Yield Components of Triploid and Tetraploid *Musa* Genotypes in Nigeria

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Abstract. The additive main effects and multiplicative interaction (AMMI) model was used to evaluate the stability patterns of 36 *Musa* genotypes in four cropping environments for bunch weight, pulp weight, and dry matter content. Alleycropping generally induced higher means for all traits than did sole cropping. The triploid plantains produced smaller bunch weights and were less stable than dessert and cooking bananas. In this ploidy group, bunch weight was highest for the cooking bananas ‘Cardaba’ and ‘Fougamou’, but only ‘Fougamou’ was stable across environments. Among the hybrids, only ‘FHIA23’ (dessert banana) expressed high and stable bunch weights, while other high-yielding hybrids displayed specific adaptation to alleycropping. Pulp weight was lower but more stable in plantains than in other triploid genotypes. Among the hybrids, pulp weight was high and stable for one cooking banana (‘FHIA3’), one dessert banana (‘FHIA1’), and three plantains (‘PITA1’, ‘PITA2’, and ‘PITA7’). Dry matter content was highest in plantains and lowest in dessert bananas at both triploid and tetraploid levels, and was also more stable than the other traits. Thus, the adaptation patterns of genotypes across environments varied according to the trait studied. When rank changes were not observed across traits for a given genotype, differences were still noted in the relative magnitude of the IPCA1 score. Hence, both farm gate traits and postharvest processing traits should be considered in selecting for broad or specific adaptation. Determination of the genetic relationships between processing traits and farm gate traits could allow *Musa* breeders to construct selection indices that would facilitate multiple trait selection and enhance breeding efficiency, with respect to cultivar stability and adaptation across environments.

Bananas and plantains (*Musa* sp.) are starchy staple crops of considerable economic importance in the developing world (Dadzie and Orchard, 1996; Robinson, 1996). They evolved from inter- and intra-specific crosses between two diploid ($2n = 2x = 22$) species native to southeast Asia, *M. acuminata* Colla. and *M. balbisiana* Colla. (Simmonds, 1962). The two species have different genomes, designated as A for *M. acuminata* and B for *M. balbisiana*. The existing cultivars are distinguished by the number of A and B genomes they harbor, e.g., AAA predominantly for dessert bananas, AAB for plantains, and ABB for cooking bananas (Robinson, 1996; Simmonds, 1962; Stover and Simmonds, 1987). For example, genes for parthenocarpy and yield are generally considered to be contributed by the A genome, whereas the B genome harbors

genes for hardiness, drought tolerance, and increased starchiness (Robinson, 1996).

In West Africa, plantains and bananas are usually grown in backyards or in small forest fields. In the first system, pure stands are grown perennially in plots that receive organic matter from household refuse. In the second

system, inter-cropping constitutes the predominant mode of cultivation. The challenge facing breeders is to select elite cultivars that will perform well under an alleycropping system, yet be amenable to intensification under a monoculture regime. Such cultivars should not display substantial trait variations over cropping systems. Thus, an understanding of trait stability is important to avoid spurious recommendations (Kang, 1998).

Yield evaluation trials provide yield estimates for each genotype in each environment, based on statistical techniques that detect and partition important agronomic variation into components (Gauch, 1992; Gauch and Furnas, 1991). Additive main effect and multiplicative interaction (AMMI) is ordinarily the model of first choice when both main effects and interactions are significant (Crossa et al., 1990; Mandel, 1971; Zobel et al., 1988). This analytical method has been applied to assess the performance of plantain–banana hybrids with respect to yield (Ortiz, 1998) and response to virus infection (Ortiz, 1996).

The harvested bunches of bananas and plantains often possess a significant proportion of nonedible and nonprocessable parts, which may reduce market potential and consumer acceptance of new cultivars. The concept of marketable yield has been used by potato (*Solanum tuberosum* L.) breeders to designate the fraction of the production accounted for by tubers that are suitable to consumers based on their weight (Ortiz et al., 1988). Market potential of plantain and banana may also be defined in that way, based on pulp weight of the harvested fruit, dry matter content of the pulp, and shelf-life of the fruit (Baiyeri et al., 1999). Dry matter content may determine the fraction of harvested crop that is available for processing into food products (Sanchez Nieva et al., 1968), i.e., the biological value of the crop. Dry matter content has

Table 1. Genome and ploidy characteristics of the genotypes used in this study.

Classification ^z	Landraces (3x)	Hybrids ^y
Dessert bananas	Pisang Ceylan (PSC) Valery (VAL) Yangambi Km5 (KM5)	FHIA-1 (F01), FHIA-2 (F02), FHIA-23 (F23), SH3436-9 (S34) SH3640 (S36), EMB 402 (EM2), EMB 403 (EM3), EMC 602 (EMC)
Plantains	Agbagba (AGB) Obino l'Ewai (OBI) UNN.DB (UNN)	PITA-1 (P01), PITA-2 (P02), PITA-3 (P03), PITA-5 (P05), PITA-7 (P07), PITA-8 (P08), PITA-9 (P09), PITA-11 (P11), PITA-12 (P12), PITA-14 (P14), PITA-16 (P16), FHIA-21 (F21), FHIA-22 (F22)
Cooking bananas	Bluggoe (BLU) Cardaba (CAR) Fougamou, (FOU) Pelipita (PEL) Saba (SAB)	BITA-1 (BT1), BITA-2 (BT2), BITA-3 (BT3), FHIA-3 (F03)

^z*Musa* cultivars are distinguished by the number of A and B genomes they harbor, e.g., AAA predominantly for dessert bananas, AAB for plantains, and ABB for cooking bananas (Robinson, 1996; Simmonds, 1962; Stover and Simmonds, 1987). Dessert banana hybrids are denoted AAA x AA, plantain hybrids AAB x AA, and cooking banana hybrids ABB x AA.

^yFHIA and SH series are hybrids from Fundación Hondureña de Investigación Agrícola, Honduras; PITA and BITA series are, respectively, plantain and banana hybrids from the International Institute of Tropical Agriculture, Nigeria; EMB and EMC hybrids are from Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) and Empresa Capixaba de Pesquisa Agropecuária (EMCAPA) in Brazil, respectively; others are landraces. Note that PITA16 is a triploid while others are tetraploids. The three-character codes that appear in parentheses after each genotype are used in Figs. 1–4.

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The objectives of this study were to determine: 1) the performance of different *Musa* genotypes across cropping systems; and 2) the effects of genome composition and ploidy level on their phenotypic stability for important yield components.

Thirty-six genotypes representative of cultivated *Musa* sp. subgroups were studied (Table 1). They included 24 primary tetraploid hybrids, one secondary triploid hybrid, and 11 triploid landraces. The landraces included three plantains, five cooking bananas, and three dessert bananas. All plantain and dessert banana landraces are susceptible to the leaf spot disease black sigatoka (caused by *Mycosphaerella fijiensis* Morelet), which causes yield losses ranging from 30% to complete crop failure (Mobambo et al., 1993). The hybrids were obtained by introgressing genes for resistance to black sigatoka from diploid accessions into landraces of plantain (13 hybrids), cooking bananas (four), and dessert bananas (eight). The 36 genotypes were evaluated under sole cropping and alleycropping with multiple species hedgerows at the High Rainfall Station of the International Institute of Tropical Agriculture at Onne (lat. 4°43' N, long. 7°01' E, 10 m altitude above sea level), in southeastern Nigeria. The station is located in a degraded rainforest–swamp characterized by an ultisol derived from coastal sediments and 2400 mm unimodal annual rainfall. Detailed characteristics of the station have been described elsewhere (Ortiz et al., 1997).

Data were collected over two crop cycles for each trial and subjected to analysis of variance (ANOVA) using the MATMODEL version 2 software (Gauch, 1993), based on the following statistical model:

where Y_{ij} is the performance observed for the

Source of variation	df	No. of days to harvest	Bunch wt (kg/plant) ^z	Pulp fresh wt (kg/plant) ^z	Dry matter content (%) ^z
Total	274	35606.23	28.18	8.38	27.53
Treatment	143	60945.44***	48.18***	13.88***	43.43***
Genotype (G)	35	37254.56 (15)***	68.36 (35)***	17.78 (32)***	136.87 (77)***
Environment (E)	3	2046475.15 (70)***	963.71 (42)***	267.79 (40)***	34.38 (2)*
G × E	105	12112.99 (15)	15.29 (23)***	5.33 (28)***	12.55 (21)
IPCA1	37	14596.62	24.20***	8.34***	23.26
IPCA2	35	7349.08	16.43***	5.57***	7.18
Residual	33	3168.81	4.10	1.70	6.22
Error	131	10442.99	6.35	2.38	10.03

Fig. 1. Relationship between bunch weight and (a) growth cycle and (b) dry matter content in some plantain and banana genotypes in Nigeria. The horizontal lines indicate the mean number of days to harvest and the mean dry matter content respectively in (a) and (b), while the vertical line represents the bunch weight grand mean. Codes used for cultivar or hybrid designation are given in Table 1. PLH = plantain hybrids, PLL = plantain landraces, CBH = cooking banana hybrids, CBL = cooking banana landraces, DBH = dessert banana hybrids, and DBL = dessert banana landraces.

Table 3. Ploidy and genome group effects on bunch weight, pulp weight and dry matter content across four cropping environments in Nigeria.

Genome group	Environment ^a	Bunch wt (kg/plant)		Pulp wt (kg/plant)		Dry matter content (%)	
		Landraces	Hybrids	Landraces	Hybrids	Landraces	Hybrids
Dessert bananas	SC/PC	6.0 ± 1.29 ^y	5.9 ± 0.85	3.4 ± 0.84	2.8 ± 0.44	23.7 ± 1.18	23.3 ± 0.89
	SC/RC	8.8 ± 0.52	8.1 ± 0.76	5.3 ± 0.64	4.0 ± 0.41	23.7 ± 1.13	24.0 ± 0.95
	AC/PC	7.2 ± 1.54	12.2 ± 1.66	3.6 ± 0.74	6.0 ± 0.86	25.3 ± 1.26	24.7 ± 0.78
	AC/RC	14.3 ± 1.16	17.4 ± 1.28	7.9 ± 0.85	9.0 ± 0.65	25.3 ± 0.99	24.5 ± 1.01
Plantains	SC/PC	5.6 ± 0.53	6.6 ± 0.32	3.1 ± 0.35	3.5 ± 0.18	33.3 ± 1.03	32.1 ± 0.51
	SC/RC	5.7 ± 0.75	8.3 ± 0.57	3.0 ± 0.38	4.6 ± 0.38	34.9 ± 1.03	29.8 ± 0.60
	AC/PC	9.3 ± 1.16	9.5 ± 0.77	5.2 ± 0.73	4.9 ± 0.43	35.2 ± 1.18	32.5 ± 0.46
	AC/RC	6.5 ± 0.67	14.7 ± 1.15	3.4 ± 0.35	7.9 ± 0.72	34.0 ± 0.46	30.6 ± 0.50
Cooking bananas	SC/PC	6.6 ± 0.59	7.5 ± 1.23	3.4 ± 0.37	3.5 ± 0.54	29.9 ± 1.40	28.3 ± 1.57
	SC/RC	10.2 ± 0.50	10.2 ± 1.74	5.5 ± 0.43	4.9 ± 0.85	30.5 ± 0.64	26.5 ± 0.61
	AC/PC	11.4 ± 1.39	11.8 ± 2.14	6.1 ± 0.85	5.6 ± 0.93	31.2 ± 1.22	29.3 ± 1.62
	AC/RC	16.1 ± 1.35	16.7 ± 2.15	8.5 ± 0.80	4.9 ± 0.93	31.2 ± 0.95	32.5 ± 5.34

^aAC = alley crop, SC = sole crop, PC = plant crop, and RC = ratoon crop.

^yMean and standard error.

i^{th} genotype in the j^{th} environment, μ is the overall mean of the trait, α_i is the effect of the i^{th} genotype ($i = 1, 2, \dots, 36$), β_j is the effect of the j^{th} environment ($j = 1, 2, 3, 4$), $(\alpha\beta)_{ij}$ is the genotype $\times$ environment interaction effect, and ε_{ij} is the residual associated with each observation. The multiplicative effects due to the interaction between genotype and environment were further partitioned into principal components, based on the following equation:

$$(\alpha\beta)_{ij} = \sum_k \lambda_k \gamma_{ik} \delta_{jk} + \rho_{ij}$$

where $(\alpha\beta)_{ij}$ is defined as above, λ_k is the eigenvalue for the k^{th} PCA axis retained in the model ($k = 1, 2, \dots, n$), and γ_{ik} is the PCA score of the i^{th} genotype for the k^{th} PCA axis, δ_{jk} is the PCA score of the j^{th} environment for the k^{th} PCA axis, and ρ_{ij} is the residual when all PCA axes are not used.

Results

Both additive and interaction effects of genotypes and environments were statistically significant ($P \leq 0.05$) for bunch weight and pulp weight, but interaction effects were not significant for days to harvest and dry matter content (Table 2).

Genetic effects. Genotype differences accounted for 15% of the variation due to treatment effects for days to harvest, and 35%, 32%, and 77% of that for bunch weight, pulp weight, and dry matter content, respectively (Table 2). Genetic differences were partly due to both genome and ploidy effects, particularly for bunch weight and dry matter content. Among the triploid landraces, cooking bananas produced higher bunch and pulp weights than did dessert bananas and plantains, but the dry matter content of landraces was highest in plantains ($\geq 33\%$) and lowest in dessert bananas ($\leq 25\%$). Similarly, the tetraploid hybrids from cooking bananas expressed higher bunch weight than other hybrids while plantain hybrids had the highest dry matter content (Table 3). Pulp weight did not differ among the genomic groups of the hybrids (Table 3). On average, triploid genotypes had higher dry matter content than did tetraploid hybrids. In contrast, tetraploid hybrids displayed greater bunch weight than their triploid counterparts

Fig. 2. AMMI1 biplot for bunch weight (kg/plant). PC = plant crop and RC = ratoon crop. The horizontal line indicates the zero ICA1 score while the vertical line represents the bunch weight grand mean. Codes used for cultivar or hybrid designation are given in Table 1.

Fig. 3. AMMI1 biplot for pulp weight (kg/plant). PC = plant crop and RC = ratoon crop. The horizontal line indicates the zero IPCA1 score while the vertical line represents the pulp weight grand mean. Codes used for cultivar or hybrid designation are given in Table 1.

in the dessert banana and plantain groups, but not in the cooking banana group (Table 3). Inter-ploidy differences were less conspicuous for pulp weight and appeared to be influenced by cropping environment, regardless of genome composition (Table 3). The cooking banana hybrid 'FHIA3' produced the highest bunch weight per plant, but this was associated with a long growth cycle and a relatively low dry matter content of the fruits (Fig. 1). Similarly, the high yields of the dessert banana hybrids 'FHIA1', 'FHIA23', 'SH3436-9', and 'SH3640' were also coupled with long growth cycles and low dry matter content (Fig. 1). In contrast, several plantain hybrids ('PITA1', 'PITA2', 'PITA5', and 'PITA7') combined high yield with a shorter growth cycle and high dry matter content.

Environmental effects. Environmental factors were the predominant component of treat-

ment effects for days to harvest (70%), bunch weight (42%), and pulp weight (40%), but accounted for only 2% of treatment effects for dry matter content (Table 2). This indicates that dry matter content is less influenced by environmental conditions than the other traits and could be used as a more reliable post-harvest descriptor of bananas and plantains. Bunch weight and pulp weight were generally higher in the ratoon crop than in the plant crop, both under solecropping and alleycropping systems, regardless of ploidy or genome classification, except for plantain landraces (Table 3). Bunch weight reduction in the ratoon crop of the plantain landraces was attributed to fruit filling during the dry season. Plants grown under alleycropping generally expressed higher mean values for all traits than did plants grown under the monocropping system in both crop cycles (Table 3); the

alleycropping system is a more resource-rich environment because organic matter build-up, moisture, and nutrient retention are higher (Ruhigwa et al., 1992). The most responsive genotypes were the dessert banana hybrids, with average superiority of more than 100% for bunch weight and pulp weight in alleycropping vs. monocropping (Table 3). The hybrids derived from cooking bananas and plantains also responded positively to improved cropping environment (<50% superiority for plantain hybrids, but >50% for cooking banana hybrids) (Table 3).

Genotype × environment interaction. The GE interaction accounted for 23% of the variation for bunch weight and 28% for pulp weight, but was not statistically significant for days to harvest and dry matter content (Table 2). The interaction was mainly attributed to cross-order performance across cropping systems rather than cropping cycles (Table 3). Principal component analysis (PCA) identified two significant interaction principal components, IPCA1 (>55% of interaction effects) and IPCA 2 (≈35% of the interaction) and a nonsignificant residual for bunch weight and pulp weight (Table 2). Thus, the AMMI2 model was appropriate to describe the response pattern of the genotypes for these traits.

Biplots were constructed from the AMMI analysis to visualize the relative magnitude of the deviations from additivity of the genotype responses and environmental effects (Gauch and Furnace, 1991). The IPCA1 scores were plotted against main effect means for the traits. The biplots explained ≈90% of the variation for bunch weight (Fig. 2), 87% for pulp weight (Fig. 3), and 93% for dry matter content (Fig. 4).

The AMMI1 model also revealed that the ratoon crop expressed higher genotype × environment interactions than the plant crop under alleycropping, whereas the opposite was observed under the solecropping system, regardless of the trait assessed (Figs. 2–4). However, the stability grading of genotypes varied between traits, both within and across genome groups and ploidy classes.

Among the triploid genotypes, plantains not only produced the smallest bunch weights, but were also less stable, i.e., had higher IPCA1 scores, than were the dessert or cooking bananas (Fig. 2). In this ploidy group, bunch weight was highest for two cooking bananas, 'Cardaba' and 'Fougamou', but appeared to be stable across environments only in the latter. 'Pisang Ceylan' (dessert banana) also expressed good stability together with a higher than average bunch weight. Among the tetraploid hybrids, 'FHIA23' (dessert banana) was the only genotype that expressed both high bunch weight and low IPCA1 score, indicating its stability across environments for this trait (Fig. 2). Most of the other high-yielding hybrids, e.g., 'FHIA3' (cooking banana), displayed specific adaptation to alleycropping. Among the plantain hybrids, 'FHIA21' had the highest IPCA1 score while 'PITA3' had the lowest. However, both hybrids produced smaller than average bunches. Only four ('PITA1', 'PITA2', 'PITA5', and 'PITA7') of the 13 plantain hybrids assessed

Fig. 4. AMMI1 biplot for dry matter content (%). PC = plant crop and RC = ratoon crop. The horizontal line indicates the zero ICA1 score while the vertical line represents the dry matter content grand mean. Codes used for cultivar or hybrid designation are given in Table 1.

produced large bunches. This was associated with relatively high IPCA1 scores (Fig. 2).

Pulp weight was also lowest in the plantains, but two genotypes, 'Agbagba' and 'Obino l'ewai', had near-zero IPCA1 scores, reflecting their stability for this trait, in comparison with other genotypes (Fig. 3). The dessert banana 'Valery' also had a near-zero IPCA1 score that was associated with a greater pulp yield than for plantains. Most cooking banana landraces expressed relatively high pulp yield, but none was stable for this trait. Among the tetraploid hybrids, only 'FHIA3' expressed both high pulp yield and near-zero IPCA1 score. However, one dessert banana hybrid ('FHIA1') and three plantain hybrids ('PITA1', 'PITA2', and 'PITA7') had relatively high pulp weight associated with |IPCA1| scores ≤ 0.5 .

Dry matter content appeared to be more stable across environments than bunch weight

and pulp weight, regardless of ploidy or genome classification (Fig. 4). Among the triploid into the plantain germplasm may shorten the landraces, only 'KM5', a dessert banana, mark-crop cycle of the hybrids, but dry matter content is also reduced (Vuylsteke et al., 1997). Nonetheless, plantain hybrids 'PITA1', from the zero score were observed for two 'PITA2', and 'PITA7' combined high bunch cooking banana hybrids ('BITA2' and 'FHIA3') and one plantain hybrid ('FHIA21').

Discussion

The occurrence and magnitude of genotype $\times$ environment interaction complicate the selection of appropriate cultivars, particularly when this results in re-ranking of genotypes across environments. This type of interaction was observed in this study, suggesting that field testing of prospective cultivars should be performed over a larger geographical and temporal scale. Ortiz (1997) has reported on the phenotypic and genetic correlation among several banana hybrids. However, pulp weight and other indicators of postharvest processing value, hence market potential, were not included in his study. Determination of the genetic relationships between processing traits and farm gate traits could allow *Musa* breeders

Our study suggests that the adaptation patterns of genotypes across environments varies according to the trait studied. For example, 'Cardaba' expressed the highest bunch weight, but was less stable than 'Fougamou', which ranked second for bunch weight among triploid entries (Fig. 2). In contrast, pulp weight, the edible component of bunch weight, was greater in 'Fougamou' than in 'Cardaba', with similar stability indices (Fig. 3). Dry matter content was also greater in 'Fougamou' but less stably expressed than in 'Cardaba' (Fig. 4). Rank reversal was also displayed by 'FHIA23', which was second best for bunch weight (Fig. 2) but second worst for dry matter content (Fig. 4), among the tetraploid hybrids. Similar trends can be defined for many other genotypes, regardless of genome or ploidy classification. When rank changes were not observed across traits for a genotype, variation was still observed in the relative magnitude of the IPCA1 score. Thus, prospective cultivars should be selected based on a combination of traits, rather than just yield. Failure to do so may reduce the rate of cultivar adoption (Plucknett et al., 1987). For example, 'Cardaba' was released in southeastern Nigeria as a temporary substitute for disease-prone plantains (Ferris et al., 1997). It was selected because of high bunch weight even under severe pressure from black sigatoka. However, this cultivar had much lower dry matter content than the plantains, which reduced its suitability for traditional processing options in Nigeria. Adoption rates markedly improved only after novel postharvest processing techniques were developed by IITA several years after the official release. Adoption rates might have been greater for 'Fougamou', a cooking banana with lower bunch weight than 'Cardaba'. However, 'Fougamou' was more stable for bunch weight, produced more pulp (the edible component of the bunch), and was closer to the plantains in dry matter content, and hence might have had a greater market potential than 'Cardaba'.

The plantain landraces are notably higher in dry matter content, but also generally display longer growth cycles, than other *Musa* genomic groups (Baiyeri et al., 1999). The introgression of genes for resistance to black Sigatoka disease from wild diploid bananas into the plantain germplasm may shorten the growth cycle, but dry matter content is also reduced (Vuylsteke et al., 1997). Nonetheless, plantain hybrids 'PITA1', 'PITA2', and 'PITA7' combined high bunch weight with high dry matter content. The former characteristic resulted from a genuine increase in dry matter production. This contrasted with the high bunch weight in dessert and cooking bananas that was primarily due to increased

to construct selection indices that would facilitate multiple trait selection and enhance breeding efficiency, with respect to cultivar stability and adaptation across environments.

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