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How fertilization affects yam (*Dioscorea alata* L.) growth and tuber yield across the years

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This study deals with the response of *Dioscorea alata* to NPK-Ca fertilization as affected by differences in weather conditions in two growing seasons. Experiments were conducted in the central Côte d'Ivoire in 2006 and 2007. The experimental design was a randomised complete block design with 4 replications. The dose of 160-10-180-110 kg ha⁻¹ of NPK-Ca, respectively was compared to the control (no fertilizers applied). Growth parameters and weather conditions were measured during the growth periods. Rainfall and solar radiation varied much between the two years. Fertilization has significantly increased the tuber yield of both years. In 2006, however, this increase in aboveground organs dry matter was not reflected in tuber dry matter increase, suggesting possible physiological imbalance in which fertilizer has favoured top growth over the tubers. This resulted in higher leaf area index and lower fresh tuber yield. This physiological imbalance could be related to higher water supply during the vegetative period in 2006. Although the weather conditions varied much between years, the leaf area index and the fresh tuber yield were similar between years under non-fertilization, indicating a good adaptation of *D. alata* to low soil fertility across the year. Explanations are needed to understand source (leaves) - sink (tubers) relationship in yam and investigation to clarify implications of mineral fertilizers in this important process is warranted.

Key words: Dry matter partitioning, fertilization, leaf area index, radiation use efficiency, water distribution, year.

INTRODUCTION

Yam (*Dioscorea* spp) is important for food security in West Africa which produces more than 90% of the worldwide production (FAO, 2009). Besides their importance as food source, yam also plays a significant role in the socio-cultural lives of people in some producing regions like the celebrated New Yam Festival in West Africa (Osunde and Orhevba, 2009) and wedding ceremonies in Oceania (O'Sullivan, 2008). Yam also provides cash income for a wide range of smallholders, including many women as producers, processors and traders (Assiedu, 2003). Therefore, improving yam productivity can increase food production and farmers' income in the producing areas, particularly in West Africa.

Progressively declining yam yields and loss of soil fertility, while at the same time having to produce their crops on increasingly scarce land, are the consequences small farmers face (Oikeh et al., 1999). The decline of yam yields associated with loss of soil fertility has led to conclude that yam requires high level of nutrient for growth (O'Sullivan and Ernest, 2008). Nitrogen (N) and potassium (K) are largely exported by the tubers (Diby, 2005; O'Sullivan and Ernest, 2008) while the calcium (Ca) is mainly accumulated in the leaves and returns to the soil with dead leaves (Diby, 2005). Organic fertilizer applied in yam has been shown to often slightly increase tuber yield in West African savannah zone (Kowal and Kassam, 1978). By contrast, the addition of inorganic fertilizer (mostly NPK) to improve tuber yield, generally, was uneven (IITA and CIRAD, 2003; O'Sullivan and Ernest, 2008). Recently, the application of inorganic fertilizer (NPKCa) to yam had no effect on the fresh tuber yield but; it increased significantly the shoot growth (Diby et al. 2009).

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However, the reasons explaining the variability of the tuber yield responses to mineral fertilizers application have not been fully investigated.

Yield in yam also varied greatly in space. In the central Côte d'Ivoire, the best yield was about 12.4 t ha⁻¹. In the more humid south of the country, the yield was higher and further north it was lower (Soro, 2007; Doumbia, 1995). Yield reported in literature for yam were not usually associated with information about climatic growth conditions or the history of the field so that it is very difficult to understand this variability and thus, investigation to clarify these differences is warranted. The fact that yam does not clearly respond to nutrient inputs and/or varies greatly in time and space might be related to the plant physiology which in some growth conditions would favour the top growth over the tuber growth. The tuber yield in yam is mainly determined by the total biomass production and its partitioning between the various plant organs (Rodriguez-Montero, 1997). However, both photo-synthetic rate and assimilate partitioning, themselves, depend strongly on the developmental stage of the plant and environmental factor such as soil fertility, water supply and intercepted solar radiation (Sotomayor-Ramirez et al., 2003). Hammer and Wright (1994) had frequently used the crop radiation use efficiency (RUE, g MJ⁻¹), which measured the amount of biomass accumulated for each unit of total solar radiation intercepted by the leaf canopy, in the calculating accumulation of crop biomass. Moreover, Sinclair and Shiraiwa (1993) and Wright and Hammer (1994) demonstrated that the sensitivity of leaf photo-synthetic rates to changes in leaf nitrogen was mainly due to the important variation in RUE. Yam is basically a creeping plant with leaves spreading on the ground or creeping on stakes. Its growth duration is long, 7 - 12 months depending on species and climate (Melteras et al., 2008). Due to the length of the growth cycle and the relatively late development of leaf area in yams, Onwueme and Haverkort (1991) stated that the solar radiation during the entire season may not be critical as the solar radiation in the second half of the season, when the requisite leaf area is already in place. Furthermore, in some of the most humid parts of the yam growing areas, persistent cloud cover during the growing season tends to keep total radiation relatively low for the duration of crop growth.

This study was undertaken to evaluate the growth and tuber yield responses to mineral fertilization over two growing seasons in *D. alata*. For better understanding plant growth and tuber yield responses to fertilization, the soil and climatic growth conditions were described during the two growing seasons.

MATERIALS AND METHODS

Site characteristics, planting material and cultural techniques

Experiments were conducted during the yam growing season from May to December in 2006 and 2007 in central Côte d'Ivoire at the

field station of the Swiss Center for Scientific Research based in Bringakro (6°40'N, 5°09'W). The region is characterized by a transitional equatorial climate zone at the interface between a moist semi-deciduous forest and a shrub savannah. Rainfall distribution was characterized by a bimodal distribution pattern with two rainy seasons from May to June and from September to October between them a small dry season was observed. Soil of the experimental site was classified as ferralsol (Ettien et al., 2009). Land was cleared of vegetation and plant debris was removed.

An improved cultivar of *D. alata*, TDa 95/00010, selected by the International Institute of Tropical Agriculture, was grown in a mound on savannah side at the density of 1 plant m⁻². The experiment was conducted in four replicates per treatment and the plot was randomly assigned to the field. Each plot had 36 plants, the plot size being 4 x 9 m². At each plot, setts were planted in rows with a distance of 1 m between plants and an interrow distance of 1 m. Each plot consisted of a border row to overcome border effects and two inner rows which have served for sampling. Treatment included the control (no fertilizers applied, treatment -F) and the dose of 160 kg N ha⁻¹, 180 kg K ha⁻¹, 10 kg P ha⁻¹ and 110 kg Ca ha⁻¹ (treatment +F). Fertilizers were applied in two equal splits by broadcasting at the maximum growth of the aerial organs (90 days after planting (DAP)) and during tuber bulking (130 DAP). Head mother setts were used for planting. Setts were treated against nematode, insect and fungi the day before planting. During the growth cycle, the plots were kept weed-free through monthly manual weeding.

Measurements

Soil samples were taken in the 0 - 20 cm depth before planting in 2006. The soil samples were air-dried and ground to pass through a 2 mm sieve. Thereafter, soil texture, pH, total N and C, Olsen P, exchangeable K, Ca and Mg and cation exchange capacity were analysed using routine analysis method.

In both 2006 and 2007, the incoming solar radiation and rainfall were measured during the growing seasons using an automated weather station (<http://www.delta-t.co.uk>) installed on the experimental site.

In each growing season, 2-plants per plot were destructively sampled at vegetative growth phase (75 DAP), at tuber initiation period (100 DAP), during the tuber growth phase (130 and 160 DAP), at tuber maturation phase (190 DAP) and at harvest time (220 DAP). At each sampling date, plants were separated into leaves, vines, roots and tuber and oven-dried at 70°C for 72 h to assess their dry matter content. The sum of dry matter produced by separate organs gave the total plant dry matter production and the dry matter of aboveground organs was obtained as the sum of leaves dry matter and vines dry matter. The fresh tuber yield was measured at harvest.

At each sampling date, all the leaves collected were counted per plot. The area of a 30-sample leaves was measured with a scanner connected to a computer program (<http://regentinstruments.com>) which gave the scanned areas automatically and then the total leaf area was determined by multiplying the average leaf area for this sample to the total number of leaves per plot. The total leaf area per plot was then divided by the plot area to determine the leaf area index (LAI).

The efficiency of tuber production by the plant (ETP) was determined by the slope (α) of the linear regression $y = \alpha x + \beta$ between tuber dry matter (y) and total plant dry matter (x) (Chowdhury, 1998; Gray, 2000).

According to Bonhomme (2000), the radiation use efficiency (RUE) was derived from the slope of the linear regression between the accumulated dry matter and the cumulated photosynthetic active radiation intercepted (PARI):

$$y = \text{RUE} \cdot x + b \quad (1)$$

Where; y represents the total dry matter accumulated by the plant; x represents the cumulated photosynthetic active radiation intercepted. b is the intercept of the model.

The photosynthetic active radiation (PAR) was assumed to be equivalent 45% of the solar radiation (Manrique et al., 1991). According to Pengelly et al. (1999), the fraction of photosynthetic active radiation intercepted (FPARi) by the canopy was calculated by the following formulas:

$$\text{PARi} = 1 - (\text{PAR}_b / \text{PAR}_a) \quad (2)$$

Where; PAR_a is the incoming PAR measured just above the crop canopy; PAR_b is the PAR measured beneath the canopy.

PAR_a and PAR_b were measured instantaneously in each plot using a 1 m line sensing (Sunscan Canopy Analysis System, www.delta-t.co.uk). These measurements were carried out in both 2006 and 2007 at each sampling date. The amount of PAR intercepted by the canopy was calculated as follow:

$$\text{PARi} = \text{FPARi} * \text{PAR} \quad (3)$$

The cumulated PARi for each DAP was calculated as the sum of the daily PARi from planting to the DAP considered.

Statistics and data analysis

Analysis of variance was performed using the general linear model in SAS version 9.1 to test the effect of year and fertilization dose on plant dry matter production and the LAI at each sampling date. Means were compared with the least significant difference (LSD) at $P < 0.05$. Graphs were performed using Origin 6.0.

The regressions from which derived the ETP and the RUE were performed using the regression procedure (PROC REG) in SAS version 9.1. The contrast method was used to compare the slopes between equations. Graphs were performed using SigmaPlot 10.0.

RESULTS

Soil and climatic growth conditions

The soil of the experimental site was acidic with a sandy loam as texture. It was characterized by low erodibility, poor in exchangeable potassium (K), magnesium (Mg) and calcium (Ca) and low in organic matter (Table 1).

The distribution pattern of solar radiation during the growing season was similar between years (Table 2). It declined from May to July, remained fairly constant between July and September and then increased again until the growth ended. However, total solar radiation recorded in 2006 was higher of about 109.6 MJ m⁻² than in 2007. By contrast, the distribution pattern of the rainfall differed markedly between years. The rainfall was well distributed over the growing season in 2007 while, in 2006, because of water shortage observed in July, August and November; water of 420 mm has been supplied by irrigation. In total, 1165 and 1012 mm of water was supplied for plant growth in 2006 and 2007, respectively. Finally, total water supply during the entire growing cycle was relatively higher in 2006 than in 2007. Irrigation in 2006 induced a higher water supply of about 209 mm

Table 1. Mean values \pm standard errors of soil properties at 0 – 20 cm depth of the experimental site in 2006 after clearing the natural vegetation.

Soil properties	0 - 20 cm
Clay (%)	30.1 \pm 3.1
Fine silt (%)	33.8 \pm 4.2
Coarse silt (%)	36.2 \pm 2.5
Exchangeable Ca (cmol kg ⁻¹ soil)	1.2 \pm 0.1
Exchangeable Mg (cmol kg ⁻¹ soil)	0.8 \pm 0.02
Exchangeable K (cmol kg ⁻¹ soil)	0.07 \pm 0.01
CEC† (cmol kg ⁻¹ soil)	2.8 \pm 0.3
pH (in water)	5.4 \pm 0.3
Total C (g kg ⁻¹ soil)	5.7 \pm 0.9
Total N (g kg ⁻¹ soil)	0.7 \pm 0.01

†CEC: Cation exchange capacity

Table 2. Monthly solar radiation and rainfall recorded during the growing season of *D. alata* in 2006 and 2007.

Month	Solar radiation [MJ m ⁻²]		Rainfall [mm]	
	2006	2007	2006	2007
May	108.0	91.7	142	90
June	102.1	88.9	189	167
July	87.6	78.2	60 (+130)†	177
August	82.6	67.1	41 (+230)†	140
September	86.5	65.4	183	195
October	97.9	79.6	108 (+60)†	165
November	91.8	75.9	22	78
Total	656.4	546.9	1165	1012

† Amount of water added by irrigation

during the vegetative period from May to October. However, water supply in November was higher in 2007 (78 mm) than in 2006 (22 mm). Climatic growth conditions clearly varied much between the two years.

Plant growth parameters

At the maximum growth period at 160 DAP, fertilisation has significantly increased the leaf area index (LAI) in 2006 (LAI = 9) but not in 2007 (Figure 1). The leaf area index in fertilized treatments in 2007 (LAI = 5) was not significantly different with those in non-fertilized treatments in 2007 (LAI = 3) and in 2006 (LAI = 5).

The effect of fertilization and year on total plant dry matter production was observed from the maximum growth stage (160 DAP) to harvest time at 220 DAP (Figure 2). During this period, total plant production in fertilized treatment was significantly higher ($p < 0.05$) than in non-fertilized treatment in both years. Comparison between years indicates that total dry produced in 2006 was significantly higher ($p < 0.05$) than in 2007 at 160 and

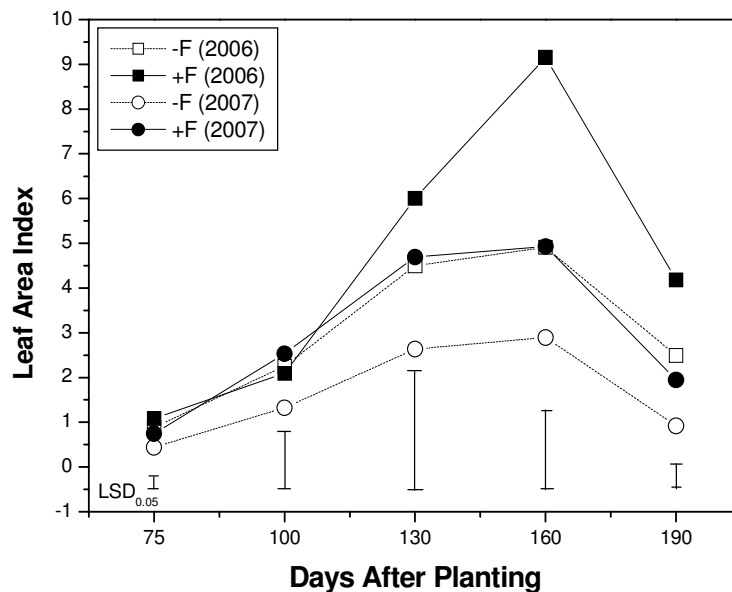


Figure 1. Leaf Area Index as affected by the fertilization and the year in *D. alata*. Bars are LSD at $p < 0.05$.

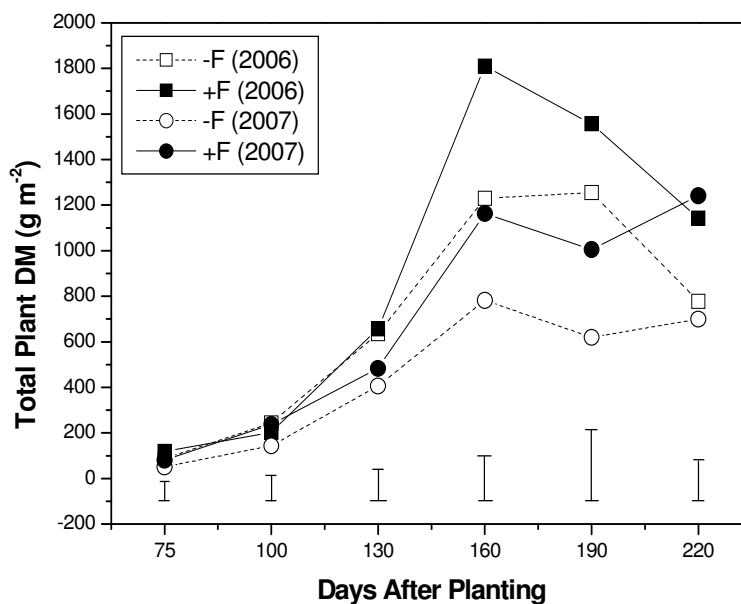


Figure 2. Effect of fertilization and year on total dry matter production in *D. alata*. Bars are LSD at $p < 0.05$.

190 DAP with respect to fertilization dose. The total plant production was similar between years at 220 DAP for each fertilization dose.

The effects of year and fertilization on dry matter partitioning between aboveground organs (leaves and vines) and tubers over time were presented in Figure 3. At the maximum dry matter production (160 DAP), aboveground organs dry matter production was significantly higher ($p <$

0.05) with fertilization than without fertilization (Figure 3a). Comparison between years indicates that dry matter production in the aboveground organs was significantly higher ($p < 0.05$) in 2006 than in 2007 during the tuber bulking phase (160 to 190 DAP) in both treatments. At the harvest time (220 DAP), aboveground organs production was significantly different neither between fertilization doses nor between years (Figure 3a). The reverse trend was

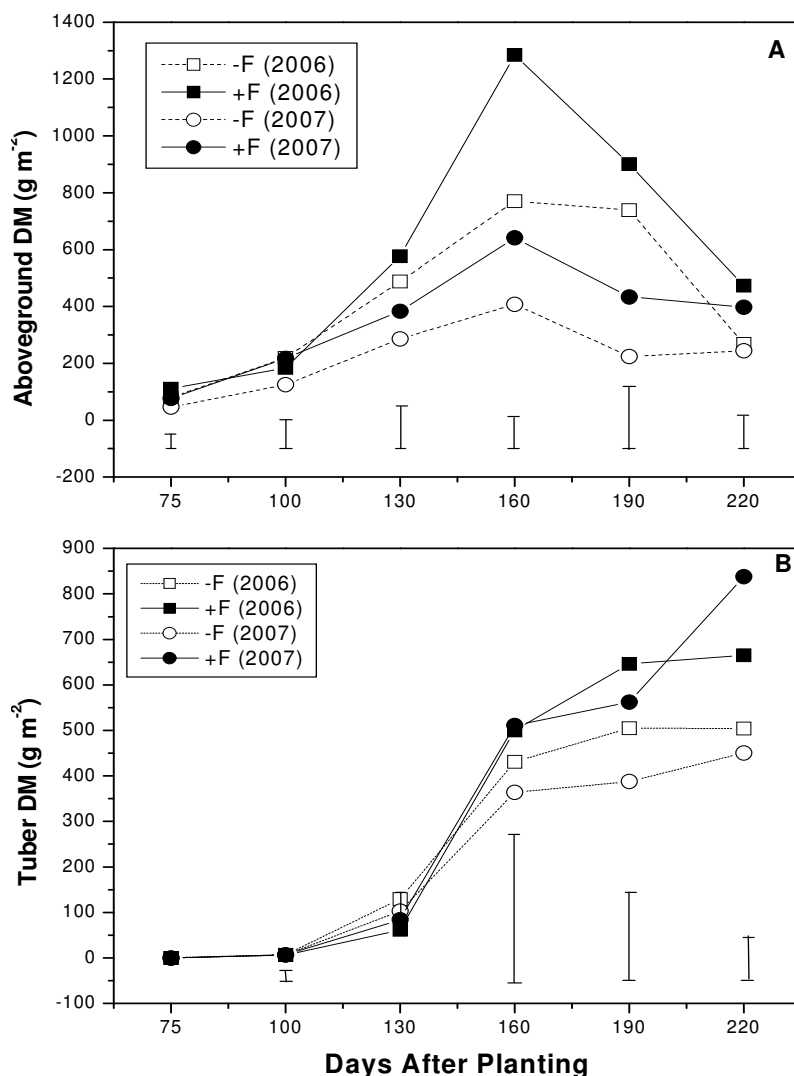


Figure 3. Effect of fertilization and year on dry matter (DM) partitioning into aboveground organs (A) and tubers (B) in *D. alata*. Bars are LSD at $p < 0.05$.

was observed with the tubers dry matter production in which year and fertilization effects were observed only at harvest (Figure 3B). At this time, tuber dry matter production was significantly higher ($p < 0.05$) under fertilization in both years. When comparing the year, the Figure 3B shows that tuber dry matter production in 2007 was significantly ($p < 0.05$) higher than in 2006 under fertilization but; under non-fertilization, no significant differences were observed between years. The Figure 3 indicates also that the year interacted with sampling date for dry matter partitioning into aboveground organs and tubers only at 220 DAP under both treatments. The dry matter partitioned into aboveground organs decreased drastically during the tuber maturation phase (190 to 220 DAP) in 2006 while; it remained fairly constant in 2007. Conversely, tuber dry matter increased sharply in 2007 during this period particularly under fertilization while; it

remained fairly constant in 2006.

The radiation use efficiency (RUE) was significantly affected ($p < 0.001$) by the year with higher values (1.22 and 1.31 g MJ^{-1}) observed in 2007 (Figure 4). The effect of fertilization on the RUE was observed only in 2006 with higher value (1.03 g MJ^{-1}) observed under fertilization.

The efficiency of tuber production (ETP) was significantly affected ($p < 0.05$) by the year but not by fertilization within a year. The Table 3 shows that the values of ETP observed in 2006 (0.45 and 0.36) were practically doubled in 2007 (0.71 and 0.73) under both fertilization and non-fertilization growth conditions. Fresh tuber yield obtained in this study was significantly higher ($p < 0.05$) under fertilization in both years but yield in 2007 (43 t ha^{-1}) was higher in 2006 (34 t ha^{-1}). Under non-fertilization, the fresh tuber yield (24 t ha^{-1}) was similar between years.

Table 3. Observed values for the efficiency of tuber production (ETP) in 2006 and 2007 under fertilized and non-fertilized treatments in *D. alata*

Year	Treatment	ETP [g tuber DM (g) total DM ⁻¹]	β [g m ⁻²]	r ²
2006	-F	0.45b	-39.2	0.53*
2006	+F	0.36b	-32.7	0.68**
2007	-F	0.71a	-101.5	0.81***
2007	+F	0.73a	-202.8	0.90***

Means following by similar letter are not significantly different at $P < 0.05$. -F = non-fertilized, +F = fertilized. ***: significant at $p < 0.001$

DISCUSSIONS

The soil of experimental site was poor as it was characterized by low exchangeable potassium (K), magnesium (Mg) and calcium (Ca) and poor in organic matter and confirmed those already reported for the region (Kone et al., 2008; Diby et al., 2009). Nitrogen (N) is known to be one of the most important single factors limiting the production of the yam tuber (Aduayi and Okpon, 1980) but, recently, Diby et al. (2009) reported that potassium (K) may be more limiting to yam growth than N. As a consequence, the additional fertilizers (NK) were plentiful in our study. On the contrary, phosphorus (P) was applied in low amounts as its demand by yam is low (Vander Zaag et al., 1980; Diby, 2005). The calcium (Ca) was also applied in large amounts in our experiment as its deficiency in yam growth may cause a shift in tuber: shoot sink strength (O'Sullivan and Jenner, 2006).

Fertilization has significantly increased fresh tuber yield in this study. This suggests that the dose of 160 kg N ha⁻¹, 180 kg K ha⁻¹, 10 kg P ha⁻¹ and 110 kg Ca ha⁻¹ may be recommended for *D. alata* production as Ettien et al. (2009) have recommended the dose of 120 kg N ha⁻¹, 103 kg K ha⁻¹ and 38 kg P ha⁻¹ for *Dioscorea rotundata*. However, our results are in contrast with those reported by Sotomayor-Ramirez et al. (2003) in Puerto Rico, O'Sullivan and Ernest (2008) in Oceania and Diby et al. (2009) in Côte d'Ivoire for *D. alata*. The response of the plant to fertilization may be affected by many factors such as climatic growth conditions, cultural practices and soil (Below, 2001). The lack of tuber yield responses to fertilization in these studies might be due to pest and diseases (Sotomayor-Ramirez et al., 2003) or the closeness of fertilized and non-fertilized plots as the length of roots can reach 5.5 m (O'Sullivan, 2008). In our experiment, no major pest and diseases attacks were observed during the 2 years of experiments. Furthermore, the roots were essentially grown inside the mound (Hgaza, CSRS, personal information). Contrary to Diby (2005) which applied fertilizer by banded side-dressings, fertilizers were applied by broadcasting in our study. Broadcasting usually yielded as much or more than four fertilizer placement methods including banded side-dressings (Nwinyi and Enwezor, 1985).

In overall, fertilization has increased yam growth and

tuber yield. In 2006, however, this increase in above-ground organs dry matter was not reflected in tuber dry matter increase, suggesting possible physiological imbalance in which fertilizers have favoured top growth over the tubers. This physiological imbalance could be related to the amount of water supply and its distribution over the growing season, irrigation in 2006 induced a higher water supply of about 209 mm during the vegetative growth phase (75 DAP in July to 130 DAP in September) and the first half of the tuber bulking phase (130 DAP to 160 DAP in October). As a consequence, fertilizers applied at 90 JAP (in July) and 130 DAP (September) had increased aboveground organs growth over the tuber. Water shortage observed during the second half of tuber bulking phase (22 mm of rainfall in November) associated with higher solar radiation may have precipitated aboveground organs senescence as their dry matter declined drastically without causing a subsequent increase in tuber dry matter. The effects of rainfall amount and distribution already reported in yam (Diby et al., 2009). The author reported that yam productivity was better under most humid growing season than dry growing season.

Higher LAI observed in 2006 may also account for lower tuber production in this year. *D. alata* with an indeterminate growth habit (Onwueme and Haverkort, 1991) has continued to produce new foliage and the LAI obtained under such conditions was 9. This value was three times higher than optimal LAI of 3 to 3.5 reported for cassava and potato (Kleinkopf et al., 2003; Ramanujam, 1987). This indicates that the LAI of 9 was excessive. Despite the high amount of solar radiation, the excessive LAI of 9 has probably caused a worse distribution of sunlight into the canopy resulting in lower RUE (1.03 g MJ⁻¹) and then would depress the whole canopy photosynthetic capacity (Sinclair and Muchow, 1999) as the efficiency of tuber production (0.36) was lower in this year. By contrast, the LAI of 5 observed in 2007 would allow better distribution of sunlight into the canopy resulting in higher RUE (1.31 g MJ⁻¹) and then would enhance the whole canopy photosynthetic capacity as the efficiency of tuber production (0.73) was higher in this year. These results suggest that the lower solar radiation of 2007 was probably enough to saturate the photosynthetic capacity of yam. Thus, the LAI of 5 was better for yam tuber production than LAI of 9. Our data seemed to

provide evidence of source (leaves) for assimilants' limitation due to worse distribution of water over the growing season. Diby et al. (2009) reported that yam is sensitive to water stress during the vegetative growth phase and at tuber bulking phase. May be too much water has been added by irrigation during vegetative growth phase in 2006. Thus, this has probably caused the imbalance between source and sink for assimilants. Crop yield is linked with photosynthetic efficiency of the source and partitioning of the photoassimilate to the economic sink (Gifford et al., 1984). As early as, Onwueme (1978) supported that the balance between source (leaves) and sink (tubers) is a determining factor in yam yield formation. The scarce data on this topic about yam is provided by Rodriguez-Montero (1997). This author found a feedback effect of sink on source photosynthetic capacity when the tuber size was reduced by physically enforced reduction. However, a drastic source reduction (75% shade) led to more dry weight accumulation in above-ground organs than in tubers. The author concluded that in yam dry matter partitioning appears to be governed by a preference for top growth like in cassava (Cock et al., 1979).

Although weather conditions clearly varied much between the 2-years, the LAI and tuber production was similar between years under non-fertilization. This confirms a good adaptation of *D. alata* to low soil fertility as reported by Kowal and Kassam (1978) and Diby et al. (2009).

Conclusions

The fertilizer applied in this study has significantly increased aboveground organs growth and the subsequent yield in *D. alata*. In 2006, however, the increase in aboveground organs dry matter was not reflected in tuber dry matter increase, probably due to possible imbalance between source (leaves) and sink (tubers) in which fertilizers (NPKCa) had favoured leaves growth over the tubers. This physiological imbalance may be related to bad water supply and distribution over the growth season in 2006. By contrast, *D. alata* has shown a good adaptation through the years under non-fertilization growth conditions by producing similar yield. From these results, explanations are needed to understand source-sink relationship in yam and investigation to clarify implication of mineral fertilizer in this important process is warranted.

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