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RESEARCH ARTICLE

Effect of suboptimal growing conditions induced by agroecological practices on the yield of 12 Cavendish banana cultivars

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Summary

In the French West Indies (FWI), practices alternative to chemical inputs are implemented to improve the sustainability of banana cropping systems. These agroecological practices are based on organic fertilization, soil covering with weed live mulch and severe prophylactic deleafing to limit sigatoka disease dissemination. However, these practices may impair the availability of soil mineral nutrients and the photosynthetic capacity of the plant and consequently induce suboptimal plant growth conditions. To assess the performance of the different banana cultivars from the Cavendish group in these suboptimal conditions, the yield components of 12 Cavendish banana cultivars were compared with four crop management modalities: i) high mineral fertilization, chemical weed control and minimum prophylactic deleafing (N + L+), ii) high mineral fertilization, chemical weed control and severe prophylactic deleafing (N + L−), iii) low organic fertilization, weed live mulch and minimum prophylactic deleafing (N−L+) and iv) low organic fertilization, weed live mulch and severe prophylactic deleafing (N−L−). The performance of all cultivars varied according to the crop management modalities in the following order: N + L+ > N + L− > N−L+> N−L−. However, the hierarchical order among the cultivars differed according to the crop management modality. Cultivar Americani exhibited the best performance in non-limiting conditions. Cultivars such as Ruby, Gua01 and Mat12 performed better with severe prophylactic deleafing while Gua02 and Ruby performed better with the low soil nutrient availability induced by organic fertilization and weed live mulch. These results can be used to guide the choice of Cavendish cultivar according to production constraints, particularly with regard to agroecological practices or abiotic stresses, such as reduced photosynthesis or limited nitrogen resource. These results suggest that there is a variability in the tolerance to abiotic stresses between the cultivars of the Cavendish group.

Keywords: Musa; deleafing; organic fertilizer; cover crop; variety; yield; yield gap

Introduction

The adoption of environment-friendly cropping practices is a major challenge for dessert banana growing. Indeed, the cultivation of dessert bananas for export has involved so far intensive monoculture with a high level of chemical inputs, that have detrimental effects. As mostly studied in the French West Indies (FWI), these cropping systems have caused soil and water pollution (Cabidoche *et al.*, 2009; Castillo *et al.*, 2000; Geissen *et al.*, 2010; Houdart *et al.*, 2009) and decreasing soil fertility (Delvaux and Dorel, 1990). Moreover, fertilization is a focus of reflection aimed at reducing applied quantities in banana crop, that reached 400 kg/ha^{-1} of nitrogen and

800 kg/ha^{-1} of potassium (Godefroy and Dormoy, 1988), so as to avoid issues related to mineral fertilizer as leaching, soil acidification and pollution (Cabidoche *et al.*, 2002; Sansoulet *et al.*, 2007) and to better adapt applied nitrogen quantities to crop requirements (Cabidoche *et al.*, 2002).

Alternatives to the use of chemical inputs are being adopted to an increasing extent, mostly in the FWI (Bellamy, 2013; Blazy *et al.*, 2010; Tarsiguel *et al.*, 2023). Prophylactic deleafing is a practice to control black sigatoka disease and reduce the use of foliar fungicides (Guillermet *et al.*, 2018). Living mulch can be used to control weeds in banana fields instead of herbicides. Living mulch can also enhance the species diversity and provide different services to benefit the banana crop (soil cover, pest control, soil structure improvement) (Damour *et al.*, 2015; Djigal *et al.*, 2012; Carval *et al.*, 2016). Living mulch can be composed of weed species mechanically controlled or sown cover crops species. Organic fertilizers (e.g. green waste, compost, chicken or cattle manure) are used to replace nitrogen-rich mineral fertilizers such as urea or ammonium sulphate. These organic fertilizers enable to improve soil health providing carbon resources to soil food web (Tabarant *et al.*, 2011) and to limit mineral nitrogen leaching due to the gradual release of mineral nitrogen from organic matter mineralization (Niedziński *et al.*, 2021).

Such practices can however lead to suboptimal growing conditions for banana. Prophylactic deleafing reduces the plant's photosynthetic leaf area, which in turn can decrease the amount of photoassimilates available to the plant and affect banana bunch weight. Living mulch may compete with banana plants for soil nutrients, mostly for nitrogen (Dorel *et al.*, 2023), and reduce the nitrogen availability for banana (Achard *et al.*, 2018). Mineral nitrogen release with organic fertilisers in banana crop is generally lower than with mineral fertilizers (Dorel *et al.*, 2023) and depends on factors such as temperature and soil water content that are not controlled by growers. Nitrogen is a major nutrient for banana nutrition, and its deficit may impair the crop yield. Indeed, low nitrogen availability can delay flowering (Damour *et al.*, 2012; Dorel *et al.*, 2023; Lahav, 1995; Nyombi *et al.*, 2010), reduce the bunch weight (Lahav, 1995; Nyombi *et al.*, 2010; Torres *et al.*, 2014) and thus decrease the banana yield.

A solution to this problem would be to crop cultivars that perform well under these suboptimal conditions induced by the agroecological practices described above.

Cavendish banana cultivars currently used have been evaluated and selected only for non-limiting cropping conditions (Cabrera Cabrera and Galán Saúco, 2005; Eckstein *et al.*, 1998; Fonsah *et al.*, 2007; Galán Saúco *et al.*, 1998; Nuno *et al.*, 1998; Robinson *et al.*, 1993). The latter studies revealed that banana cultivars of the Cavendish group exhibited differences in terms of morphology and yield in non-limiting conditions. However, cultivars that can perform well under suboptimal conditions have yet to be identified.

In this context of changes in farming practices to improve the sustainability of banana cropping system, the principal objective of the study was to find Cavendish cultivars that can perform in cropping systems where agroecological practices are implemented. The specific objectives were firstly (i) to compare the performance of 12 different Cavendish cultivars in the suboptimal conditions that could occur with the practices implemented as alternative to chemical inputs in the FWI. More precisely, we focused on conditions resulting from low organic fertilization and maintenance of weed live mulch as alternatives of high mineral fertilization and chemical weeding (reduction of the amount of soil nutrient available for the banana), and prophylactic deleafing as alternative to control of black sigatoka with fungicide (reduction of leaf area and consequently photosynthetic assimilation), and secondly, (ii) to find the most performant cultivar for each suboptimal cropping condition. An experiment was conducted in Guadeloupe (FWI) to assess the performance of 12 Cavendish cultivars with different crop management modalities that were, on one hand, cultural practices generally used in industrial banana crops (high mineral fertilization, chemical weed control and chemical control of black sigatoka associated to minimum prophylactic deleafing) and on the other hand their agroecological alternatives (low organic fertilization, weed live mulch and severe prophylactic deleafing). This aimed to induce contrasted conditions in terms of plant leaf area and soil nutrient availability, mostly nitrogen. A cultivar was

Table 1. Soil chemical properties of the experimental crop between 0 and 40 cm deep. CEC: cation exchange capacity

Water pH		5.73
KCl pH		4.90
Organic Matter		
Organic matter	%	5.81
Organic Carbon	%	3.37
Total Nitrogen	‰	2.93
C/N		11.50
Olsen Assimilable Phosphorus	mg/kg	26.40
Exchangeable Complex		
Exchangeable Calcium	me/100g	7.97
Exchangeable Magnesium	me/100g	2.34
Exchangeable Potassium	me/100g	2.34
Exchangeable Sodium	me/100g	0.20
Sum of exchangeable bases	me/100g	12.85
CEC	me/100g	42.48

considered with high performance in a suboptimal cropping condition if (i) it exhibited a higher yield than the other cultivars in this condition, and (ii) it had a low relative yield gap between the plot considered as the agricultural potential and the suboptimal condition.

Material and methods

Experimental design

The experiment was conducted at Capesterre-Belle-Eau (Guadeloupe, FWI), in the Bois-Debout banana plantation (16°01'43"N, 61°35'48" W, average annual rainfall 2,600 mm, mean temperature 26°C) from June 2019 to March 2021, during two banana crop cycles. The soil is classified as Andosol (FAO, 2014). Analysis of the 0–40 cm soil layer is presented in Table 1. Banana trees were planted after three years of sugarcane crop. The soil was ploughed twice before planting with a spading machine. The planting materials were micropropagated derived plants supplied by Vitropic SA, hardened two months in greenhouse before the planting in June 2019.

Four crop management modalities were applied on four 0,22 ha elementary plots (see Supplementary Information Figure S1): i) high mineral fertilization, chemical weed control and minimum prophylactic deleafing (N + L+), ii) high mineral fertilization, chemical weed control and severe prophylactic deleafing (N + L−), iii) low organic fertilization, weed living mulch, and minimum prophylactic deleafing (N−L+) and iv) low organic fertilization, weed living mulch and severe prophylactic deleafing (N−L−). In each elementary plot, a totally randomized design plot was planted with 12 cultivars and 15 repetitions per cultivar. One repetition consisted of one plant. An edge row around each plot was planted with the same cultivars randomly disposed. The plants were studied at the individual scale and planted in single row with 3 m × 3 m spacing, assuming that plant density was low enough to avoid competition for light between adjacent plants, even between size extremum cultivars (e.g. Dwarf Cavendish and Robusta).

The bunches were not bagged, and no fruit ablation was applied. To avoid seasonal variation due to rain differences among the cycle, the plants were irrigated all year round with a drip system. A mixture of paraffinic oil and triazole fungicide was sprayed 3 times per year with an air-blast sprayer to control black sigatoka disease on the whole experimental plot.

Crop management modalities

Each management modality was a combination of practices having an effect on banana leaf area (L modalities: L+/L−) and practices having an effect on soil nutrient availability (N modalities: N+/N−):

- Minimum prophylactic deleafing (L+) consisted in removing weekly the necrotic part of the leaves to limit black sigatoka disease dissemination.
- Severe prophylactic deleafing (L−) consisted in completing the minimum prophylactic deleafing by the removal of additional healthy leaves to maintain a difference of three leaves between the minimum deleafing and the severe prophylactic deleafing. The purpose of this practice was to simulate a case of high pressure of black sigatoka without fungicide control.
- High mineral fertilization and weed chemical control (N+) consisted of an application of 200 g per plant of complete mineral fertilizer (NPK 14-4-28) each month, that was higher than the amount applied in the FWI productions, and in a systemic herbicide sprayed 4 times per year to avoid the competition between weeds and banana. These practices aimed at providing sufficient amount of nutrient available for the banana that will not limit its production.
- Low organic fertilization and weed living mulch (N−) consisted in an application of 200 g per plant of organic fertilizer AB'FLOR® (NPK 7–5–7) each month that was under the recommended 400 g in the context of FWI's Andosol. This fertilizer is a mixture of vegetal compost and animal products and present mineral fertilizer equivalency values of 0.5 for nitrogen availability and 1 for potassium and magnesium availability according to results of Peraire-Brudey *et al.*, (2022).

Weeds were also mowed 15 cm above ground level each time the vegetal cover height exceeded 50 cm. According to the results of Dorel *et al.* (2023), who used the same organic fertilization with different cover management, for this amount of fertilizer, the competition between weed and banana for nutrients mostly concerned nitrogen and was unsignificant for potassium and calcium.

Moreover, soil content in exchangeable potassium is 2.34 meq per 100 g of soil (Table 1) which represent a reserve of about 3,000 kg of exchangeable K /ha. This reserve was far higher than the requirements for establishing a banana plantation, which are about 1,500 kg of exchangeable K/ha. We thus considered that, even in the N− plots, bananas did not experience any limitation for potassium nutrition.

The objective of this practice was to limit nutrient availability for the banana, and mostly nitrogen, through a low release of mineral nitrogen by organic fertilizer and weed competition for nitrogen uptake.

Banana cultivars

The experiment was conducted with 12 Cavendish banana cultivars presented in Table 2 and also described by Rapetti and Dorel (2022). These cultivars can be grouped in three types depending on their height, according to Robinson and Galán Saúco (2010) and Simmonds (1954): Dwarf, Giant and Robusta type. Some morphological characteristics of the cultivars are presented in Supplementary Information (Table S1).

Measurements

Only measurements performed on the second crop cycle were presented because no significant effect of the crop management modalities on banana growth was observed at the first cycle (see Supplementary Information, Figure S2). It could be explained, at first, by a high black sigatoka disease pressure during the first crop cycle which makes impossible to remove additional healthy leaves after minimum prophylactic deleafing (L+) without jeopardize plant survival. Consequently, there was no difference in leaf area between L+ and L−. Then, the degradation of the residues of the previous sugarcane crop could have also offset, at the beginning of the first crop cycle, the effect of N− practices aiming to reduce nutrient availability.

Table 2. Description of the cultivars studied. They are all commercial cultivars from Vitropic SA

Cavendish type	Cultivar name	Cultivar description
Dwarf type *The most cultivated in the subtropics.*	DC01	Selected from a standard Canarian cultivar
Giant type *Major cultivars cultivated for world export.*	Gua01	Considered as the standard Grande Naine. High yield in various cropping conditions. worldwide
The nine monitored commercial Giant cultivars were selected in Grande Naine populations.	Gua02	Got a typical salmon-coloured pseudostem and was known as more resilient with seasonal stresses.
	Cot01	
	Mat01	
	Mat02	
	Mat03	
	Mat11	
	Mat12	
	Ruby®	Got a typical red pseudostem. Nematode-tolerant in field conditions and TR4 tolerant under *in vitro* conditions. Ruby is a trademark
Robusta type *Once major export cultivars replaced the Gros Michel cultivar, which is highly susceptible to Panama disease. In many exporting areas, they have now been replaced by Giant Cavendish types, which are shorter and produce larger bunches.*	Ame01	Americani cultivar. This kind of cultivar used to be mostly cropped in Latin America
	Poyo	Poyo cultivar. used to be traditionally cultivated in the West Indies.

Table 3. Presentation of the measured and calculated (*) variables

Variable	Abbreviation	Unit	Type of measurements/Calculation formula
Number of living leaves at bunch emergence	NLL_{be}	/	At bunch emergence
Number of living leaves at harvest	NLL_h	/	At harvest
Soil mineral nitrogen content	$[N]_{soil}$	mg/kg^{-1}	
Indicator of leave chlorophyll content	SPAD	/	At bunch emergence
Bunch weight		kg	Harvested at 900 degree days ± 90 degree days with a base temperature of 14°C
Production rate (*)		$year^{-1}$	$\frac{1}{\text{cycle duration}}$ With cycle duration = Interval between the 1st and 2nd cycle harvests
Fruit number		/	At harvest
Fruit diameter		cm	At harvest. on an external fruit of the 3rd hand
Yield		$kg/year^{-1}$	Bunch weight x Production rate
Relative Yield Gap (*)		/	$\frac{\text{Yield in N+L+} - \text{Yield in the plot i}}{\text{Yield in N+L+}}$ Where i = {N+L−; N−L+; N−L−}
Relative Bunch Weight Gap (*)	Relative BW Gap	/	$\frac{\text{Bunch weight in N+L+} - \text{Bunch weight in the plot i}}{\text{Bunch weight in N+L+}}$
Relative Production Rate Gap (*)	Relative PR Gap	/	$\frac{\text{Production rate in N+L+} - \text{Production rate in the plot i}}{\text{Production rate in N+L+}}$
Relative Fruit Number Gap (*)	Relative FN Gap	/	$\frac{\text{Fruit number in N+L+} - \text{Fruit number in the plot i}}{\text{Fruit number in N+L+}}$
Relative Fruit Diameter Gap (*)	Relative FD Gap	/	$\frac{\text{Fruit number in N+L+} - \text{Fruit number in the plot i}}{\text{Fruit number in N+L+}}$

All the studied variables are presented in Table 3. To verify the differences between the practices L+ and L−, the number of living leaves at bunch emergence (NLL_{be}) and harvest (NLL_h) was counted. To quantify the differences of nitrogen availability between practices N+ and N−, soil mineral nitrogen content ($[N]_{soil}$) was assessed monthly from May 2020 to October 2020. The plant nitrogen status was also assessed through chlorophyll-metre readings (SPAD-502 Minolta, Bullock and Anderson, 1998) performed on the third leaf at the bunch emergence.

Yield at the plant scale was considered as the weight of bunches produced per year. It depended on the bunch weight and on the number of bunches produced per year, which was called here the production rate. The bunch weight depended on the fruit number per bunch and on the individual fruit weight, whose diameter was an indicator. Bunches were harvested 900 degree days after bunch emergence calculated in thermal time with a base temperature of 14°C (Ganry and Sioussaram, 1978). A tolerance of ± 90 degree days was accepted to optimize the fruit size. The fruit number and the weight of each bunch were determined at harvest. The diameter of two fruits of the third hand was also measured. The cycle duration, expressed in year, was calculated as the interval between the first and second cycle harvests. The production rate ($year^{-1}$) was calculated for each studied plant as $\frac{1}{cycle\ duration}$. The yield, at the plant scale, was calculated as follows:

$$Yield\ (kg/year^{-1}) = bunch\ weight\ (kg) * production\ rate\ (year^{-1}).$$

Calculation of Relative Gaps of yield and yield components

It was assumed that cultural practices in N + L+ plot allowed the expression of the agricultural potential of Cavendish plants in the farming area of the study. The agricultural potential was defined as the performance of the crop with non-limiting cultural practices in given environmental conditions. In the other plots (N + L−, N−L+ and N−L−), Relative Yield Gap to the agricultural potential was calculated for each cultivar as follows:

$$Relative\ Yield\ Gap\ in\ plot\ i = (Yield\ in\ the\ plot\ N + L + -Yield\ in\ the\ plot\ i)/Yield\ in\ the\ plot\ N + L+$$

For each yield component (bunch weight, production rate, fruit number, fruit diameter), a Relative Gap to the agricultural potential was similarly calculated for each cultivar.

Statistical analysis

All statistical analyses were performed with R software (version 3.5.3) (R Core Team, 2018). For each plot and variable, the effect of the cultivar on the variables was assessed using ANOVA ($\alpha = 0.05$). A Tukey post hoc test was used to compare average values per cultivar.

The difference in the number of leaves at bunch emergence (NLL_{be}) and at harvest (NLL_h) between the plots L+ and L− was assessed using a Kruskall-Wallis test. The difference in SPAD values between N+ and N− was assessed with a Kruskall-Wallis test.

The effects of L modality (L+/L−), cultivars and their interaction, whatever nutrient availability involved by the N modality (N+/N−), were assessed with ANOVA test performed with a linear mixed model with N modality as random effect. Conversely, the effects of N modality, cultivars and their interaction, whatever the L modality, were assessed with ANOVA test performed with a linear mixed model with L modality as random effect. Linear mixed models were performed using the function 'lmer' (Kuznetsova *et al.*, 2017). For every variable, the most parsimonious model was selected with a backward stepwise procedure. The effect size of the factors selected in the final models was assessed by calculating eta squared values of each factor (Cohen, 1973, 1988). The effect was considered small when $0.01 \leq eta^2 < 0{,}06$, medium when $0.06 \leq eta^2 < 0{,}14$ and large when $eta^2 \geq 0{,}14$.

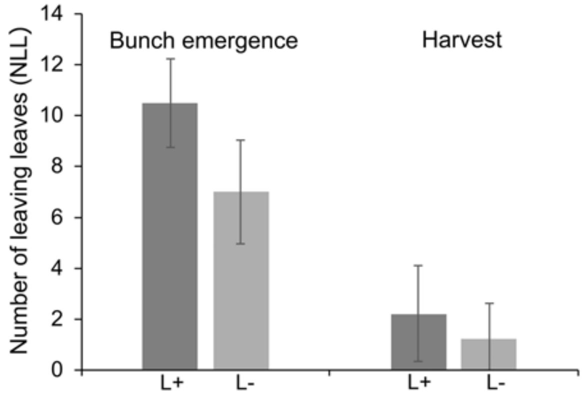

Figure 1. Number of living leaves at bunch emergence (NLL_{be}) and at harvest (NLL_h) in the second crop cycle plots with minimum prophylactic deleafing (L+) and severe prophylactic deleafing (L−). The error bars represented the standard errors, derivated from the 360 repetitions for each L modality. Kruskall-Wallis results indicated highly significant differences between L+ and L− (p-value <0.001), in terms of NLL_{be} and NLL_h.

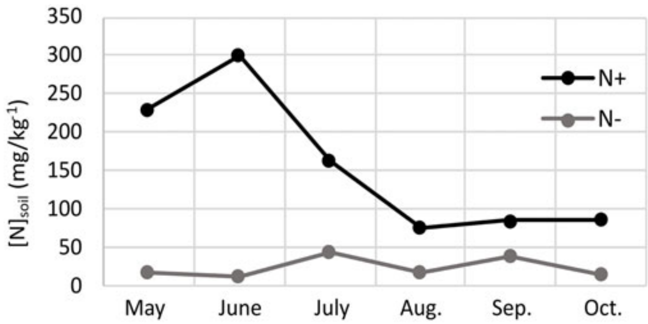

Figure 2. Soil mineral nitrogen concentration in N+ and N− plots from May 2020 (beginning of the second cycle in every plot) to October 2020 (N+ harvest and beginning N− bunch emergence).

Results

Differences of nitrogen availability and NLL in the plots

There were significant effects of the crop management modalities on NLL and mineral soil nitrogen dynamics. Indeed, at first, there was significantly more NLL_{be} and NLL_h in L+ than in L− (Fig. 1), as shown by the Kruskall-Wallis test results.

Then, Fig. 2 shows that $[N]_{soil}$ was higher in N+ plots and constantly above 70 mg/kg. In N− plots, $[N]_{soil}$ was remained close to 25 mg/kg. Godefroy and Dormoy (1983) considered that, in banana plantation, 25 mg/kg was a minimum critical threshold for banana nutrition and that above 50 mg/kg, soil mineral nitrogen was excessive and easily leached. Moreover, the chlorophyll content of the third leaf was significantly higher with N+, as shown by the SPAD results presented in Fig. 3. Thus, those results highlighted differences of nitrogen status in soil and in plant between N+ and N−, suggesting a nitrogen shortage in the latter modality.

Yield and yield components in each plot

Cultivar yields in the four elementary plots are presented in Fig. 4. N + L+ plot had the highest yields, followed by N + L−, N−L+ and N−L−, with mean yields of 91 $kg/year^{-1}$, 84 $kg/year^{-1}$,

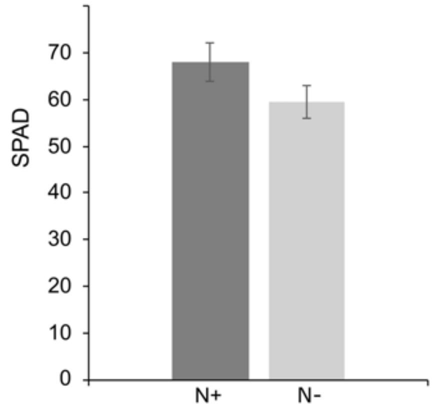

Figure 3. SPAD values in the plots with high mineral fertilization and weed chemical control (N+) and low organic fertilization and weed living mulch (N−) in the second crop cycle. The error bars represented the standard errors, derivated from the 360 repetitions for each L modality. Kruskall-Wallis results indicated highly significant differences between N+ and N− (p-value <0.001).

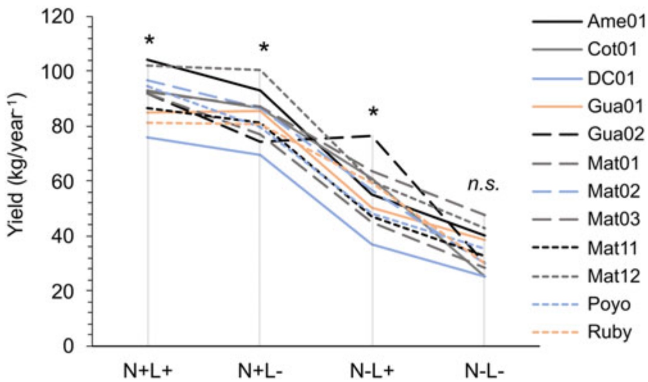

Figure 4. Average yield of cultivars in the four elementary plots: N + L+: high mineral fertilization, chemical weed control and minimum prophylactic deleafing; N + L−: high mineral fertilization, chemical weed control and severe prophylactic deleafing; N−L+: low organic fertilization, weed living mulch, and minimum prophylactic deleafing; N−L−: low organic fertilization, weed living mulch and severe prophylactic deleafing. ANOVA: n.s.: non-significant; * <0.05.

55 kg/year^{-1} and 34 kg/year^{-1}, respectively. The ANOVA findings revealed significant differences between cultivars in the plots N + L+, N + L− and N−L+. Ame01 and Mat12 had the highest yields in N + L+ and N + L−, whereas Gua02 had a significantly higher yield in N−L+ compared to the other cultivars. In every plot, DC01 had the lowest yield.

It was noteworthy that the yield differences between plots were not similar between the cultivars. Indeed, Mat12, Gua01 and Ruby had the same yield in N + L+ as in N + L−. Gua02 was the only cultivar to have a higher yield in N−L+ than in N + L−.

When focusing on the yield components in the plot N + L+ where the cultivars expressed their agricultural potential in this environment (Table 4), the Tukey test findings showed few significant differences between most of the cultivars. However, some cultivars stood out, including Ame01, which had the highest yield in this plot as well as the highest bunch weight with large fruits. Conversely, DC01 exhibited the lowest yield and lowest bunch weight and the shortest fruit despite having the highest fruit number.

The yield components of the three other plots (N + L−, N−L+, N−L−), as presented in Table 4, revealed some marked differences between cultivars. Comparing the yield components of N + L+ with those in the other plots, N + L+ exhibited the highest values, followed by N + L−, N−L+ and finally N−L−. Despite the low values for all yield components in N−L−, all fruit diameters were above 30 mm, which is the minimal diameter required to market bananas. Firstly, it was noteworthy that for every plot, DC01 had the lowest bunch weight, the smallest fruit diameter, but the highest fruit number. Secondly, Poyo always had the lowest fruit number, yet while always having one of the highest fruit diameters. Thirdly, Gua02, which exhibited the highest yield in N−L+, had the highest production rate in this plot. Concerning the other cultivars, the Tukey tests showed few differences in terms of yield components in all plots.

Effect of crop management modalities on yield and yield components

Interferential models (linear mixed effects) showed that yield and most of yield components were affected both by the crop management modality (L or N) and the cultivar, but not by their interaction (Table 5). Only the production rate, whatever the N modality, only depends on the cultivar effect and not the L effect. Also, the cultivar had a small effect on production rate, whatever the L modality, with eta^2 of 0,01.

The size effect of cultivar and of crop management modality was not the same between L and N. Indeed, in the models where L effects were tested, the cultivar eta^2 was higher than the L eta^2 for two variables (fruit number, fruit diameter) among four (no significant effect of L for production rate). On the opposite, in the models where N effects were tested, the cultivar eta^2 was far lower than the N eta^2 for all the studied variables, except for the fruit diameter.

Relative gaps of yield and yield components

The Relative Gaps of yield and yield components (production rate, bunch weight, fruit number and fruit diameter) measured in each suboptimal plots (N + L−, N−L+, N−L−) and for all cultivars are presented in Fig. 5. For each variable, the Relative Gaps values in N + L− were lower than the Relative Gaps values in N−L+ that were in turn lower than the Relative Gaps values in N −L−. The Relative Gaps of yield and yield components in N−L− were higher and are further presented below. The Relative Gaps of fruit diameter were low.

There were few differences between N + L+ and N + L−, as the mean Relative Gaps values in N + L− were less than 0.25 for all variables and cultivars. Concerning the Relative Yield Gaps in N + L−, Mat01, Poyo and Gua02 had the highest ones. For the other cultivars, the values were less than 0.12. Ruby, Gua01, Mat03 and Mat12 had very low Relative Yield Gaps in N + L−, i.e. under 0.05. Concerning Relative Production rate Gap in N + L−, the values were under 0.10 for all cultivars, while negative values were obtained for five cultivars (Mat12, Mat03, Gua01, Mat11 and Ruby). Ruby was the sole cultivar with a null Relative Bunch weight Gap in N + L−, whereas Gua02 had the highest one (0.22). For all cultivars, there were few differences in fruit number, with Relative Fruit number Gaps in N + L− being less than 0.10.

There were noteworthy differences between N + L+ and N−L+, notably for the yield, with Relative Yield Gaps in N−L+ ranging from 0.19 to 0.52, while Poyo, Ame01, Mat01 and DC01 had the highest values. In contrast, Gua02 had the lowest Relative Yield Gap in N−L+ (< 0.19), followed by Ruby and Mat03. Gua02 was also the cultivar with the lowest Relative Production rate Gap in N−L+ (< 0.10). Ruby was the only cultivar with a Relative Bunch weight Gap in N−L+ of less than 0.05, followed by Gua02. For the other cultivars, the values were higher than 0.20.

Marked differences appeared between N + L+ and N−L−, with Relative Yield Gaps in N−L− higher than 0.50. For all cultivars, the Relative Gaps values in N−L− in term of production rate, bunch weight and fruit number ranged from 0.25 to 0.50. Otherwise, there were no clear differences between cultivars.

Table 4. Average yield components (production rate, bunch weight, fruit number and diameter) of cultivars in the four plots. ANOVA: n.s.: non-significant; **: <0.01; ***: <0.001. Different letters indicate that the average values are significantly different (Tukey test, $\alpha = 0.05$)

	N+L+				N+L-				N-L+				N-L-			
Cultivar	Production rate (year-1)	Bunch weight (kg)	Fruit number	Fruit diameter (mm)	Production rate (year-1)	Bunch weight (kg)	Fruit number	Fruit diameter (mm)	Production rate (year-1)	Bunch weight (kg)	Fruit number	Fruit diameter (mm)	Production rate (year-1)	Bunch weight (kg)	Fruit number	Fruit diameter (mm)
Ame01	2.00	52 a	242 b	39 a	2.03	46	247 bc	39 a	1.44 b	34	194 bc	36 a	1.48	26	181 ab	35 ab
Cot01	2.03	46 abc	263 ab	37 ab	2.00	43	266 ab	36 ab	1.55 ab	37	243 ab	35 a	1.26	20	179 ab	31 cd
DC01	1.96	39 c	283 a	34 c	1.94	36	297 a	32 c	1.31 b	27	250 a	31 b	1.30	20	205 a	30 d
Gua01	1.87	45 abc	249 b	37 ab	1.98	41	246 bc	37 ab	1.45 b	34	222 abc	35 a	1.45	24	189 ab	34 abc
Gua02	1.96	46 abc	248 b	37 abc	1.85	38	231 cd	35 abc	1.75 a	40	218 abc	36 a	1.36	20	175 ab	32 bcd
Mat01	1.94	47 abc	265 ab	37 ab	1.88	41	258 bc	36 abc	1.31 b	32	216 abc	35 a	1.27	21	178 ab	33 abcd
Mat02	2.03	48 abc	256 ab	38 a	1.98	43	242 bc	37 ab	1.47 b	38	214 abc	36 a	1.38	22	195 ab	33 abcd
Mat03	1.91	48 ab	256 ab	38 ab	2.05	43	251 bc	37 ab	1.56 ab	40	220 abc	37 a	1.51	28	187 ab	35 a
Mat11	1.87	46 abc	259 ab	37 ab	1.95	41	254 bc	36 abc	1.37 b	33	219 abc	35 a	1.40	22	186 ab	33 abcd
Mat12	2.00	49 ab	272 ab	37 ab	2.17	46	257 bc	37 ab	1.52 ab	38	224 abc	35 a	1.42	28	213 a	34 ab
Poyo	2.09	45 abc	213 c	38 ab	1.93	40	203 d	37 a	1.45 b	32	176 c	36 a	1.46	23	161 b	34 ab
Ruby	1.96	40 bc	269 ab	34 bc	1.99	40	270 ab	33 bc	1.49 ab	38	251 a	34 a	1.36	21	195 ab	31 d
p-value	n.s.	**	***	***	n.s.	n.s.	***	***	***	n.s.	***	***	n.s.	n.s.	**	***

Table 5. Most parsimonious linear model selected to explain the effect of cultivar (cult), crop management modality (L or N) and their interaction, whatever the N or L modality (1|N, 1|L), on the yield and its components. The size effect (eta^2) of each factor along with its class of *p*-value was reported. *P*-value: *: <0.1; **: <0.01; ***: <0.001 ; n.s. : non-significant

Variable	Linear mixed model	Eta^2 cult	*p*-value	Eta^2 L	*p*-value	Eta^2 cult:L	*p*-value
Yield	~cult * L + 1|N	0.40	***	0.51	***		*n.s.*
Bunch weight	~cult * L + 1|N	0.24	**	0.65	**		*n.s.*
Production rate	~cult * L + 1|N	0.38	*		*n.s.*		*n.s.*
Fruit number	~cult * L + 1|N	0.58	***	0.20	***		*n.s.*
Fruit diameter	~cult * L + 1|N	0.19	***	0.07	***		*n.s.*
Variable	**Linear mixed model**	**Eta^2 cult**	***p-value***	**Eta^2 N**	***p-value***	**Eta^2 cult:N**	***p-value***
Yield	~cult * N + 1|L	0.07	**	0.86	***		*n.s.*
Bunch weight	~cult * N + 1|L	0.09	**	0.80	***		*n.s.*
Production rate	~cult * N + 1|L	0.01	*	0.34	***		*n.s.*
Fruit number	~cult * N + 1|L	0.19	***	0.46	***		*n.s.*
Fruit diameter	~cult * N + 1|L	0.10	***	0.08	***		*n.s.*

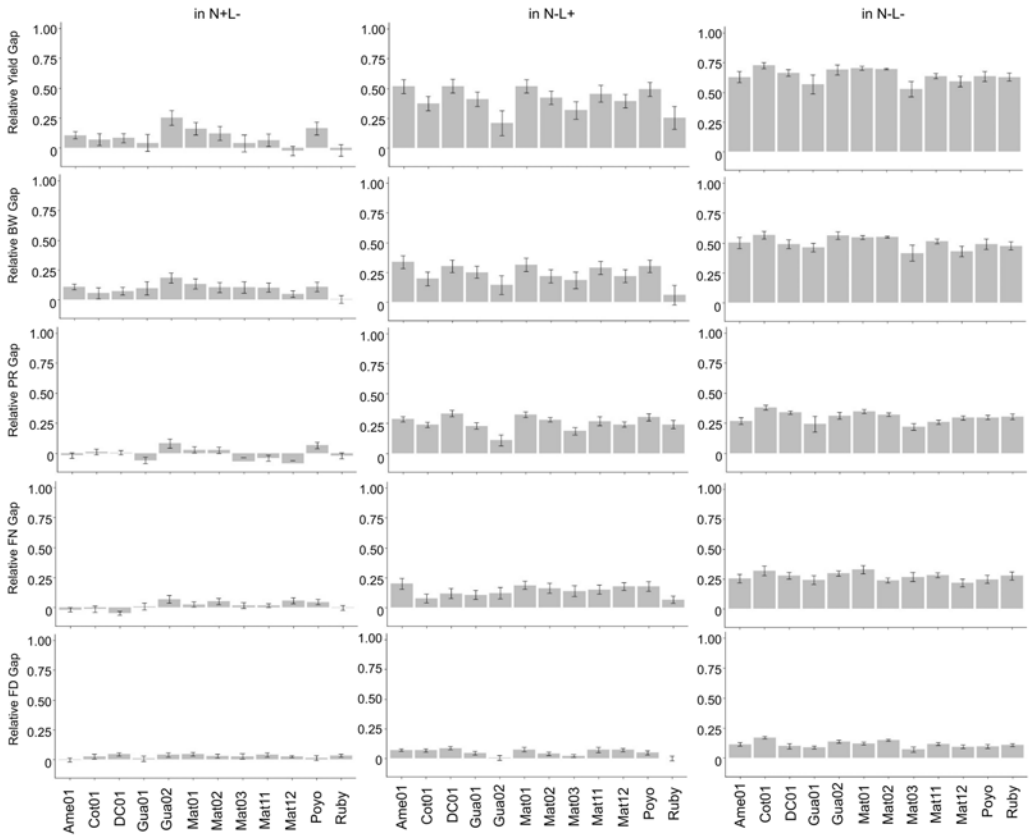

Figure 5. Average relative gaps for yield (line 1), production rate (PR) (line 2), bunch weight (BW) (line 3), fruit number (FN) (line 4) and fruit diameter (FD) (line 5) in N + L− (on the left), in N−L+ (in the centre) and in N−L− (on the right). The error bars represented the standard errors, derivated from the 15 repetitions for each cultivar.

Discussion

Difference of the highest yielded cultivars according to the crop management modalities

The results showed that the highest yields were obtained by Ame01 in N + L+, Mat12 in N + L− and Gua02 in N−L+. In the N + L+ plot, Ame01 had the heaviest bunches with the largest fruits, thereby explaining its higher yield. In the N + L− plot, Mat12 had average values for all yield components. Finally, in N−L+, Gua02 had the highest production rate and the highest bunch weight, so it had the highest yield in this plot. This suggested that the flowering delay that may be induced by nutrient shortage, as described for nitrogen deficiency (Damour *et al.*, 2012; Dorel *et al.*, 2023), could be less marked with regard to Gua02 as compared to the other cultivars. These results showed that, depending on the cultivars and the plot, the yield components responsible for the high yields differed.

However, DC01 had the lowest yield in every plot, with the lightest bunches and smallest fruits despite the high fruit number. This result differed with those of Cabrera Cabrera and Galán Saúco (2005) who found that Dwarf Cavendish cultivars performed better than Giant Cavendish banana cultivars such as Grande Naine and Williams in the Canary Islands. Dwarf banana cultivars are known to perform well in subtropical regions. DC01 might not be adapted to the tropical climatic conditions of the French West Indies and thus not express its full potential in this environment.

This study showed the high productivity of Ame01, i.e. a Robusta cultivar, in N + L+ with plot with high mineral fertilizer and minimum deleafing. Historically, Robusta cultivars were abandoned in favour of Giant cultivars because of their smaller stature and their better yields. Similar findings were obtained in some studies involving Cavendish cultivar assessment, where the authors found that Giant cultivars such as Grande Naine and Williams had a greater agronomic potential than Robusta cultivars, such as Poyo, Valery and Americani (Robinson *et al.*, 1993; Stover, 1982). In the light of our results, despite of its height, Ame01 should be reconsidered for some banana production, notably in area where the risk of falling is low due to the absence of cyclone and to a good telluric parasitism control.

Effects on the banana yield of suboptimal conditions induced by agroecological practices: severe deleafing, low mineral fertilization and weed live mulch

In this study, the yield and yield components significantly depend on the cultivar and the crop management modalities but not on their interaction. Moreover, the eta^2 values showed that the N modalities, depending on the fertilization and the weed control, had higher effect than the cultivar. That was not the case of L modalities, that depended on the black sigatoka management, which had lower effect than the cultivar for most of the studied variable. This last result suggests than N modalities had higher effect than L modalities, that was strengthened by the values of Relatives Gaps for yield and yield components. In this study, Relatives Gaps for yield and yield components were measured to compare the values in suboptimal cropping conditions and in N + L+, considered as the plot where the cultivars expressed their potential in this farming area. Relative Gaps in N + L− were found to be the smallest values (all values < 0.25), followed by Relative Gaps in N−L+ and finally in N−L−. All values for the latter were above 0.50, with some as high as 0.75. Between-plots differences of the Relative Gaps were more marked regarding the yield, bunch weight and production rate as compared to the fruit number and the fruit diameter.

Our results can be analysed based on the findings of studies focused on the effects of severe deleafing and nutrient shortages due to low fertilizer application or competitive weed on banana growth and yield. Meanwhile, severe deleafing reduced the photosynthetic leaf area and hence the biomass production and yield. Indeed, severe deleafing may decrease the amount of carbohydrates allocated to the bunch and thus the hand and fruit number, fruit diameter and bunch weight (Engwali *et al.*, 2013; Ocimati *et al.*, 2019; Robinson *et al.*, 1992). As presented in Turner and Gibbs (2018), in their study, Turner and Hunt (1987) observed a negative effect of severe deleafing before flowering on the number of hands, that depended on the developmental stage of the plant. Indeed, the impact of severe deleafing was higher few weeks before floral induction (between 20 and 11 leaves before flowering) but was null when the defoliation was implied before or after. However, several authors found that deleafing had impacts on the bunch weight only when the plant was left with a certain number of leaves at flowering, i.e. 4 to 10 depending on the author (Daniells *et al.*, 1994; Ocimati *et al.*, 2019; Robinson *et al.*, 1992). Moreover, in response to deleafing, compensatory mechanisms have been observed, with an increase in photosynthetic activity and in the length of the bunch-filling period (Daniells *et al.*, 1994; Robinson *et al.*, 1992; Turner *et al.*, 2007).

Concerning the effects of nutrient shortage caused by low fertilization or competition with weed, nitrogen is a major chlorophyll component, and its shortage or absence reduces the photosynthetic assimilation rate. The main impacts of fertilization with little or no nitrogen are a reduction in biomass production and flowering delay, that induced lighter bunches, less fruits per brunch and smaller yield (Damour *et al.*, 2012; Nyombi *et al.*, 2010; Torres *et al.*, 2014). Also, some papers found that competition with weeds or intercrop for nutrient uptake may impair banana crop yield, with less fruits per bunch and a flowering delay (Achard *et al.*, 2018; Dorel *et al.*, 2023), or smaller fruits, lighter bunches and smaller yields (Ocimati *et al.*, 2019). Damour *et al.* (2012) interpreted the cycle duration increase, caused by the flowering delay, as compensatory effect for biomass accumulation. No study had compared the effect of severe deleafing with the effect of nutrient shortage on banana plants, but our results suggested that nutrient shortage, mostly nitrogen, impacted more the banana yield than severe deleafing. Moreover, as compensatory mechanisms in response to deleafing involved the increase of the photosynthetic activity and as nitrogen shortage reduced the photosynthetic capacity, the high value of Relative Gaps in N−L− suggested that the nitrogen shortage greatly affects the deleafing compensatory mechanism that is no longer as effective.

Between-Cultivar difference of stresses effects on the yield

Our results showed no statistical effect of the interaction between cultivar and crop management modalities, but between-cultivar differences in term of Relative Gaps, that can be interpreted as tendencies. For instance, yield and yield components of Ruby were not altered in N + L− relatively to N + L+ while yield and yield components of Gua02 were markedly impaired. Yield and yield components of Gua02 exhibited the lowest decrease in N−L+ compared to N + L+, followed by Ruby and Mat03, whereas DC01 exhibited the highest decrease. Finally, yield and yield components of Mat03 exhibited the lowest decrease in N−L− compared to N + L+. Stress tolerance can be assessed according to the yield stability despite the stress and is generally measured by the yield difference between stressed conditions and the potential (Clarke *et al.*, 1992; Tollenaar and Lee, 2002). Our experimental design did not include any treatment replication, but the maintenance of the yield and yield components between plots for some cultivars (Ruby, Gua01 and Mat12 between N + L+ and N + L−; Gua02 between N + L+ and N−L+) suggests that these cultivars could be respectively tolerant to the stress induced by severe deleafing and nutrient shortage due to low fertilizer associated to weed live mulch.

Conclusions

As a conclusion, this work showed that the Cavendish banana cultivars exhibited differences in term of yield and yield components in different suboptimal cropping conditions in FWI. It allowed to identify cultivars of interest to be cultivated with alternative practices to chemical inputs or suboptimal conditions due to abiotic stresses. Indeed, Ruby, Gua01 and Mat12 performed well with severe deleafing and thus are interesting for cropping system without chemical fungicide to control black sigatoka or cropping conditions with low photosynthetic activity. Otherwise, Gua02 and Ruby were the most performant with a nutrient shortage resulting from a low organic fertilization and weed living mulch to reduce chemical weeding. Moreover, our results highlighted tendencies of between-cultivars differences in terms of stress effects on the yield, which may suggest that the cultivars of the Cavendish group have differences of tolerance to abiotic stresses. This is a very innovative finding which needs to be invested to confirm the observed tendencies. Indeed, there were very few studies about the diversity with regard to the plant response to abiotic stresses between cultivars within banana groups, such as the Cavendish group and the Plantain one. Thus, there is a need to better characterize the genetic diversity of the cultivated bananas to identify cultivars adapted to various cropping practices and growing contexts.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479724000231

Data availability statement. The experimental data of the trial are deposited on a Dataverse: https://doi.org/10.18167/DVN1/J4MT4P

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