub-county × cumulative rain × mulch depth	131	3	2140	4.643	0.003

harvested bunches not being recorded, resulting in lower yield estimates. The exact equation for calculating yields was not reported by (Wairegi et al., 2010), and our study showed that different methods result in different estimates (Appendix 2), so this could have also contributed to differences between studies. The latter fact highlights the importance of establishing a clear protocol for yield estimations in banana (Hauser and Van Asten, 2010).

A limitation in our dataset was the absence of data on ‘crop cut yields’ (i.e. a situation in which all mats are monitored and all bunches from a field of known area are weighed for one year) because this makes comparing the yield estimation methods with an absolute benchmark impossible. In addition, the lack of on-field replicates for yield

estimations in our study could result in inflated estimates of field-to-field variation (Nziguheba et al., 2021). This implies that the ‘true’ variation in yields might be smaller than our results suggest, and that our 95th percentile yield estimate may be an overestimation of true maximum yields. Nevertheless, this caveat also applies to the few other studies reporting on banana yields in farmers’ fields. Moreover, to our knowledge, potential and attainable water limited yields for East-African Highland banana in Uganda are unknown, so we don’t know how high the yields reported in our study are compared to potential and attainable water-limited yield. A modelling study suggested potential yields of over 100 ton FW/ha (Nyombi, 2010). Our study sites are well-known in Uganda as major banana growing areas with high productivity. Hence, we think that the yields reported in this study are relatively high, and extrapolation to other banana production areas with different agroecological zones, such as Central and East-Uganda, is not realistic. However, our yield estimates for the southwestern region maybe applicable to other main production areas nearby, such as Bushenyi and Ntungamo. Future research should compare crop cut yield data with the different yield estimation methods to verify the accuracy of the described methods. In addition, for reliable mat density assessment, it is important to design optimal sampling strategies and to establish minimal sample sizes. Finally, further modelling studies should aim to unravel potential yields, both under water limited conditions and under water and nutrient limiting conditions.

Based on our results, we conclude that one-off surveys (i.e. single field visits) to estimate yield in kg/ha/year would not result in reliable yield estimations. Bunch weight reduces with increase in mat density in the drier subcounty thus confounding the yield-increasing effect of higher mat density. The only yield component that can be reliably estimated in a single visit is mat density, but this variable is only weakly correlated with yield. The assessment of bunch weights in a single visit may not result in yields representative for a whole year because our results show that bunch weights fluctuate over time (Appendix H). This is in agreement with Birabwa et al. (2010) who also found that bunch weights fluctuated over seasons. They correlated these fluctuations with rainfall distribution and the flowering seasons. Suckers that flowered in a dry period had lower bunch weights compared with those that flowered in a wet period (Birabwa et al., 2010).

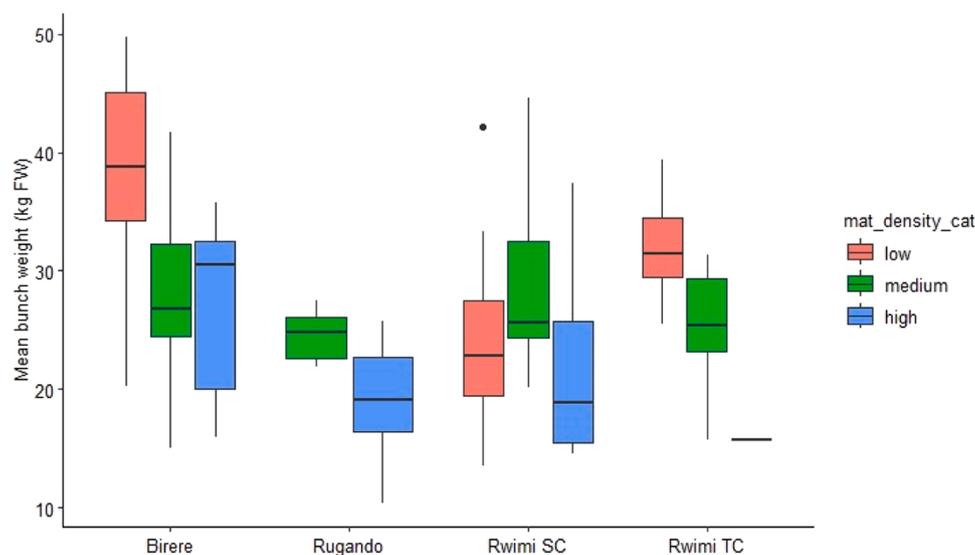


Fig. 8. Interactive effects of sub-county and mat density on mean bunch weight from the yield monitoring dataset. FW = Fresh weight; SC = Sub County; TC = Town Council; mat_density_cat = Mat density category; low mat density: 570 – 890 mats/ha (n= 40); medium mat density: 890 – 1111 mats/ha (n= 39); high mat density: 1111 – 1900 mats/ha (n=39).

4.2. Yield component interrelations

Yields were most strongly correlated with the yield components 'bunch weight', the 'number of bunches per mat per year' and with 'the annual yield per mat'. To our surprise, we found that mat density was only weakly correlated with yields, and that both high and low mat densities can result in high yields. This weak correlation was negative (-0.18), which is in line with findings by (Ndabamenye et al., 2013a), who also reported lower yields of East-African Highland banana cooking cultivars with higher densities, although for beer cultivars, a reverse relation was found. However, banana farmers in Uganda are not used to assess productivity in terms of annual yields in kg per ha, but rather in terms of 'big bunches'. In addition, markets may favour large bunches over small bunches (Ndabamenye et al., 2012). Further research is needed to find the optimal range of mat density for different agroecological zones in Uganda. We found large differences in mat density between sub-counties, suggesting that farmers have different strategies regarding mat density management. The optimal density is likely to depend on the farmer's production objective. Optimizing for large bunches may require lower mat densities than optimizing for highest total yield, because of the strong inverse relation between mat density and bunch weights (correlation coefficient of -0.57). Our results show that the fields with the highest bunch weights (>40 kg) always had mat densities below 1100 mat/ha. The standard advice for mat density in Uganda is 1111 mats/ha in low rainfall areas, or 1600 mats/ha in higher rainfall areas (NARO, 2019) but our results show that lower densities in southwest Uganda can result in large bunches and relatively high yields.

4.3. Factors influencing banana productivity

Our study shows that BXW is an important yield reducing factor in two major banana-producing regions in Uganda. BXW is a bacterial disease affecting all known East-African Highland Banana (Tripathi et al., 2009). The distribution of the disease is spatially clustered and variable in time (Shimwela et al., 2016) and this spatial-temporal clustering may explain why we find clear evidence that BXW stands out as a factor influencing yields, while a previous on-farm study did not find this result (Wairegi et al., 2010). Another factor explaining this discrepancy in findings could be that farmers participating in the study by Wairegi et al. (2010) were trained for controlling BXW, which probably contributed to the low BXW pressure in that study. Yields in our study were affected by BXW because farmers removed suckers infected by BXW, hence the number of bunches harvested was lower. In addition, mean bunch weights from BXW-infested fields were lower than those from BXW-free fields. We noted a clear interaction between BXW and fertilizer in influencing yields. Our results show that BXW overrides the effect of (small) doses of fertilizer. Even though fertilizer rates and blends were different between fields, our results suggest that applying modest amounts of fertilizer only has positive effects in fields where BXW is absent. We found no evidence that applying fertilizer reduced BXW infestation. This finding is contrary to findings by Atim et al. (2013) who showed that nutrient application (N,K, Ca) strongly reduced susceptibility to BXW in in-vitro banana plantlets, suggesting that BXW could be managed through nutrient applications. Most likely, the modest nutrient applications in our fields were not enough to induce this effect. Our findings are more in line with Ochola et al. (2014) who showed in a pot experiment that BXW severity and incidence were not affected by various N, P and K treatments.

Manure application had a significantly positive effect on bunch weights, as shown by the results from the bunch weight survey. However, the effect of manure on bunch weights and yields was less clear in the yield monitoring dataset. The contrast in findings from the two datasets can be explained by the fact that in the bunch weight survey, past manure applications were taken into account, while this was not the case in the yield monitoring survey. The lack of coherent findings regarding the influence of manure and its interaction with fertilizer

underscores that further experimentation with different combinations of manure and fertilizer is needed. In addition, manure is in short supply, and supplementing manure with fertilizer is likely to have environmental and economic benefits over the use of manure only (den Braber et al., 2021). Experiments with manure and fertilizer have been conducted in Tanzania by Meya et al. (2020), who found that the combination of manure and fertilizer as a source of N was more effective than the sole use of manure or fertilizer. However, this experiment was conducted in locations where N was the main limiting nutrient, and their findings may therefore not be applicable to the main production areas in Uganda, where K is the main limiting nutrient (Wairegi et al., 2010; Taulya, 2013).

Mulch had strong significant positive effects on yield and on bunch weight. Our findings are in line with experimental evidence showing that banana yields increased in treatments with a full mulch cover as compared with no-mulch treatments. For instance, mulch increased soil water content in the upper 30 cm soil layer (Ssali et al., 2003), suggesting that mulch could play a role in mitigating water stress (van Asten et al., 2011). Nutrient addition could explain the positive effect of mulch, but only if external mulch is used, since the use of self-mulch merely recycles nutrients. The use of large quantities of external mulch (i.e. mulch layers of 10 cm depth) can improve soil nutrient content (McIntyre et al., 2000). However, it is unlikely that this played a role in our study, since median mulch depth was around 1.1 cm, while the use of external mulch was limited. The use of external mulch did not have benefits over the use of self-mulch. This is in agreement with findings by (Muliele et al., 2015), who found that the source of mulch (external/internal) had no effect on bunch weights, while there was a clear difference between mulch and no-mulch treatments. While the strong positive effect of mulch may have practical relevance, it is not said that the observed relation is actually causal. Since bunch weight and plant biomass are positively related (Nyombi et al., 2009), plantations with high yields and high mean bunch weights are also likely to produce large quantities of self-mulch, making high quantities of mulch a consequence, rather than a cause of high yields. Unfortunately, our data does not allow us to disentangle if self-mulch is causing higher yields and bunch weights through the mitigation of water stress, or if large quantities of self-mulch are merely a by-product of a productive plantation. Recent results from a modelling study found that removal of self-mulch may reduce yields by 10% which would support the interpretation that self-mulch is actually causing higher yields by mitigating water stress (Taulya, 2015).

We found that bunch weights were influenced by interactions between sub-county, mat density, and cumulative rain. Similarly, Ndabamenye et al. (2012) showed that the relation between mat density and bunch weights differed between agro-ecologies, and they suggested that optimal densities were higher in areas with more rainfall and higher soil fertility. In the study site receiving most rainfall -Rwimi sub-county- our statistical model predicted that bunch weights were not significantly influenced by increases in rainfall, nor by changes in mat density (Appendix G). This may explain why mat density in Rwimi sub-county was much more variable than in the other sub-counties. To better understand the interactive effects between mat density and rainfall on bunch weights, we draw attention to the differences between the two sites in South-West Uganda. Birere is drier than Rugando (Table 5) and mat densities were much lower (Fig. 2B), but in terms of mean bunch weights (Fig. 2B) and yields (Fig. 2D), Birere outperformed Rugando. Mat densities tend to increase over time because mats regularly split (Hauser and Van Asten, 2010). The fact that most plantations in Birere and Rugando were more than 15 years old (data not shown) implies that farmers in Birere actively maintain low mat densities, knowing how marginal their region is in terms of rainfall. Much higher mean bunch weights and slightly higher yields in Birere as compared to Rugando suggest that farmers in Birere have found an appropriate response to otherwise unfavourable (i.e., dry) growing conditions. This is further supported by our statistical model predictions for Birere, which showed that under dry

conditions and with high mat densities, there was a strong reduction in bunch weights. However, under dry conditions and at low mat densities, bunch weights hardly decreased (Appendix G).

5. Conclusions

This study was conducted to explore which yield components are most important in determining banana yields in farmers' fields, to provide reliable yield estimates and to understand which agronomic factors have a discernible influence on yields in two major banana producing region in Uganda. We also explored various yield estimation methods and identified easy-to-measure yield components. It is important to understand how the abovementioned factors shape yields in farmers' fields because farmers' management practices are more diverse than what can be tested in experiments.

Median yields in West and South-West Uganda were respectively 31 and 32 ton/ha/year in year 1 and 38 and 36 ton/ha/year in year 2, which is higher than previously reported, but still half of maximum suggested attainable yields. We found that different yield estimation methods result in large differences in outcomes. Yields were most strongly correlated with the yield components 'bunch weight', the 'number of bunches per mat per year' and with the 'annual yield per mat'. Our results suggest that optimal densities are dependent on rainfall and agroecology, but also on farmers' objectives because bunch weight declined strongly with increasing mat densities. This was stronger in Birere subcounty than Rwimi subcounty, which were respectively the driest and wettest in our study. Our results regarding manure and mulch application effect on bunch weight and yield are inconclusive. In the absence of BXW, which was a major yield reducing factor, modest amounts of fertilizer had positive effects on yields and on bunch weights within 24 months.

Implications and significance

There is need to standardize banana yield estimation methods, focusing on fresh bunch weights, mat densities and annual number of bunches harvested per mat, which were relatively easy to assess, unlike cycle duration, loss fraction and the number of suckers per mat. In addition, experiments with different quantities and combinations of manure and fertilizer should be conducted since manure is a preferred soil fertility input but seems to take effect after 24 months, whereas mineral fertilizers do so within 24 months in the absence of BXW. Future initiatives aiming to improve banana yields should focus on controlling BXW prior to advocating input use. Using inputs on BXW infested fields is likely to result in poor yield responses. High yields and heavy bunches were associated with mulching, but further studies are needed to understand the causality underlying this correlation.

Funding sources

The study was conducted within the framework of the project

"Improving Scalable Banana Agronomy for Small Scale Farmers in Highland Banana Cropping Systems in East Africa" led by the National Banana Research Program (NBRP) of the National Agricultural Research Organization (NARO) with financial support from the Bill & Melinda Gates Foundation (BMGF), Grant ID: OPP1134098. The funding agency had no role in study design, data collection, preparation of the manuscript or decision to publish. <https://www.gatesfoundation.org/about/committed-grants>. We also acknowledge funding from the International Institute of Tropical Agriculture (IITA) and the Plant Production Systems Group of Wageningen University & Research.

CRedit authorship contribution statement

Godfrey Taulya: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Harmen den Braber:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gerrie van de Ven:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization. **Joost van Heerwaarden:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Wytze Marinus:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Esther Ronner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Katrien Descheemaeker:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

We are thankful to Martin Maku for conducting the yield monitoring. We thank Allan Jabungu and Zahara Najjuma for the banana mat density enumeration. We thank all participating farmers for sharing information and for allowing us to collect data in their fields.

Appendix A. Reference mat and distance to four nearest mats

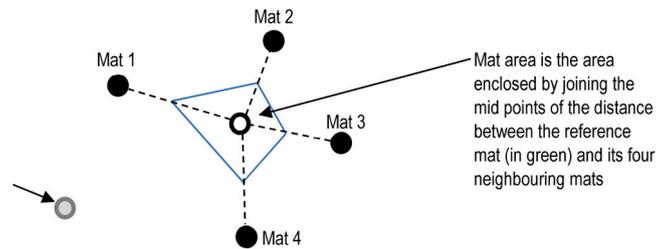


Fig. A.1. Example of a selected reference mat (white dot), its four nearest neighbours (black dots) and a mat that should not be selected as nearest neighbour (grey dot). The blue line indicates the mat area.

Appendix B. Estimation of banana mat density from inter-mat distances

The actual density (Observed density) was determined from physical counts of the number of banana mats in sections of selected banana fields of known area. Inter-mat distances were determined and used to estimate mat density in 2 ways (Predicted density 1 and Predicted density 2) as described below:

1. 30 farms in Isingiro district (South western Uganda) and 26 in Kabarole district (Western Uganda) were randomly sampled for enumeration.
2. On each farm a section of the banana field was demarcated such that it was representative of the variability observed for the entire field.
3. The area of the demarcated section was determined using a mobile phone App.
4. Banana mats in the demarcated area were then counted in duplicate by two enumerators whose consensus value was then recorded.
5. The observed mat density was computed as the number of mats counted divided by the area of the demarcated section of the field converted to hectares.
6. 15 reference mats were randomly selected within the demarcated section of the field and the distance to the 4 nearest neighboring mats (Appendix A) from each reference mat measured.
7. The density for each enumerated field was computed as the ratio of 10,000 to the square of the average inter-mat distances for the field as Predicted density 1.
8. The mat density was also extrapolated to 1 hectare for each of the 15 reference mats as the ratio of 10,000 (m^2 per hectare) to the square of the average distance (in m) to the 4 nearest mats of a given reference mat. The average extrapolated density for all 15 reference mats was then determined as Predicted density 2 for the enumerated section of the field.

Comparison of the observed density vs. either of the predicted densities (Predicted density 2 or 1) was poor (Fig. B.1). Prediction from inter-mat distances systematically over-estimated the actual mat density.

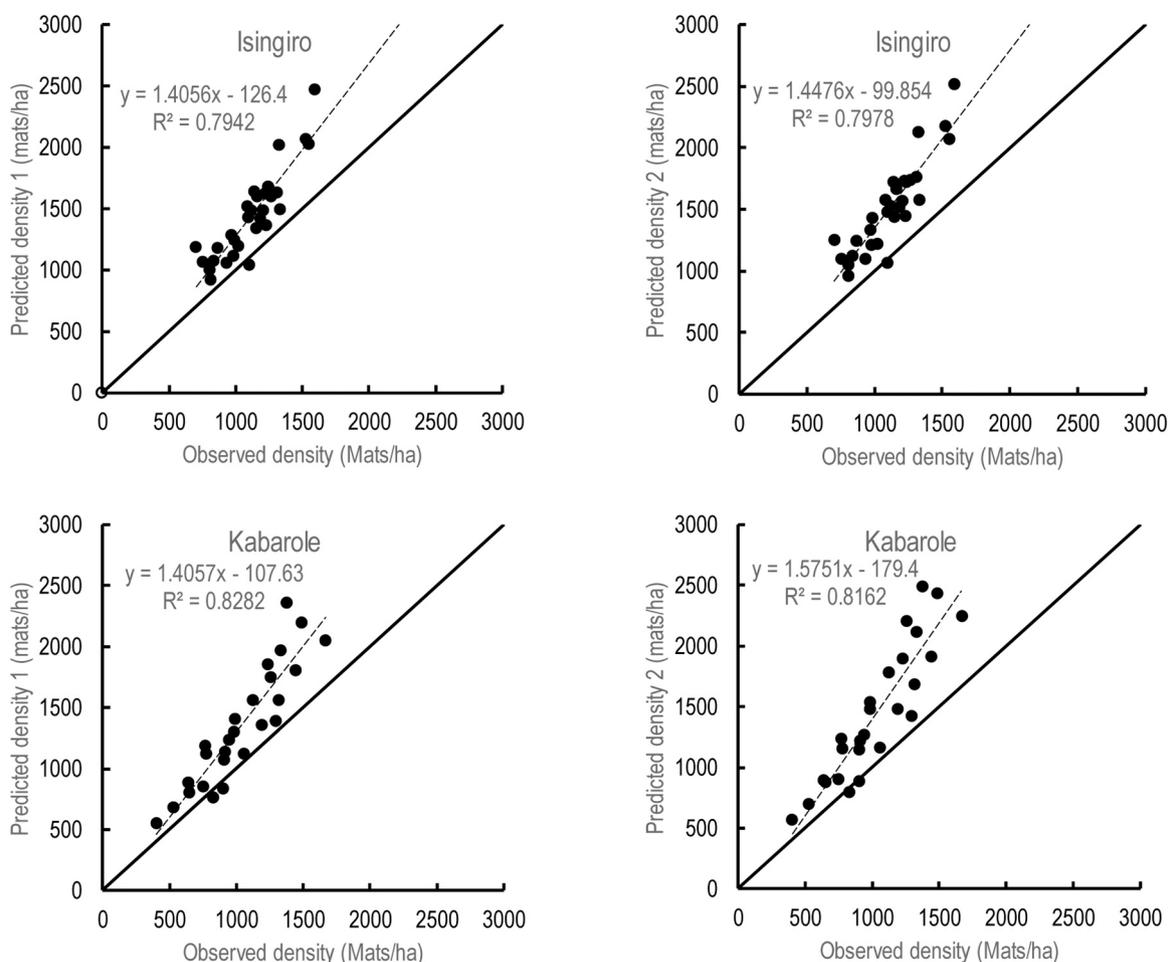


Fig. B.1. Comparison of predicted density 1 and predicted density 2 approaches against the observed densities in Isingiro (Southwestern Uganda) and Kabarole (Western Uganda) districts.

The over-estimation of mat density from inter-mat distances was adjusted as follows:

The observed density vs inter-mat distance dataset was randomly split into a calibration sub-dataset (n=28 of which 13 were from Rwimi sub-county, Kabarole district in western Uganda and 15 from Birere sub-county, Isingiro district in southwestern Uganda) and a testing sub-dataset (n=28 of which 13 were from Rwimi sub-county in western Uganda and 15 from Birere sub-county in southwestern Uganda).

The Predicted density 1 and Predicted density 2 were computed as described above.

Linear regression in R was used to generate a function (Model B1) for estimating the observed banana density from Predicted density 1 in the calibration sub-dataset (Table B.1).

Linear regression was used to generate a function (Model B2) for estimating the observed banana density from Predicted density 2 in the calibration sub-dataset.

In both step 3 and 4 above, including site (western or southwestern) in the model did not significantly improve the reduced model without site as an input according to the partial F-Test. Therefore, in both cases, only the reduced model is presented.

The resulting functions from 3 and 4 were used to adjust the Predicted Density 1 and 2, respectively in the Testing sub-dataset as Adjusted Banana density 1 and 2, respectively.

Correspondence between the Observed density and either Adjusted density 1 or 2 was evaluated using unit plots.

Table B.1
Coefficients for the linear regression of Observed banana density on predicted density 1 and 2

Model	Intercept		Slope		F pr.	Adj. R ²
	$\alpha \pm se$	t-value (df=26)	$\beta \pm se$	t-value (df=26)		
1	264.447 ± 85.5162	3.092***	0.588 ± 0.0601	9.874***	<0.001	0.7782
2	339.105 ± 88.0842	3.850***	0.498 ± 0.0575	8.663***	<0.001	0.7328

Model B1: Observed density = $\alpha + (\beta * \text{Predicted density 1})$.

Model B2: Observed density = $\alpha + (\beta * \text{Predicted density 2})$.

Where α and β is the linear regression intercept and slope, respectively.

Both models performed quite well in estimating the observed density (as adjusted density 1 or 2) on the Testing sub-dataset, regardless of site (Fig. B.2).

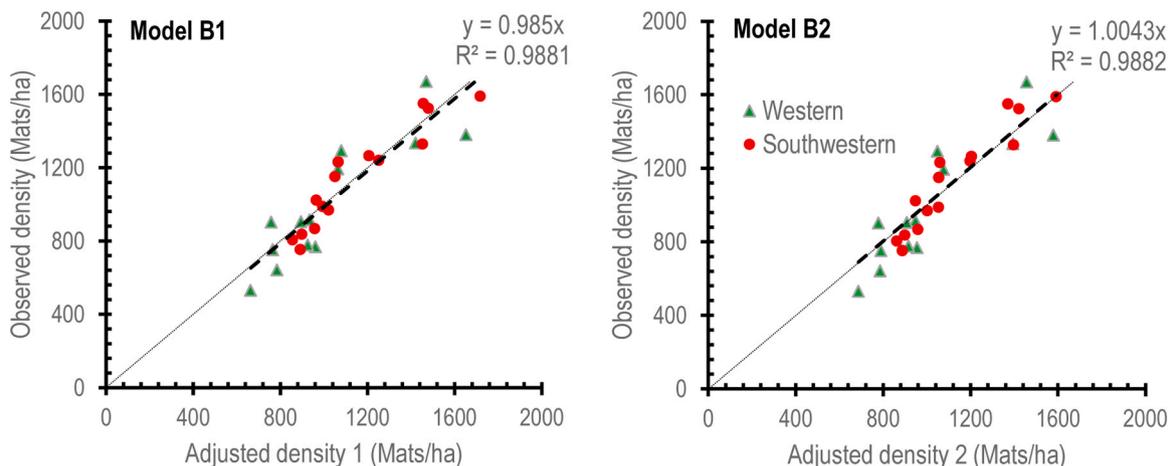


Fig. B.2. Comparison of adjusted density 1 and adjusted density 2 against the observed densities in Southwestern Uganda and Western Uganda on the testing sub dataset

The thin dotted line is the 1:1 line while the thick dashed line is the best-fit across sites.

Both models performed well on an independent dataset from other enumerators collected on a different occasion from 11 different farms in western Uganda (Fig. B.3)

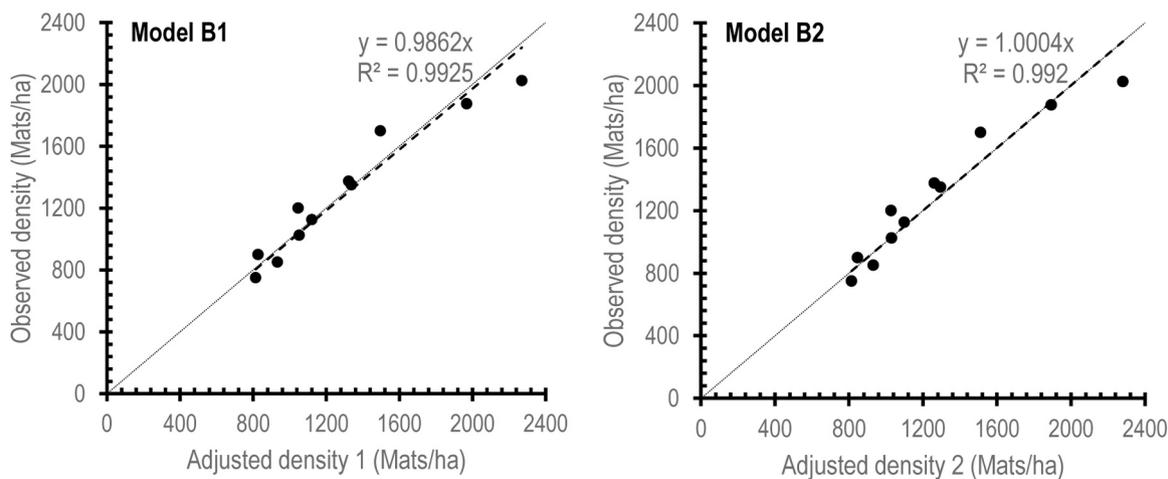


Fig. B.3. Comparison of adjusted density 1 and adjusted density 2 against the observed densities independently collected from 11 farms in Western Uganda

The thin dotted line is the 1:1 line while the thick dashed line is the best-fit through the plotted points.

Since there were minor differences between Model B1 and Model B2, we chose to use Model B2 to adjust the banana densities for subsequent analyses requiring estimates of banana density in this study.

Appendix C. Yield calculations

Four methods were used and compared for consistency and ease of application in farmers’ fields. These are M1, M2, M3 and M4. For M1, the fresh weights of all bunches harvested from a mat in a certain year were summed. Then, the average yield of all mats (kg FW/mat/year) was calculated for each monitored field. Yield (kg FW/ha/year) was then calculated as:

$$M1 : Yield = mat \text{ yield} * mat \text{ density} \tag{C.1}$$

The second method resembles standard crop-cut methods. Multiplying mat density by the number of bunches harvested per mat per year gives the total number of bunches harvested per hectare. Multiplied by the average bunch weight in a field, this also gives yield in kg FW/ha/year:

$$M2 : Yield = \#bunches \text{ per mat per year} \times mat \text{ density} \times bunch \text{ weight} \tag{C.2}$$

M3 and M4 were adapted from (Ndabamenye et al., 2013a) who calculated yields based on plant density, bunch weights and cycle duration. In M3, multiplying the average number of suckers per mat by the mat density gives the sucker density. All suckers could in theory produce a bunch, but following the suggestion by Hauser and Van Asten (2010), a ‘loss fraction’ was introduced, because in practice, not all suckers produce a bunch. This loss fraction was calculated at field level:

$$\text{Loss fraction} = \frac{\# \text{suckers not bearing a bunch}}{\# \text{emerged suckers}} \quad (\text{C.3})$$

Multiplying sucker density (Eq. 3, Section 2.2.1) with average bunch weight and correcting this with the loss fraction gives yields per cycle (FW yield/ha/cycle). To calculate yields per year, a correction for cycle duration, expressed in days, is needed, resulting in the following formula:

$$\text{M3: Yield} = \text{sucker density} \times \text{bunch weight} \times \frac{365}{\text{cycle duration}} \times (1 - \text{loss fraction}) \quad (\text{C.4})$$

A last method is to calculate yields based on the number of mother plants. A mother plant is a sucker that flowers within the reference year. Since the number of flowering suckers per mat per year is directly dependent on cycle duration, a correction for cycle duration is no longer needed:

$$\text{M4: Yield} = \# \text{mother plants/mat/year} \times \text{mat density} \times \text{bunch weight} \times (1 - \text{loss fraction}) \quad (\text{C.5})$$

Yield calculation methods M1 and M2 gave very similar results, whereas the correlations between M1 and M3 and between M1 and M4 were weaker (Fig. C.1). The yield components 'mat density' and 'bunch weight' cannot have influenced these differences because they were included in all yield estimation methods. M3 overestimated yields compared to M1 (Fig C.1B), which was most likely caused by inaccuracies in estimating the variables 'number of suckers/mat', 'loss fraction' and/or 'cycle duration' (in M3). This resulted in an overestimation of the 'number of bunches harvested/mat year', leading to an overestimation of annual yields per mat. Median loss fractions in year 1 and year 2 were 0.10 and 0.13 respectively, with large fluctuations between fields. The main reasons for non-producing suckers were removal by farmers due to BXW and toppling due to wind or nematode damage.

M4 had the lowest correlation with M1 and M2 (Fig. C.1 C), which was probably due to the fact that not all mother plants (i.e. flowering suckers in the reference year) bear a bunch. If suckers started flowering in the last one or two months of the reference year, these suckers would not bear a bunch in the reference year, leading to an overestimation of M4 as compared to M1 and M2. Conversely, plants that started flowering before the start of the reference year but yield a bunch in the reference year led to underestimations.

M3 and M4 required more variables, which were also difficult to assess reliably in the field and they required monitoring over time. We deemed the simpler and more direct methods (M1 and M2) to be more reliable, and the methods based on cycle duration, number of suckers and loss fraction (M3, M4) difficult to use. For instance, the number of suckers per mat changes constantly as new suckers emerge throughout the year and because farmers remove suckers to manage densities. In addition, cycle duration estimations in the first year of yield monitoring were not reliable because estimating emergence dates of already established suckers is difficult (Appendix D). Even though variables used in M1 and M2 also required monitoring over time, the yield components needed for these methods were more straightforward to assess and more reliable. M1 required only two yield components that were relatively easy to assess, and we therefore used the yields obtained by M1 in this study.

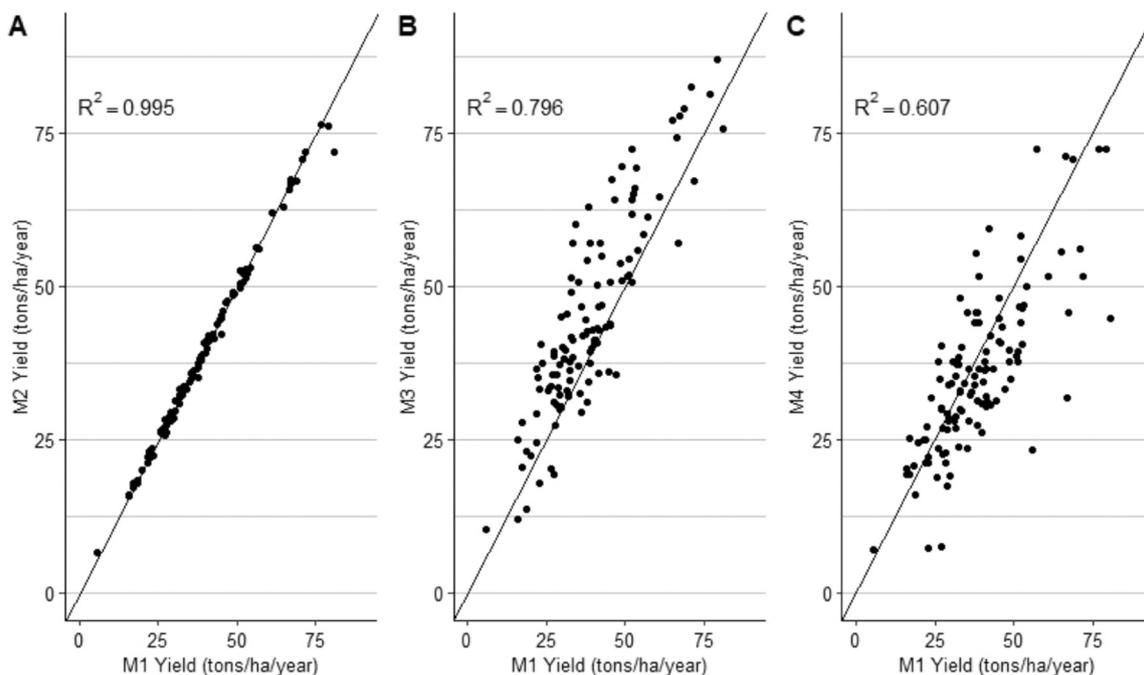


Fig. C.1. A) Comparison between yield calculation methods M1 and M2, (B) between M1 and M3 and (C) between M1 and M4.

Appendix D. Cycle duration estimations

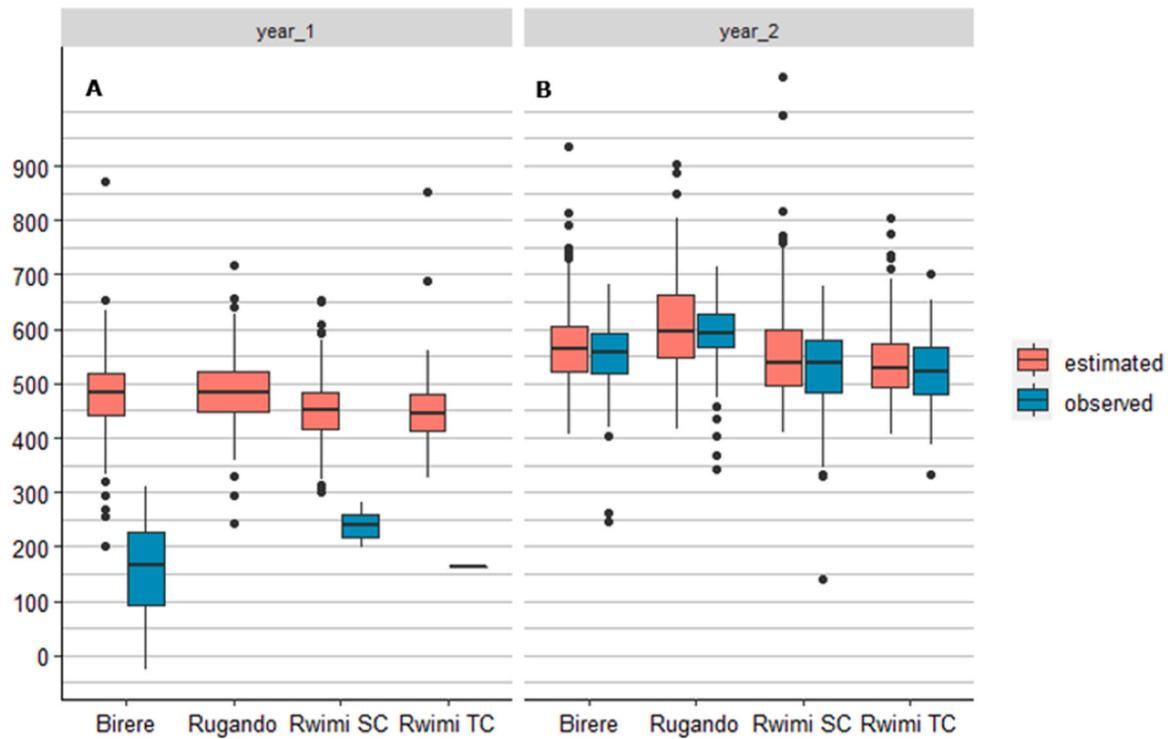


Fig. D.1. Estimated and observed cycle duration in year 1 (July 2019 – June 2020) and year 2 (July 2020 – June 2021). At the start of the yield monitoring, emergence dates of already established suckers were estimated. Cycle duration is regarded as ‘observed’ when dates of emergence and harvest were both observed.

- Observed and estimated cycle durations in year 1 are lower than in year 2. In year 1, number of observed cycle durations is very low. These are most likely not representative, because these pseudostems have cycle durations shorter than one year. Estimated cycle durations in year 1 are probably not reliable; it seems that the surveyors systematically underestimated the age of the already established suckers at the start of the yield monitoring.
- In year 2, no systematic difference between estimated and observed cycle durations.
- Observed and estimated cycle duration from year 2 can be regarded as reliable, for year 1, both estimated and observed are not reliable, and are not included in analysis.

Appendix E. Influence of density on yields

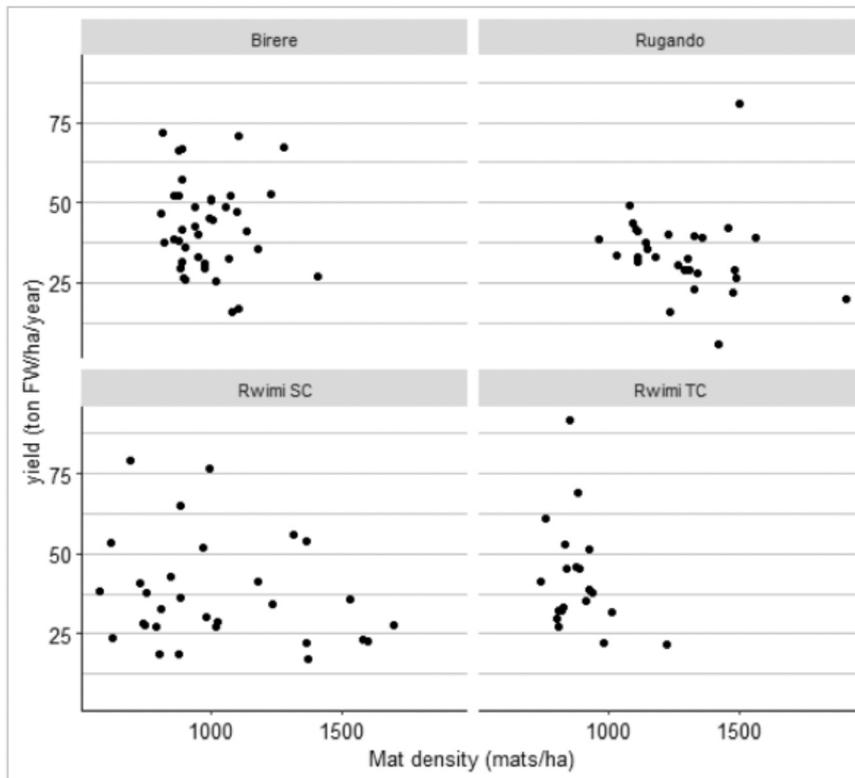


Fig. E.1. Relationship between yield (ton FW /ha/year) and mat density (mats/ha) in the four study sites.

Relation between sucker density and yield

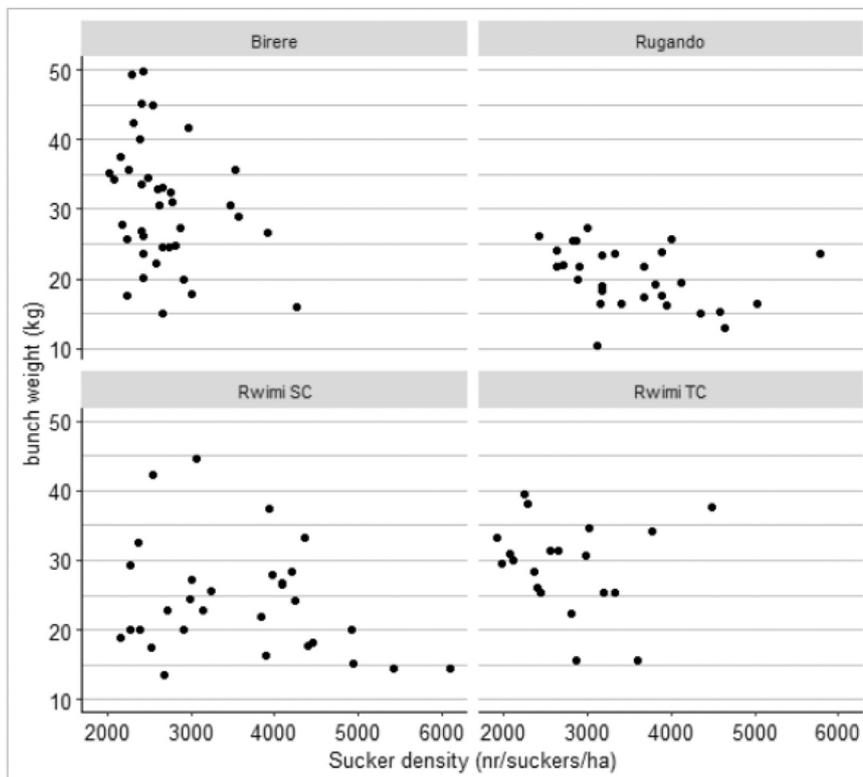


Fig. E.2. Relationship between yield (ton FW /ha/year) and sucker density (suckers/ha) in the four study sites.

Appendix F. Yield analysis on disease-free subset

Dependent variable: Yield (kg FW/ha/year) Dataset: Subset of yield monitoring dataset, only containing fields where no BXW was reported Level of analysis: Field level N = 73

$$Yield = \text{subcounty} + \text{mulch depth} + \text{weed height} + \text{manure} + \text{fertilizer} + \text{landscape position} + (\text{village/farm}) + \epsilon$$

Table F.1

ANOVA table of a linear mixed model with yield (kg/ha/year) as dependent variable. Based on a subset of the dataset yield monitoring, only containing fields where no BXW was reported

Variable	Effect pos (+) or neg (-)	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr (>F)
Sub-county		383516979	127838993	3	2	1.117	0.505
Mulch depth	+	657881235	657881235	1	47	5.747	0.021
Weed height	-	7706303	7706303	1	54	0.067	0.796
Manure	+	1670161	1670161	1	47	0.015	0.904
Fertilizer	+	806933051	806933051	1	55	7.049	0.010
Catena position		153207047	76603524	2	49	0.669	0.517
Manure × fertilizer	-	66344673	66344673	1	52	0.580	0.450

Appendix G. Significant three-way interactions from detailed bunch weight analysis

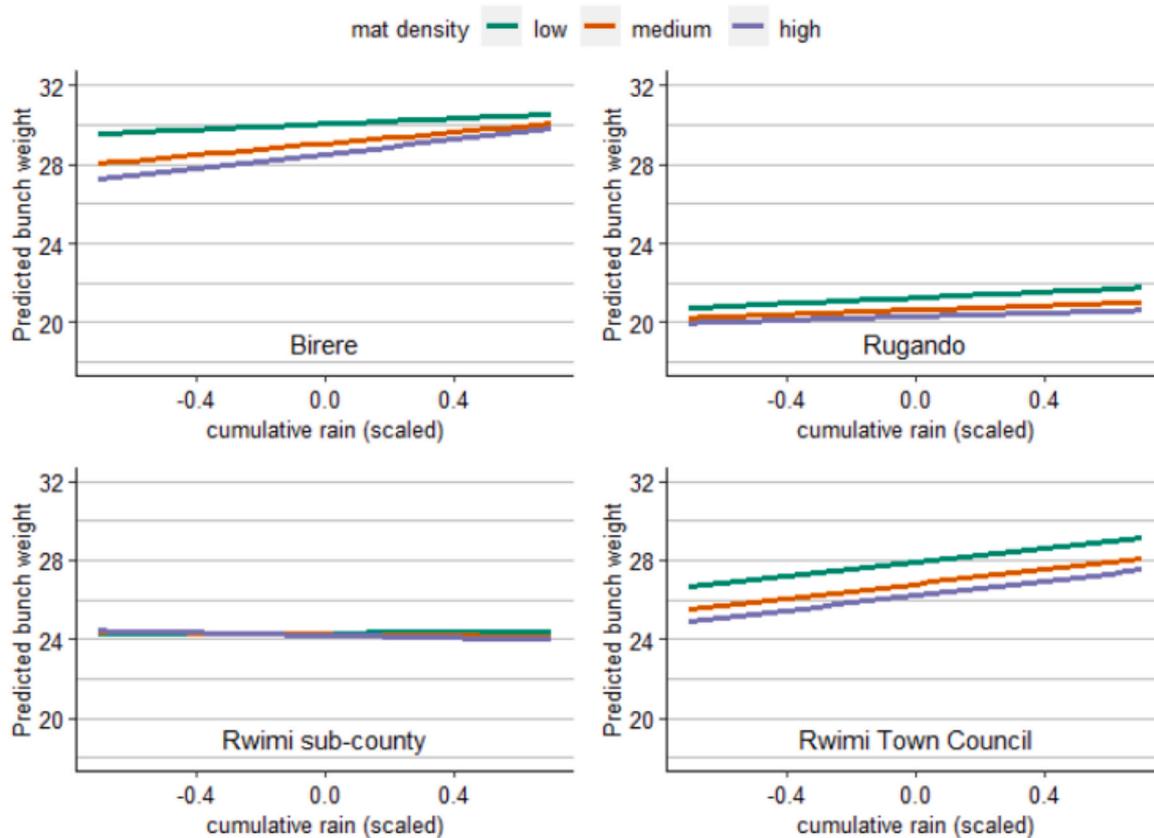


Fig. G.1. Interaction rain, sub-county and mat density.

For each sub-county, predicted bunch weights are presented as a function of cumulative rain, for different mat density levels. The high, medium and low levels for variable 'mat density' are respectively 3rd quartile, average and 1st quartiles values for this variable.

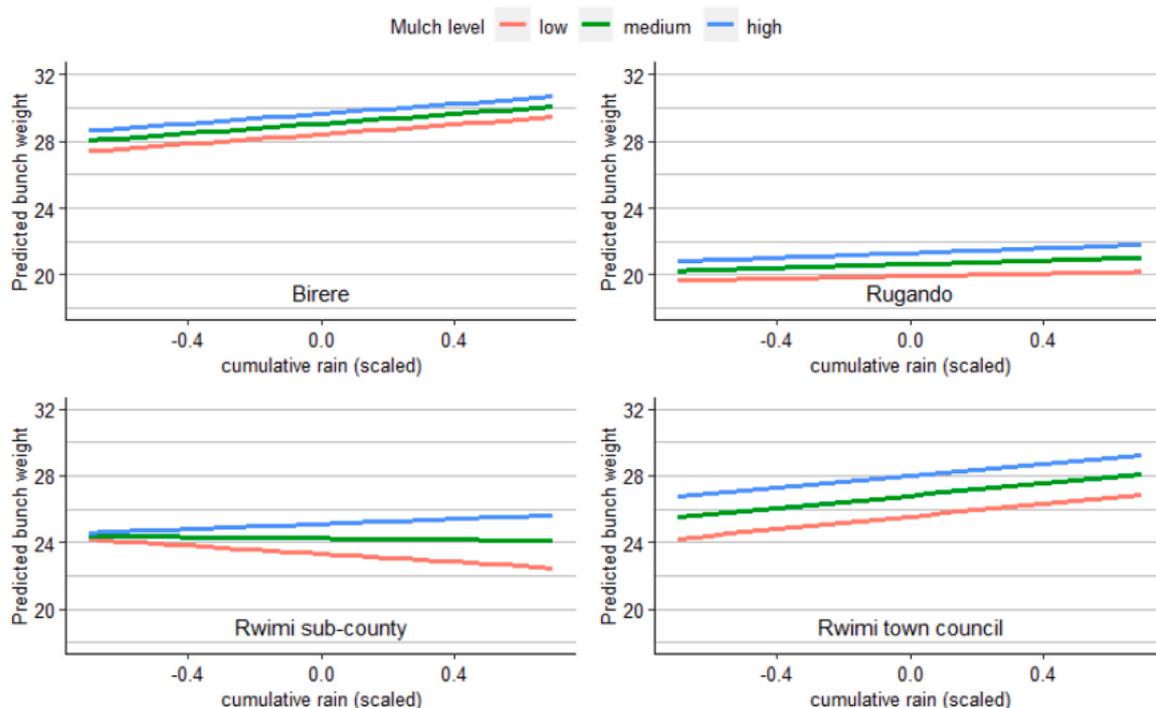


Fig. G.2. Interactions between sub-county, rain and mulch.

For each sub-county, predicted bunch weights are presented as a function of cumulative rain, for different levels of mulch application. The high, medium and low levels for variable 'mulch' are respectively 3rd quartile, average and 1st quartiles values for this variable.

Appendix H. Bunch weight fluctuations over time

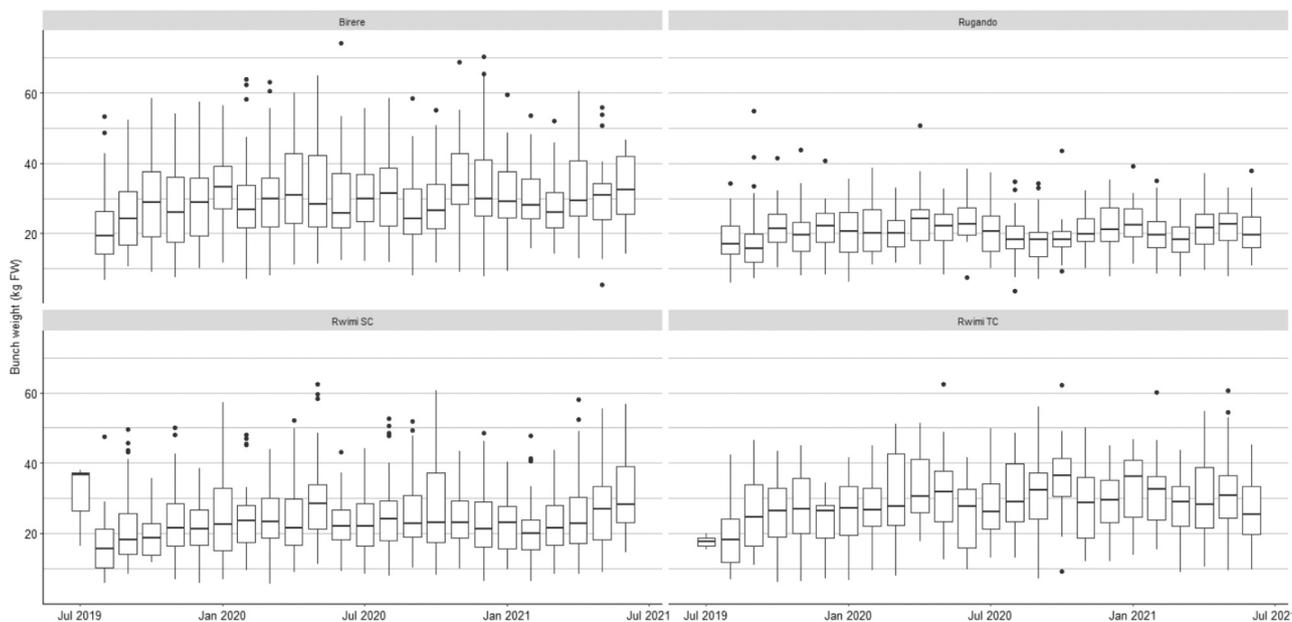


Fig. H.1. Bunch weights per month (kg FW) in the four study sites of the yield monitoring dataset.

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