Management Effects on Yam Production in Benin Republic
- Experimental Analysis and Modeling -

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Bonn, den 30. Oktober, 2009

Amit Kumar Srivastava

“Nature does nothing uselessly”

Aristotle (384-322 BCE.)

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Dedication

To my parents

Abstract

Declining productivity in the Republic of Benin (West Africa) highlighted the need for a study to determine both the effect of fertilization on yam (*Dioscorea* spp.) yield and biomass production, as well as the best agronomic management options available for stabilizing yam productivity, via the modeling of yam growth and development. This study addressed the above issues by conducting plot experiments in the Benin Republic, which analyzed the effect of mineral fertilizer, manure and crop residue application on total biomass production, tuber yield and dry matter partitioning pattern, in two species of yam (*Dioscorea alata* var. Florido and *Dioscorea rotundata var.* Kokoro). Significant positive effects of mineral fertilizer were observed on yam total biomass production and tuber yield, but the magnitude of its effect were dependent on the species of yam. Crops receiving crop residues and manure also registered increases in yield, but were not significantly different from the yield under unfertilized conditions. Regarding partitioning pattern of dry matter to different plant organs, no significant difference was observed between control and fertilized treatments. An attempt has been made to simulate the effect of fertilization and fallow availability on yam (*Dioscorea alata* var. Florido) production by using the Environmental Policy Integrated Climate (EPIC) model. A new crop parameter file for *Dioscorea alata* was developed. The model accurately simulated the effect of fertilizer on the yam yield as indicated by a relatively low mean relative error (MR) ranging from 4.3 to 9.7 %. Different scenarios of fallow availability (Scenario S1 [100 % of the bush savannah is available as fallow land], Scenario S2 [50% of the bush savannah is available as fallow land] and Scenario S3 [25% of the bush savannah is available as fallow land]) were explored in the Upper Ouémé basin of Benin Republic (West Africa) by incorporating the EPIC model into the spatial decision support system (SDSS) PEDRO (Protection du sol Et Durabilité des Ressources agricoles dans le bassin versant de l'Ouémé). The best agreement between simulated and observed crop yields was found under the assumption that 50% of the bush savannah is available as fallow land under the prevailing cropping patterns. The results show the capacity of the EPIC model in connection with the SDSS PEDRO to capture both the biomass production and sensitivity of regional yields of yam to fallowing. They further reveal how a crop model can be used to analyze fallow practices at the regional scale. However, the models accuracy is most likely to be improved by a more detailed modeling of the phenological development of yam. In order to increase yam productivity and maintain soil fertility in the Upper Ouémé basin, fallowing the crop land is not a viable option due to increased demographic pressures. Mineral fertilizer application appears to be essential, but its high cost and accessibility restraints, limit its use by the farmers. The solution lies in providing mineral fertilizers to the farmers at subsidized rates. Additionally, nitrogen fixing crops could partially provide the N inputs needed, if included within crop rotations.

Kurzfassung

Abnehmende Produktivität von Yam (*Dioscorea* spp.) bedingt durch Einschränkungen der Bodenfruchtbarkeit in der Republik Benin (West-Afrika) erfordern eine Analyse der Auswirkungen von Düngungsmaßnahmen auf das Wachstum und die Biomasseproduktion von Yam. Diese Analyse wird begleitet von der Modellierung der Entwicklung und Ertragsbildung von Yam um geeignete Managementoptionen zur Stabilisierung der Erträge zu identifizieren. Dazu wurden in der Republik Benin in einem ersten Schritt Feldexperimente durchgeführt, um die Auswirkungen der Anwendung von Mineraldüngern, Mist undErnterückständen auf die Biomasseproduktion, Knollenerträge und Trockenmasseverteilung in zwei Yam-Arten (*Dioscorea alata* var. Florido und *Dioscorea rotundata* var. Kokoro) zu untersuchen. Durch den Einsatz von Mineraldüngern wurden signifikant positive Effekte auf die Biomasseproduktion und die Knollenerträge beobachtet, jedoch hingen diese Effekte von der Art und der Düngermenge ab. Bei der Anwendung von Ernterückständen und Mist wurden ebenfalls Ertragszuwächse festgestellt jedoch unterschieden sich diese nicht signifikant von den ungedüngten Varianten. Bezüglich der Verteilung der Trockenmasse in die einzelnen Pflanzenorgane konnte kein signifikanter Unterschied zwischen gedüngten und ungedüngten Varianten festgestellt werden.

Basierend auf den Daten der Feldexperimente wurde der Versuch unternommen die Effekte der Düngung sowie Bracheeffekte auf die Produktivität von Yam (*D. alata* var. Florido) mit dem EPIC (Environmental Policy Integrated Climate) Modell zu simulieren. Für Dioscorea alta wurde ein neuer Datensatz von physiologischen Parametern zusammengestellt. Mit diesem Datensatz simulierte das Modell hinreichend genau den Düngungseffekt auf den Ertrag von Yam ausgedrückt durch einen relativ kleinen relativen Fehler von 4,3 bis 9,7%. Unterschiedliche Landnutzungsszenarien mit unterschiedlicher Bracheverfügbarkeit [Szenario S1 (100% der Buschsavanne als Brache verfügbar), Szenario S2 (50% der Buschsavanne als Brache verfügbar) und S3 (25% der Buschsavanne als Brache verfügbar)] wurden im Oberen Einzugsgebiet des Ouémé untersucht, indem man das EPIC Modell in das räumliche Entscheidungsunterstützungssystem PEDRO einbaute. Die beste Übereinstimmung zwischen beobachteten und simulierten Erträgen erzielte man unter der Annahme dass, unter den momentanen Anbaubedingungen, 50% der Buschsavanne als Brache in der Rotation mit den Kulturpflanzen zur Verfügung stehen. Die Ergebnisse zeigen das Potential des EPIC Modells, in Verbindung mit dem SDSS PEDRO, die Biomasseproduktion und die Sensitivität des regionalen Yam-Ertrages auf die Veränderung der Bracheverfügbarkeit zu erfassen. Es wurde aufgezeigt, wie ein Pflanzenwachstumsmodell dazu beitragen kann die Anbaupraktiken in Brachesystemen auf regionaler Ebene zu analysieren. Allerdings könnte die Genauigkeit des Modells

voraussichtlich weiter verbessert werden, indem man die die phänologische Entwicklung der Yam-Pflanzen in detaillierterer Weise beschreiben würde. Um die Produktivität im oberen Einzugsgebiet des Ouémé zu erhöhen und die Bodenfruchtbarkeit zu erhalten, ist die Brachewirtschaft kein nachhaltiges System angesichts des ständig steigenden Bevölkerungsdrucks. Die Anwendung von Mineraldüngern scheint unabdingbar, aber die hohen Kosten und das Verfügbarkeitsproblem erschweren die Anwendung durch die Bauern. Die Subventionierung von Mineraldüngern könnte eine Lösung für dieses Problem sein. Zusätzlich könnte ein Teil des Stickstoffbedarfs durch den verstärkten Einbau von stickstoffbindenden Pflanzen in der Fruchtfolge gedeckt werden.

CHAPTERS

CHAPTER 1

General introduction

1.1. Yam (*Dioscorea* spp.)

Yams are members of the genus *Dioscorea* and belong to the family Dioscoreaceae. Yams are dioecious plants and produce tubers and bulbils (aerial tubers) of economic importance. The stems are viny, leaves are cordate or ovate, tubers mostly cylindrical and rich in carbohydrate which make them suitable to be used as food (Mandal,1993). Tuber development is an evolutionary adaptation to a dry season, when leafy shoots die back and tubers become dormant (Purseglove,1972). During the evolution of the edible Dioscoreas, the thickening and lobbing of the ancestral rhizome gave way to a well developed tuber system (Burkill,1960). In most species, they are renewed and produced annually, while in others they are perennial. As crops, yams are harvested every season and replanted using tuber pieces to regenerate the plant. Unlike other tropical root and tuber crop species, once harvested, yams can be stored for 4-6 months in ambient tropical conditions without significant deterioration of their nutritional properties. Tubers are also often dried and later milled into flour for reconstituting as a stiff paste (fufu), which is highly appreciated in West Africa.

The family Dioscoreaceae comprises six genera but the genus *Dioscorea* is the major one. About 600 species of *Dioscorea* have been identified, among which 12 species are edible (Coursey,1976). Within this genus, edible and marketable species are: *Dioscorea rotundata* (white yam or Guinea yam), *Dioscorea alata* (greater yam or water yam), *Dioscorea esculenta* (lesser yam or Asiatic yam), *Dioscorea bulbifera* (aerial yam or potato yam) and *Dioscorea cayenensis* (yellow yam) which produces edible tubers and bulbils (aerial tubers located in the axils of leaves). Among these, *D. alata* (Figure 1) covers major areas in Asia, whereas *D. rotundata* and *D. cayenensis* is commonly cropped in Africa (Mandal,1993). Some *Dioscorea* species, like floribunda and composite, are appreciated due to their high tuber content of steroidal saponins, being used in the manufacturing of oral contraceptives, sex hormones and cortisone (Purseglove,1972; Applezweig,1977). The drug yams are still essentially wild species (Coursey,1976).

The English term “yam” is most likely derived from the Portuguese word, *ynhame*, found in early documents, itself being the transcription of *niam*, the word used in the Malinke language spoken widely through the Guineas, Sierra Leone and Ivory Coast (Coursey, 1976).

Yam tuber **Yam plant** **Yam cakes**

Figure 1: Yam (*Dioscorea alata*)

1.2. Domestication

Dioscorea alata is probably the most widely distributed cultivated yam species in the world and is likely also one of the oldest cultivated. It was not found in the wild and was thought, based on morphological affinities, to result from interspecific hybridization between two Asian species (*D. hamiltonii* and *D. persimilis*) (Burkill,1960). However, AFLP markers indicate that *D. alata* shares a common genetic background with *D. nummularia* and *D. transversa* (Malapa *et al.*, 2005a,b). As these two species do not occur on the western, Asian side of the Wallace line, it is possible that *D. alata* was domesticated after the arrival of the Australoids, 60,000 years ago on the Sahul plate, in the present New Guinea, or in Melanesia (Lebot, 1999). This geographic region is also the centre of diversity of the species (Martin and Rhodes, 1977; Lebot,1992; Lebot *et al.*,1998) and hundreds of different morphotypes exist.

In West Africa, Paleolithic man, while food gathering, most likely domesticated edible yams during his wanderings. A tuber from a wild plant can be removed without fatal damage to the vine and roots and the plant will recover and produce another one in a year or so. Possibly, hunter-gatherers noticed such an interesting phenomenon and would have come back regularly to harvest edible wild forms. Selection of the most palatable genotypes would then follow naturally. It has been suggested that this process could have started c. 7000 BP for West African yams (Dumont *et al.*, 2006), although there is no accurate dating to support this hypothesis.

In Benin, many cultivars are clones of edible wild forms and a few putative wild forms are probably feral plants escaped from cultivation. Some cultivars are also clones of hybrids between wild forms and feral or cultivated plants. Human selection operates on the most vigorous plants and vigor is sometimes associated with heterozygosity or heterotic effect.

1.3. Present Geographical distribution

Yams are now cultivated in about 50 tropical countries, but not all (e.g. China) provide their annual production statistics to the Food and Agriculture Organization (FAO). The world annual production is approximately 50 million t fresh tubers. More than 96% of it are cultivated in Africa. Four countries (Nigeria, Ivory Coast, Ghana and Benin) produce 90% of this output with more than 45 million t yr $^{-1}$. The greater yam, *D. alata*, is the most widely distributed species in the humid and semi-humid tropics and, together with *D. rotundata*, accounts for the greater part of world production.

A few temperate countries also grow yam (Japan, France) and this is where, thanks to the long days and maximum solar radiation, the highest yields are obtained, reaching more than 20 t ha^{-1}. Traditionally, and in most countries, yam farmers maintain a wide range of genetic diversity but as pressures on land availability increase, so fewer varieties are grown, intensifying the effects of yam diseases. The most important producing countries in Africa, Latin America, and Asia are presented in Table 1.

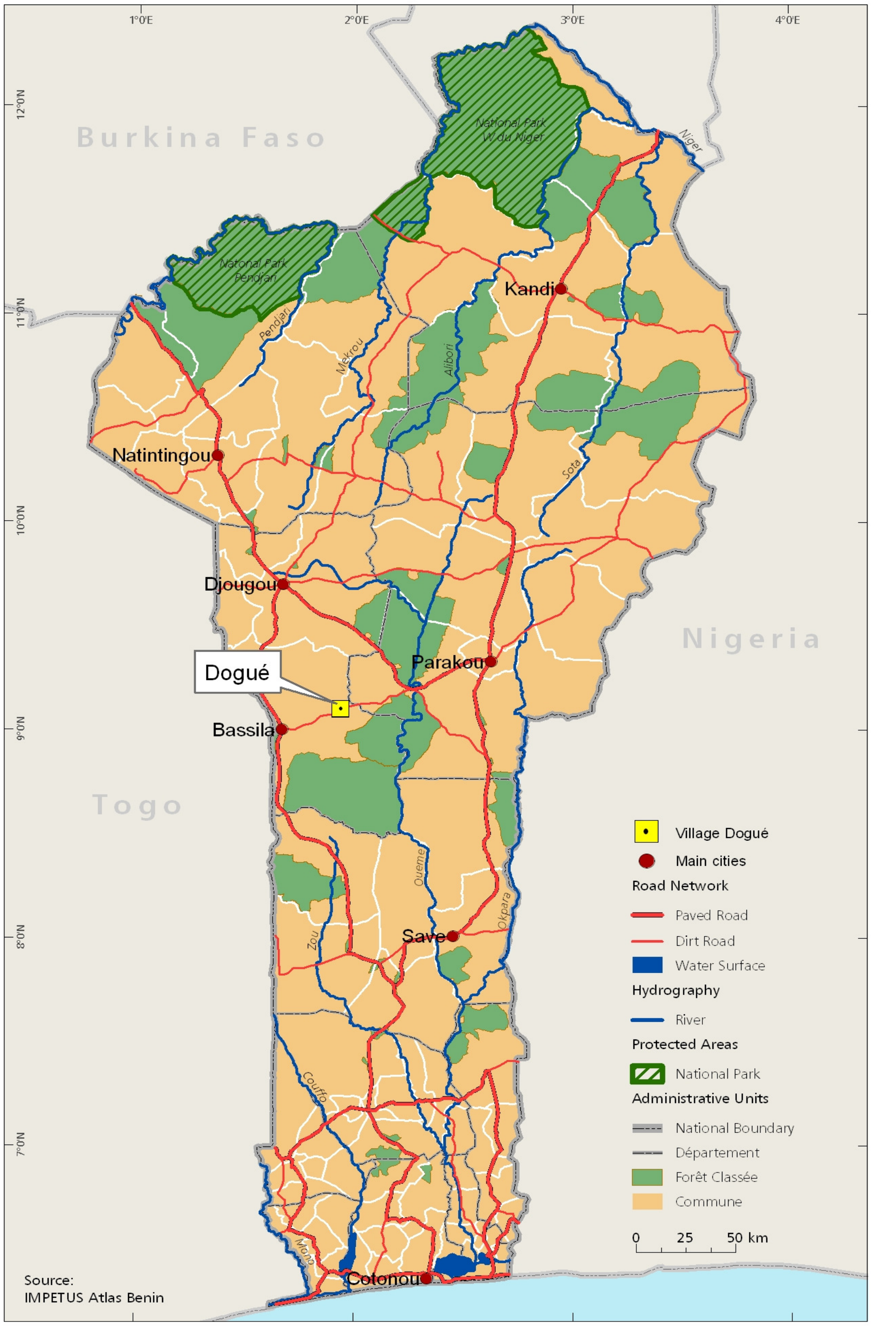
Table 1: Major yam producing countries in the world

Region	Country	Production(t *10^3)	Area (ha*10^3)	Av. yield (t ha^{-1})
Africa	Nigeria	34,000	2,957	11.5
	Ivory Coast	5,012	577	8.6
	Ghana	4,102	319.4	12.8
	Benin	2,084	178	11.7
America	Colombia	333	28	11.8
	Brazil	236	25.7	9.2
	Haiti	207	37.3	5.5
Asia	Papua New Guinea	256	15.5	16.5
	Japan	204	8.8	23.3

Source: www.fao.org (2007).

1.4. Geographical location of the study site

The experiments were carried out for six years (2001 to 2006) at Dogué village (Southern Donga Department) in Benin Republic (West Africa); which is located at 9° 06 N and 1° 56 E; at a distance of about 87 km from Parakou (Figure 2). The climate on the site is Soudano-Guinean. The rainfall distribution is unimodal with two seasons; a rainy season from mid of April to mid of October, and the subsequent dry season. The maximum temperature is 40℃ in the dry season, the minimum is 10℃ and the average is 25℃. On the average, rainfall shows its peak in August. First rainfall begins in March, and becomes significant from May to September, the period of intensive farming activities. Harmattan (cold and dry wind) and the monsoon (warm and humid wind) are the wind systems in the north of Benin, with harmattan as the dominating system.



Source:
IMPETUS Atlas Benin

Figure 2: Geographical location of the study area (Judex and Thamm, 2008).

1.5. Problem statement

Falling yam productivity has fuelled calls for increased research activities in yam – a crop that serves as staple food to millions of people in Africa. There are great differences in yield between individual countries (FAO, 2007), but for all countries, the average yield level is far below the potential one, which has been estimated (Gurnah,1974; Martin,1972) at 15-20 t for dry tubers ha^{-1} yr^{-1} (equivalent to 60-75 t ha^{-1} yr^{-1} on a fresh weight basis). Particularly in the Upper Ouémé basin (Benin Republic), the average recorded yield for dry tubers was only 4.3 t ha^{-1}yr^{-1} from 1988 to 2005 (INRAB, 2005). One major constraint highlighted for its contribution to declining yam productivity is soil fertility degradation, due to nutrient depletion by leaching, and erosion, and the loss of organic matter from most soils in the savannah zone of Benin Republic. With increasing demographic pressure, land use intensity and reduced forest cover, suitable land for yam cultivation becomes gradually scarcer (Carsky *et al.*, 2001). In Benin Republic, farmers practice slash-and-burn agriculture for yam production, which places great pressure on scarce virgin and fallow land resources. Natural fallow, crop rotation with grain legumes, and mineral fertilizer are the main soil fertility management strategies practiced here. However, most farmers do not use fertilizers and manures to any appreciable extent on yams. Furthermore, fallow periods in the savannahs are shorter and most farmers increasingly cultivate yam without any fallow or fertilizer application, leading to increased pathogen and pest attacks, and soil fertility degradation (Manyong *et al.*, 1996; Carsky *et al.*, 2001). These constraints call for appropriate management techniques to restore, replenish, conserve and maintain the quality of agricultural land, in order to increase yam yield. There is a lack of information on the usage of different sources of fertilization for soil fertility maintenance in yam production systems. Most studies on fertilizer use in yams have observed an increase in tuber yield with nitrogen application. Yield increases recorded are normally about 10%. In Trinidad, Chapman (1965) obtained a 30% tuber yield response, only when nitrogen fertilizer application was delayed until three months after planting. No or limited effects are reported in other studies in the humid forest in Côte d'Ivoire (Dibby *et al.*, 2004), as well as the savannahs and coastal humid regions in Benin (Baimey *et al.*, 2006). Therefore, this study sought to obtain more quantitative information on the effect of fertilizer on tubers and total dry matter production of the yam species used in Benin Republic (*D. alata* and *D. rotundata*), and to derive growth parameters that could further be used for modeling of yam growth.

Modeling plant growth has a tradition starting long before today's computer models. Their core questions – *what is limiting crop growth and what is the optimal management ?* – are still being addressed by modern crop models. Due to the complexity and dynamics of agro-ecosystems, in addition to a detailed analysis of yield determining processes, the use of dynamic simulation models for describing crop production is recommended. At present, a multitude of simulation models for one or several field crops is available. Most of them have been developed in temperate or subtropical regions, under management practices inherent to industrialized countries. Tropical regions like Benin Republic, however, show some differences with regard to soil conditions (highly weathered, low pH, etc.) and land use management (slash-and-burn, low-input agriculture), which necessitate the detailed testing and potential adjustment of existing models to tropical conditions. Modeling of yam growth can be an effective aid for the interpretation of experimental data and for the assessment of constraints affecting yam production. Concerning yam (*Dioscorea* spp.), only a few attempts of modeling have been made. In 1997, YAMSIM (a crop growth model), was used to model the growth and development of *Dioscorea alata* (Montero, 1997); more recently, a potato development model has been used to simulate the effect of temperature and photoperiod on yam development (Marcos *et al*., 2009). Tillage date, yam growth and tuber formation has never been modeled in Benin Republic. Hence, the second aim of this study was to model the yield and biomass production of yam species used in Benin Republic (the sub-humid Guinea Savannah of West Africa).

As shown above, soil fertility restoration and crop performance in many developing countries (with low input agriculture), strongly relies on fallow management. Yams are known to demand high levels of soil fertility; therefore, they are given first priority in the cropping cycle of traditional farmers employing long bush-fallow rotations (O'Sullivan, 2008). In general, farmers in Benin Republic practice intensive agriculture on a small piece of land i.e., the land is cropped for a long duration and they do not clear new land every year for yam cultivation (Adjei-Nsiah, 2006). Yam occupies the first place in the sequence of cropping after a bush fallow, in which yam has the advantage of using the mineral reserves accumulated during the soils rest period or after the burning of vegetation (Bamire and Amujoyegbe, 2005). Hence, the third goal of the study was to analyze the effect of fallow management on yam production in the Upper Ouémé basin of Benin Republic.

Thus, the three objectives of this thesis can be summarized as follows:

- Measuring the influence of fertilizer application on biomass production and partitioning pattern of yam (*Dioscorea alata* L.) in Benin Republic;
- Calibrating the EPIC model for yam production under rainfed conditions in Benin Republic;
- Using the calibrated EPIC model for analyzing the effect of fallow availability on yam productivity.

CHAPTER 2

Effect of different source of fertilization on Yam (*Dioscorea rotundata*) biomass production

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2.1. Introduction

Edible yam (*Dioscorea* spp.) production occurs in nearly every region of the tropical world, and it is considered the most important tuber crop in West Africa and the Caribbean Basin (Purseglove,1972). Worldwide, > 20 million tons of yam tubers are produced annually in an area of ≈ 2.5 million hectares (FAO,1987). White Guinea yam (*Dioscorea rotundata*) is indigenous to West Africa, and Nigeria produces the largest quantity of the tubers in the world. However, yam as a staple and traditional food is not always available at affordable prices to the poor, and the farmers complained of low and unattractive price which does not cover their cost of production. In Edo state, Nigeria and under traditional landuse and cropping system, yam is usually the first crop to be planted after the land has been cleared (Coursey,1967). This is due to the high fertility requirement of the crop; it has relatively long seasonal growth (Onwueme,1978). Under this practice, yam has the advantage of utilizing the nutrient reserve accumulated when the soil is rested.

Rising population pressure and increased demands on land for non-agricultural purposes have made soil fertility maintenance through prolonged fallows an untenable proposition, leaving maintenance of soil fertility through fertilization the only viable alternative. The poor crop yields on degraded land further suggest that soils involved in the production of yam require supplementary application of nutrients if they are to do well. However, lack of knowledge and information on such usage and their importance in yam production constitute a constraint to their use by resource-poor farmers. In this present study the dry matter production of white yam (*Dioscorea rotundata*) “kokoro”, late variety of yam, tuber biomass and dry matter distribution to the plant parts as influenced by different fertilization practices (i.e., N, P and K fertilizers, crop residue and manure) was determined by analyzing data from field experiments set up in the Upper Ouémé basin, (Republic of Benin) in the years 2001, 2002 and 2003.

2.2. Materials and methods

2.2.1. LOCATION

The experiments were carried out in year 2001, 2002 and 2003 at Dogué village (Southern Donga Department) in Benin Republic (West Africa); which is located at 9° 06 N and 1° 56 E; at a distance of about 87 km from Parakou.

2.2.2. CLIMATE

The climate on the site is Soudano-Guinean. The rainfall distribution is unimodal with two seasons; a rainy season from mid of April to mid of October, and the subsequent dry season. Weather stations close to the experimental plots registered average total annual rainfall of 1167.6 mm. The temperature does not vary within the year. The maximum temperature is 40℃ in the dry season, the minimum is 10℃ and the average is 25℃. On the average rainfall shows peak in August. First rainfall begins in March, and becomes significant from May to September (Table 1), the period of intensive farming activities. Harmattan (cold and dry wind) and the monsoon (warm and humid wind) are the wind system in the north of Benin, with harmattan as the dominating system.

Table1: Monthly rainfall measurement in year 2001, 2002 and 2003

Months	**Year 2001 Rainfall (mm)**	**Year 2002 Rainfall (mm)**	**Year 2003 Rainfall (mm)**
January	0	0	0
February	0	0	11
March	0	62	17.7
April	0	110	79.5
May	122	94.3	86
June	224	95.9	253
July	86	152.6	138
August	144	177.1	263
September	288	291.5	194.3
October	71	101.1	12.8
November	0	1.3	25.3
December	0	0.2	0.4
Total	935	1087	1081

2.2.3. SOIL CHARACTERIZATION

Soil textures found in the top 20 cm were loamy sand with 3-10% of clay and 76-81% of sand. According to FAO soil classification the soils on the experimental plots are characterized as Lixisols and Plinthosols.

2.3. Treatments and Field layout

The experimental design was a randomized complete block with four replications. Altogether there were eight plots divided into two groups consisting of four plots each, one was treated with manure (at the rate of 10 t ha^{-1}), second plot with mineral fertilizer (N30:P30:K60 kg ha^{-1}), third plot with combination of manure and mineral fertilizer, whereas the fourth plot was left as control (no application of fertilizer). In year 2002 and 2003 the same combinations were made taking crop residues (at the rate of 10 t ha^{-1}) from external sources as a source of organic matter at the place of manure (Table 2).

Organic matter was either farmyard manure provided by the farmers or crop residues at the rate of 10 t ha^{-1}.

Table 2: Average composition of manure and crop residue (DM) applied in Dogué. DM= Dry Matter

	%						mg kg^{-1}	
Organic fertilizer	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Mn**	**Zn**
Manure	1.59	0.24	1.51	0.66	0.36	0.05	542.19	49.57
Crop residue (Maize)	0.90	0.13	0.42	0.31	0.48	-	-	-

2.4. Field and plant sample preparation

The trial was established on a fallow land during the previous 3 years and had not received fertilizer before. The soil was ploughed once and harrowed twice. Hand hoe was used to manually establish 0.5 m high mounds spaced 1.0 m apart. Perennial weeds were controlled by weeding manually using a hand hoe before planting and at crop emergence. Sections from tubers heavier than 1 kg and without damages were used as planting material. In order to avoid heterogeneity, “head” and “tail” of the tubers were eliminated. Thus only middle tuber sections were used as cuttings. At planting, cuttings were placed 10 cm deep at the top of the mounds with the epidermal tissue area facing down. Plants were allowed to grow in the field and three samples of crop were harvested at maturity from each plot randomly. Aboveground plant parts were harvested by cutting the stem just above the soil surface. Fallen leaves were also collected. The plant tubers were harvested, and the soil and fine roots were gently washed off in a water bath. Tubers and shoots (leaves, fallen leaves, stems) were rinsed with de-ionized water before oven drying at 70° C to constant weight. Dry matter yield of tubers and shoots was determined by weighing.

2.5. Data analysis

Treatment effects were determined by analysis of variance by ANOVA using computer package SPSS version11 (SPSS Inc. ©2002, Chicago, Illinois, USA) and SAS program package (SAS Institute, 1987). Significance was regarded at $p \leq 0.05$.

2.6. Results and discussion

2.6.1. THE EFFECT OF MANURE APPLICATION IN COMBINATION WITH MINERAL FERTILIZER ON YAM (*DIOSCOREA ROTUNDATA*) BIOMASS PRODUCTION.

Table 3: Comparison of Total biomass production and tuber yield of yam under control and different source of fertilization (i.e., Manure, mineral fertilizer and combination of manure and mineral fertilizer) at Dogué (value in parentheses are values of standard deviation).

	Control	Manure (M)	Mineral Fertilizer (MF)	M + MF
Total Biomass	2669 (1952)	2969(1526)	3149 (1877)	2863 (1262)
Tuber yield	2130 (1760)	2470(1378)	2621 (1755)	2348 (1174)

Table 3 shows the effect of manure in combination with mineral fertilizer on the biomass production of yam (*Dioscorea rotundata*). The poor biomass production of yam under unfertilized condition could be explained by the negative nutrient balance in the soil because of high removal of nutrients through the harvested tuber. In this study an increase of 18% in total biomass production under mineral fertilizer application was registered compared to control (without fertilization) although its not significant. There is also no significant effect of manure application and its combined effect together with mineral fertilizer on the yam biomass production in this experiment. Normally yam is grown just after fallow, i.e. at a relatively high level of available nutrients, and thus no fertilizer is applied to this crop. This was also the case in this experiment which may explain the overall poor effect of fertilizer application. Little research has been conducted on the effect of fertilization on yam crop growth and productivity. Studies by Nwinyi (1983) with *D. rotundata* showed significantly higher yields in fertilized plants; however, the yields among fertilizer treatments were not significantly different. The same study showed no significant yield differences between control and fertilizer treatments when yam was grown at locations with soil of higher fertility. Gbedolo (1986) reported that experimentation with mineral fertilizers in Benin has rarely produced positive results, and that the application of N fertilizer has resulted in tubers of low organoleptic quality. In contrast, Chapman (1965) obtained a 30% increase in tuber yield of *Dioscorea alata* when the application of N fertilizer was delayed until 3 months after planting. In a 2-yr. study, Obigbesan *et al*. (1977) obtained positive yield responses to K fertilization in three species of yam in West Nigeria.

2.6.2. THE EFFECT OF MANURE APPLICATION IN COMBINATION WITH MINERAL FERTILIZER ON YAM (*DIOSCOREA ROTUNDATA*) TUBER PRODUCTION.

Table 3 shows the effect of manure in combination with mineral fertilizer on tuber biomass production of yam (*Dioscorea rotundata*). There is an increase of about 23% in tuber biomass production under mineral fertilizer application, 16% increase under manure application and around 10% increase under combined application of manure and mineral fertilizer when compared to the unfertilized control. The positive response of yam tuber to fertilization was due to a prolonged vegetative growth phase leading to longer growth duration. However, the increase in tuber biomass production is not significant. Working with *D. rotundata*, Sobulo (1972) found no significant differences in dry matter yield when plots were fertilized with 0, 28, 56, 84, and 112 kg N ha^{-1} and attributed the lack of response to the high level (0.06%) of total N in the soil.

2.6.3. THE EFFECT OF MANURE APPLICATION IN COMBINATION WITH MINERAL FERTILIZER ON PARTITIONING PATTERN OF YAM (*DIOSCOREA ROTUNDATA*) BIOMASS.

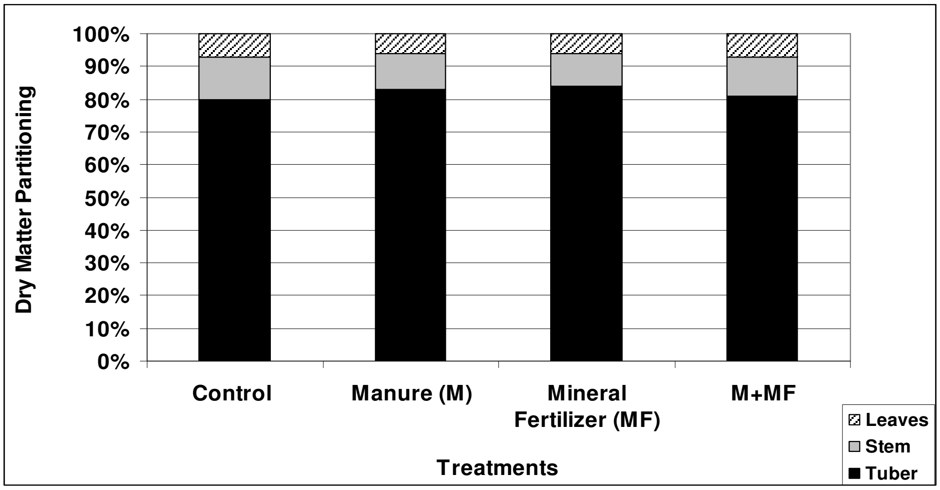

Figure 1: Comparison of dry matter partitioning of yam under control and different sources of fertilization (i.e., Manure 10 t ha^{-1}, mineral fertilizer 30 kg ha^{-1} and combination of manure and mineral fertilizer) at Dogué.

Figure 1 shows the effect of manure in combination with mineral fertilizer on dry matter partitioning of yam (*Dioscorea rotundata*). No significant effect of fertilization on partitioning rate of dry matter within the crop was observed. The crop behaves identically (i.e., partitioning rate) in both fertilized and unfertilized management practices (Srivastava *et al.*, 2008).

2.6.4. THE EFFECT OF CROP RESIDUE IN COMBINATION WITH MINERAL FERTILIZER ON YAM (*DIOSCOREA ROTUNDATA*) BIOMASS PRODUCTION.

Table 4: Comparison of Total biomass production and tuber yield of yam under control and different source of fertilization. (i.e., Crop residue, mineral fertilizer and combination of crop residue and mineral fertilizer) at Dogué (value in parentheses are values of standard deviation).

	Control	Crop Residue (CR)	Mineral Fertilizer (MF)	CR +MF
Total Biomass	3968(1476)	4486 (1955)	4811 (1880)	4528 (1560)
Tuber yield	3501(1401)	3985 (1805)	4570 (1733)	3953 (1412)

There is significant ($p<0.05$) positive effect of mineral fertilizer treatment on yam total biomass production. We observed an increase in total biomass production of yam by 21% under mineral fertilizer treatment, increase of 13% under crop residue treatment whereas 14% increase was registered under the combination of crop residue and mineral fertilizer when compared to control (no fertilization). An overall increase of about 52% in yam total biomass production was observed under fertilized condition in year 2002 and 2003 compared to that in year 2001. This could be due to the higher rate of nitrogen application (42 kg ha^{-1} compared to 30 kg ha^{-1} in 2001) and high rainfall in year 2002 (1087mm) and 2003 (1081mm) compared to a lower precipitation in year 2001 (935mm). Sufficient water supply enhances the uptake of nutrients by the crops from the substrate. It is known from earlier experiments that the Leaf Area Index (LAI) generally increased with mineral fertilizer treated yam plants. This is caused by an increased leaf production and longer leaf life span (Law-Ogbomo *et al.*, 2007). As a consequence, a higher amount of radiation was intercepted contributing to an increase in tuber yield. LAI of any plant is an indicator of its photosynthetic capacity and translocation into tubers (Igwilo, 1988).

2.6.5. THE EFFECT OF CROP RESIDUE APPLICATION IN COMBINATION WITH MINERAL FERTILIZER ON YAM (*DIOSCOREA ROTUNDATA*) TUBER BIOMASS.

There was a positive effect of all fertilizer treatments (CR, F and CR+F) on yam tuber biomass production. However, only mineral fertilizer treatment showed a significant effect ($p<0.05$). An increase of 14%, 30% and 13% in tuber biomass production under crop residue, mineral fertilizer and combined treatment of crop residue and mineral fertilizer was observed, respectively. The beneficial effects of crop residue on tuber yield were probably due to favorable hydrothermal regimes of the soil for emergence and early development of yam plants. The crop residue also increased growth and tuber yield of yam possibly by reducing nutrient losses through controlling runoff in the rainy season. The beneficial effect is partly due to possible release of nutrients, particularly N and K, from the decomposition of previous year crop roots and shoots. In our experimental field, the previous crop was cotton which is usually fertilized and maize in the years 2002 and 2003 respectively, where maize frequently also receives a (low) amount of fertilizer.

2.6.6. THE EFFECT OF CROP RESIDUE APPLICATION IN COMBINATION WITH MINERAL FERTILIZER ON PARTITIONING PATTERN OF YAM (*DIOSCOREA ROTUNDATA*) BIOMASS.

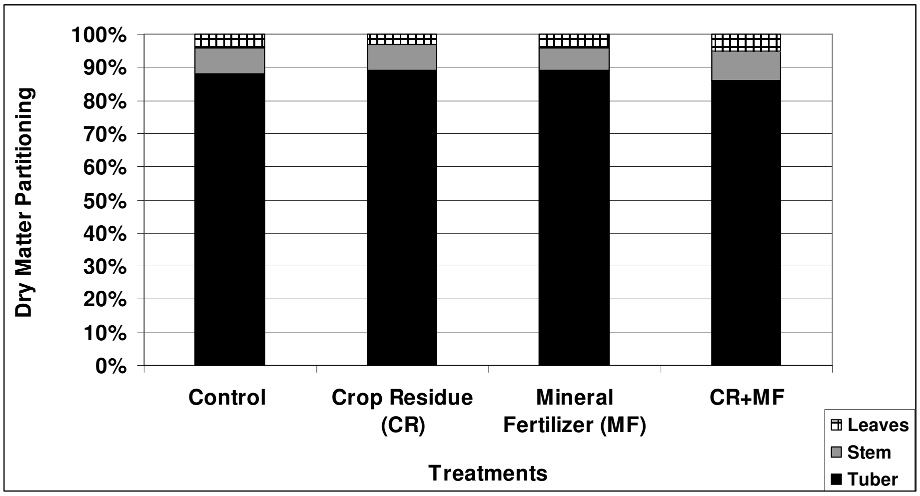

Figure 2: Comparison of dry matter partitioning of yam under control and different sources of fertilization (i.e., Crop residue 10 t ha^{-1}, mineral fertilizer 42 kg ha^{-1} and combination of crop residue and mineral fertilizer) at Dogué.

Figure 2 shows that there was no significant effect of different source of fertilization on yam dry matter partitioning. The crop behaved identically (i.e., partitioning rate) in both fertilized and unfertilized treatments. An adequate balance between shoot, root and tuber growth should be achieved in order to obtain high yields, as it has been proposed by Osaki *et al.* (1996).

CHAPTER 3

Biomass production and Partitioning pattern of Yam (*Dioscorea alata*)

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3.1. Introduction

Tuber yield of yam (*Dioscorea alata*) is determined by the total production of dry matter (DM) and its distribution within the crop. Dry matter partitioning is of great importance in crop production. Improvement of crop yield by plant breeding has resulted from higher harvest indices rather than improved DM production (Cock & El-Sharkawy, 1988; Gifford *et al.*, 1984). However, there are limits to the fraction of assimilates that can be diverted to the harvestable organs. A plant should invest sufficient assimilates in other plant parts to realize and maintain a high production capacity. The balance between assimilates for different plant parts is of importance for optimal crop production (Marcelis, 1994). In this present study the distribution of dry matter increments to the plant parts of white yam (*Dioscorea alata*) in relation to the application of mineral fertilizer was determined by analyzing data from field experiments set up in the Upper Ouémé basin (Benin Republic) over two years where yam was harvested periodically during the entire stages of its growth. The distribution tended to follow a regular pattern if expressed as a function of phenological growth phase of the crop.

3.2. Materials and methods

3.2.1. FIELD AND PLANT SAMPLE PREPARATION

The study was conducted as on-farm trials at Dogué village on latitude 9° 05´N and longitude 01° 55´E of Benin Republic. The village is characterized by a bimodal rainfall pattern with a short rainy season which usually starts in May and lasts till September. The soil was ploughed once and harrowed twice. Spade was used to manually establish 0.5 m high mounds spaced 1.0 m apart. Perennial weeds were controlled by weeding manually using hand hoe before planting and crop emergence. Sections from tubers heavier than 1 kg and without damages were used as planting material. In order to avoid heterogeneity, the “head” and “tail” of the tubers were eliminated. Thus only middle tuber sections were used as cuttings. At planting, cuttings were placed 10 cm deep at the top of the mounds with the epidermal tissue area facing down. The experiments were laid out as a randomized complete block design with three replications. Altogether there were six sub-plots of 8m × 8m size (three main plots with two sub-plots within each main plot). Out of these six sub-plots, three were fertilized with 200 kg NPK ha^{-1} at planting, 100 kg NPK ha^{-1} (60 days after planting) and

100 kg ha^{-1} Urea (60 days after planting) for assuring that nutrients would not become a limiting factor for crop growth and development. The remaining three sub-plots were treated as control. Plants were allowed to grow in the field and four samples of crop were harvested at five different times i.e., first harvesting at 55th day after planting, 2nd at 126th day, 3rd at 154th day, 4th at 168th day and final harvest at 231st day after sowing from each sub-plot randomly. Aboveground plant parts were harvested by cutting the stem just above the soil surface. Fallen leaves were also collected. The plant tubers were harvested then put into a water bath, gently washing the soil and fine roots from the tubers. The tubers and shoots (leaves, fallen leaves, stems) were rinsed with deionized water before oven drying at 70° C to constant weight. Dry matter yield of tubers and shoots was determined by weighing.

3.2.2. DATA ANALYSIS

Treatment effects were determined by analysis of variance by ANOVA using computer package SPSS version 11 (SPSS Inc. ©2002, Chicago, Illinois, USA). Significance was regarded at $p \leq 0.05$.

3.3. Results and discussion

3.3.1. THE EFFECT OF FERTILIZER TREATMENT ON YAM (*DIOSCOREA ALATA*) BIOMASS PRODUCTION.

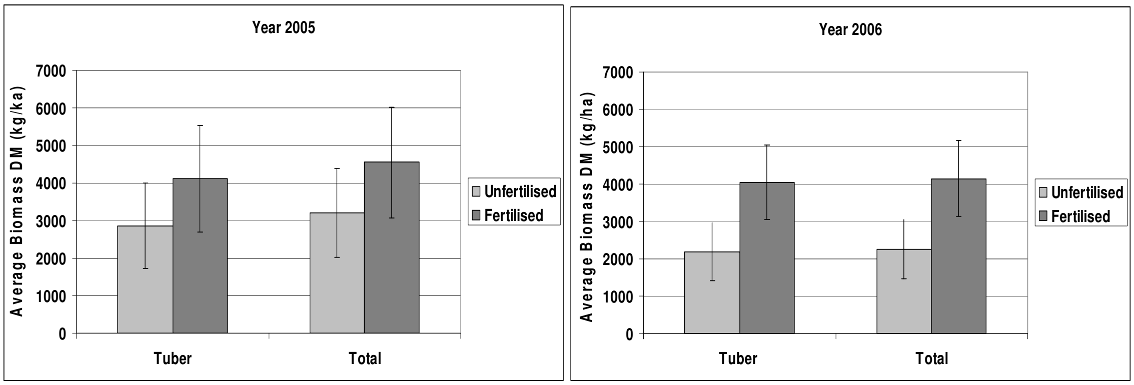

Figure 1: Comparison of total biomass and tuber biomass production of Yam under control and fertilized conditions in year 2005 and 2006 ($p<0.001$).

There is highly positive significant effect of fertilizer on biomass production of yam in year 2005 and 2006. In year 2005, under fertilized condition, an increase of 44% in tuber yield and

42 % in total biomass production of yam had been registered, whereas it was higher in year 2006, which accounted 85% and 84% of increase in tuber yield and total biomass production respectively when compared with control (without fertilizer) (Figure1). The stronger effect in year 2006 could be explained by the better water use efficiency (WUE) of the crop as this year was dry and mineral nutrition may improve the stomata regulation and the metabolic efficiency as higher nutrient availability may enhance the uptake of nutrients under lower soil moisture condition (Payne *et al.*, 1992). Normally yam is grown just after fallow and no fertilizer is applied to this crop. The poor biomass production in yam under unfertilized condition could be explained by the negative nutrient balance in the soil because of high removal of nutrients through the harvested tuber. The poor performance of yam in terms of total biomass production in year 2006 compared with the total biomass production in year 2005 could be explained by the shorter vegetation period due to erratic distribution of rainfall in the year 2006.

Table 1: Total biomass yield at five harvesting dates in relation to the application of mineral fertilizer (p<0.05) in year 2005 and 2006.

Days after Planting (DAP)	**Control**	**Fertilized**	**Level of Significance (*p*)**
Year 2005			
57	327	196	0.012
126	1482	2257	0.052
154	3313	5921	0.002
168	3501	5527	0.021
231	3217	4553	0.002
Year 2006			
55	532	988	0.028
125	2325	4094	0.0002
155	3845	6168	0.0005
165	4760	7381	0.0005
216	2254	4142	0.00001

3.3.2. RELATIVE DRY MATTER DISTRIBUTION

Partitioning is the differential distribution and deposition of assimilates among tissues. Because in yams the tuber yield is more relevant than the total dry matter yield, it is important to study the distribution of the produced dry matter among the different plant parts.

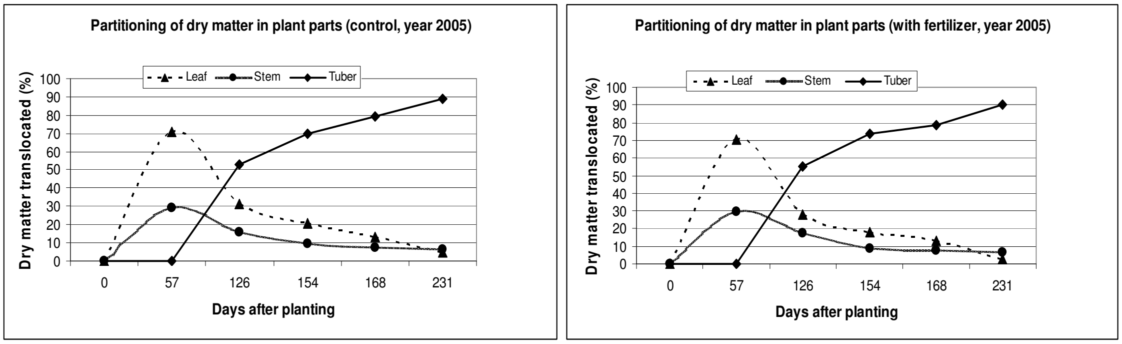

Figure 2: Comparison of partitioning rate of dry matter in different yam tissues under control and fertilized condition in year 2005.

Figure 2 shows the partitioning rates of leaves, stems and tubers in year 2005. The proportion of leaves and stems was increasing until 57th day after planting and gradual decrease can be observed until day of final harvest (i.e., 231st Days after planting). By contrast, the tuber partitioning rate was always positive, increasing rapidly during the period between 57 and 126 Days after planting. There was no effect of fertilizer observed on the partitioning pattern within the crop.

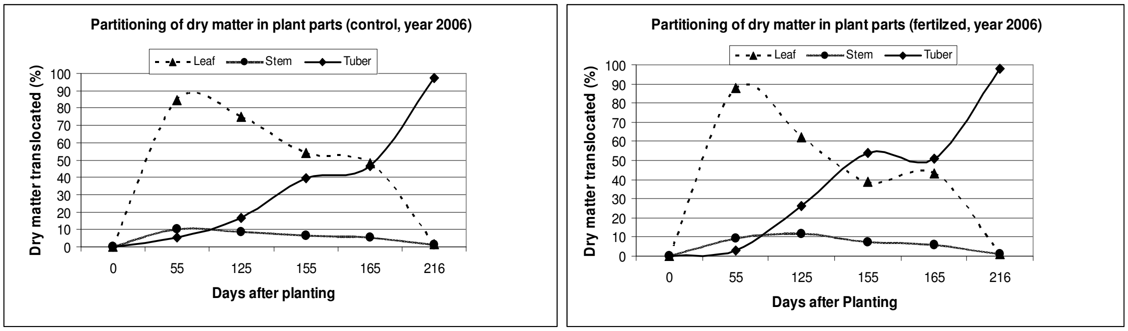

Figure 3: Comparison of partitioning rate of dry matter in different yam tissues under control and fertilized conditions in the year 2006.

Figure 3 shows the partitioning rates of leaves, stems and tubers in year 2006. In case of 2006, we observed the same pattern of dry matter distribution in yam crop as we saw in year 2005. There was a gradual decrease in leaves and stem partitioning rates after about 55th DAP, whereas it was positive until 55th DAP. However, tuber partitioning rate followed always positive trend and showed a rapid increase during the period between 55 and 155 DAP. The probable reason for the decrease in tuber dry matter partitioning between 155 and 165 DAP is not yet known. No fertilizer effect was observed on the partitioning rate of dry matter within the crop. In case of tubers, environmental factors such as light and temperature contributed less to explain DM accumulation than time. As in potatoes, tuber production in yams is determined by time of tuber initiation and bulking rate (Bremner & Taha, 1966; Enyi, 1972ab). According to Milthorpe (1963), the bulking rate is the first derivative of tuber growth which in our experiment rapidly increased after about 55 DAP (Figure 2 and 3).

Haynes *et al.* (1967) for the same yam species (*Dioscorea alata*) showed that leaf area declines at the onset of tuber formation. An adequate balance between shoot, root and tuber growth should be achieved in order to obtain high yields, as it has been proposed by Osaki *et al*. (1996). They found that high productivity root crops are able to maintain a balance between root and shoot activity since in root crops the main sink is underground, photosynthates are actively distributed also to roots. Additional information is needed to optimize shoot-root, shoot-tuber and root-tuber interactions in root crops such as yam.

CHAPTER 4

Simulating biomass accumulation and yield of yam (*Dioscorea alata)* in the Upper Ouémé basin (Benin Republic) – I. Compilation of physiological parameters and calibration at field scale

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4.1. Introduction

Two of the key topics in current agronomic research are: finding management strategies that maximize crop production and minimizing environmental degradation. An appropriate complement to experimental data is the utilization of simulation models, which can provide both an efficient interpretation of data and an analysis of the behavior of agricultural systems under diverse environmental conditions. Investigations using models are faster and more economical than experimental studies alone – they (models) further represent helpful tools through which decision-making processes in sustainable agricultural systems can be assisted. The testing of models against experimental datasets is an essential step towards evaluating either the performance of the model as a whole, or simply a set of its components. A large range of crop growth models have been developed for an array of crops including major root and tuber crops like potatoes (*Solanum tuberosum*). Some examples of these models, for potatoes for instance, include the DSSAT model (Clavijo, 1999; Mekinnie *et al.*, 2003); SUBSOTER-potato model (Travasso *et al.*, 1996) and the NPOTATO model (Wolf, 2000; Van Delden *et al.*, 2003). Models used for cassava (*Manihot esculenta*) include Richard's growth model (Amanullah *et al.*, 2007) and the GUMCAS model (Matthews *et al.*, 1994). However, none of these have yet been used to simulate the biomass development and yield of yam (*Dioscorea alata*). The Environmental Policy Integrated Climate (EPIC) model (Williams, 1995), originally named Erosion Productivity Impact Calculator, is an agro-ecosystem model capable of simulating crop growth as a function of weather, soil, and management conditions (e.g., tillage, fertilization, irrigation, crop rotations), as well as other processes related to managing agro-ecosystems (e.g., wind and water erosion, water balance, pesticide fate, etc.).

EPIC has been evaluated and used worldwide under many types of management practices and climatic soil conditions with reasonable success, indicating the robustness of the model. One of the most comprehensive tests of the crop growth sub-model was performed by Williams *et al.* (1989), who describe the results of testing an updated EPIC crop growth model for simulating barley, corn, rice, soybean, sunflower, and wheat yields at several U.S. locations and sites in Asia, France, and South America. The predicted yields were compared with measured yields for periods ranging from 1 to 11 years. The average predicted yields were always within 7% of the average measured yields, and there was no significant difference between any of the simulated and measured yields at the 95% confidence level. EPIC has also been evaluated at both the continental and global scale against national (Liu *et al.*, 2008; Tan and Shibasaki, 2003) and regional (van der Velde *et al.*, 2009) yield data. Although several authors have observed the overestimation of yield predictions in water limited conditions or for summer crops (Ceotto *et al.*, 1993; Steduto *et al.*, 1995; Kosovan, 1998), the model has been used to evaluate cropping systems and crop yields in Argentina (Bernardos *et al.*, 2001), France (Cabelguenne *et al.*, 1990), and Jordan (Hughes *et al.*, 1995). This model has been calibrated for several crops but remains unused in the simulatation of yam (*Dioscorea alata*) biomass accumulation and yield. Considering the urgent need for effective and efficient management practices that maximize yam yields, the objectives of the present study were to develop a set of phenological parameters and to calibrate the EPIC model for simulating yam (*Dioscorea alata*) growth and yield.

4.2. Materials and methods

4.2.1. MODEL DESCRIPTION

The EPIC model consists of nine integrated sub-models: hydrology, weather, erosion, carbon and nutrient cycling (N, P, and K), plant growth, soil temperature, tillage, economics, and plant environment control. In its current form, EPIC is well suited for assessing the effects of soil erosion on crop productivity; predicting the effects of management decisions on soil, water, nutrient, and pesticide movements, and tracing the allocation and turnover of C and N in soil. The model operates with a daily time step.

4.2.2. CROP GROWTH MODEL

A single crop growth model is used in EPIC to simulate biomass accumulation and crop yield for approximately 130 crops, each with a unique set of growth parameters (e.g., radiation use efficiency [RUE]; potential harvest index [HI]; optimal and minimum temperatures for growth; maximum leaf area index [LAI]; and stomatal resistance). The final HI is an estimation based on the potential HI, minimum harvest index, and water use ratio. The potential biomass estimate is based on the interception of solar radiation and the RUE that is affected by both the vapor pressure deficit and atmospheric carbon dioxide level. Water, nutrient, temperature, aeration, and radiation stresses restrict the daily accumulation of biomass, root growth, and yield (Williams, 1995). Stress factors are calculated daily and range from 0.0 to

1.0. The estimation of the daily increase in crop biomass, considers, on a given day, the maximum among water, nutrient, temperature, and root zone aeration constraints. For root growth, calculated soil strength, soil temperature, and aluminum toxicity stresses are chosen as maximum constraint factors. Water stress occurs when available water in the soil is below crop-water demand. The same holds for nitrogen stress, that is, when available nitrogen is lower than crop nitrogen demand. The water stress factor is computed daily by considering the supply and demand concept, while the nitrogen stress factor is calculated by comparing accumulated crop nitrogen content to the optimal nitrogen content. The nitrogen stress factor varies non-linearly from 1.0, at sufficient nitrogen supply of the crop, to 0, when nitrogen supply is half the nitrogen demand. For non-stressed conditions, the HI is affected only by the heat unit index.

4.2.3. EXPERIMENTAL DATA

Data for the models calibration were obtained from researcher managed on-farm trials at Dogué village (9°05´N, 01° 55´E), Benin Republic (Figure 1). The rainfall distribution is unimodal with two seasons; a rainy season from mid April to mid October, and the subsequent dry season. Weather stations close to the experimental plots registered an average annual total rainfall of 1168 mm, which peaks in August. The first rains start in March, and become significant from May to September – the period of intensive farming activities. The mean temperature varies only slightly within the year. The maximum temperature is 40°C in the dry season, the minimum is 10°C and the average is 25°C. Harmattan (cold and dry winds from the Sahara desert) and monsoon (warm and humid wind) wind systems occur in the north of Benin, with the Harmattan being most dominant.

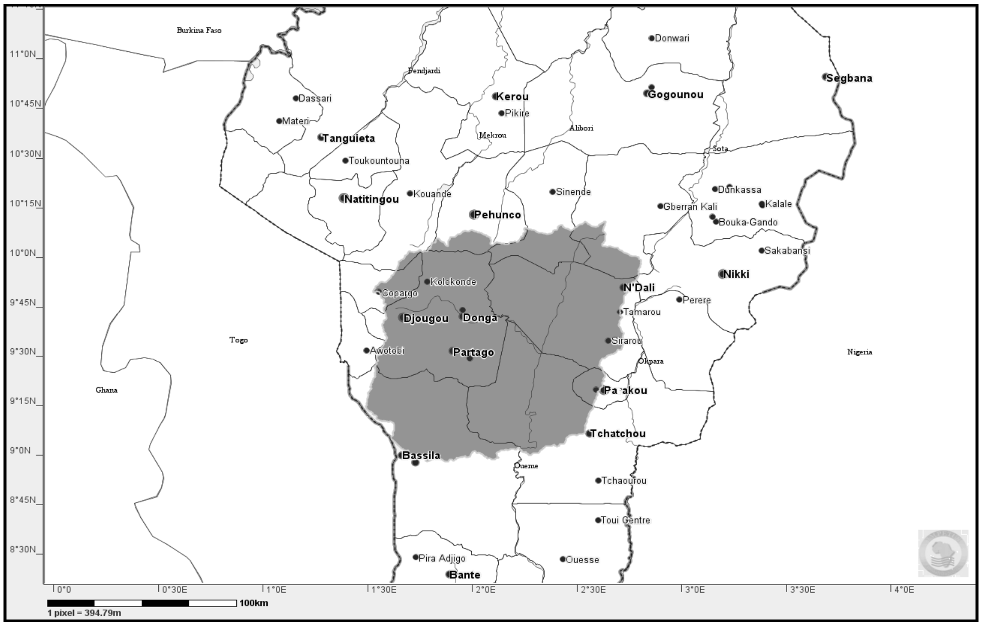

Figure 1: Map of the study area (Dogué, Upper Ouémé basin).

The experiments were laid out as a randomized complete block design with three replications (Figure 2).

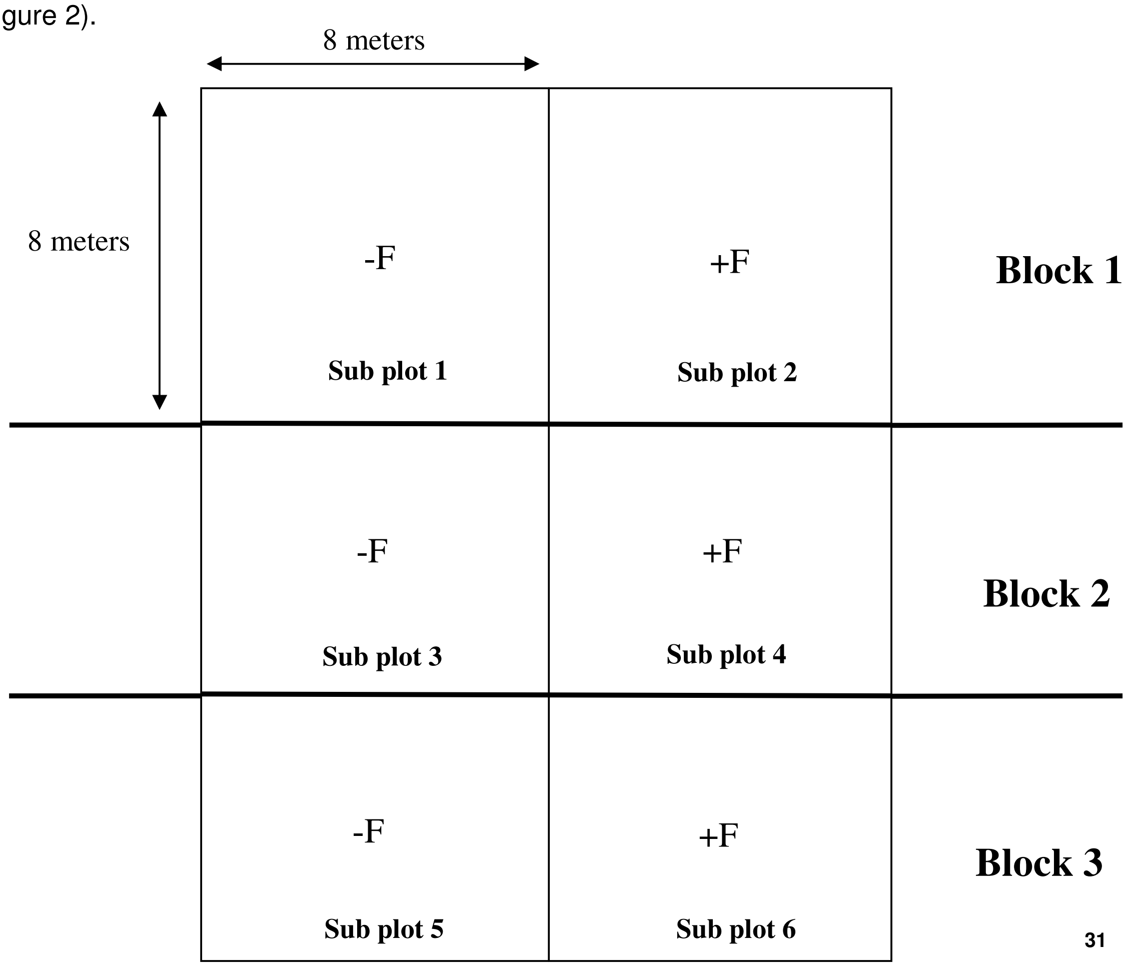

Figure 2: Schematic diagram of Experiment, where –F = Without fertilization, +F = With fertilization.

The experiments were laid out as a randomized complete block design with three replications (Figure 2). Altogether there were six sub-plots of 8m × 8m size (three main plots with two sub-plots within each main plot). Of these six sub-plots, three were fertilized, via manual incorporation into the soil, with 200 kg NPK ha^{-1} (at planting), 100 kg NPK ha^{-1} (60 days after planting), and 100 kg Urea ha^{-1} (60 days after planting), to ensure that nutrients would not become a limiting factor for crop growth and development. NPK fertilizer contained 14% N, 23% P_2O_5 and 14% K_2O. The remaining three sub-plots were treated as control. The soil was ploughed once and harrowed twice. A spade was used to manually establish 0.5 m high mounds spaced 1.0 m apart. Weeds were manually controlled using a hand hoe both before planting and after crop emergence. Plant density was 0.88 plants per square meter because the germination rate was only 88%. Undamaged tuber sections heavier than 1 kg were used as planting material. Middle tuber sections were used as planting setts after removing the "head" and "tail" of the tubers. At planting, setts were placed 10 cm deep in the top of the mounds. Plants were grown without staking the vines.

4.3. Model input preparation

4.3.1. WEATHER

A 2 year database (2005 and 2006) was used in the models calibration for daily records of precipitation (mm); maximum and minimum temperature (℃); solar radiation (MJ m^{-2}); relative humidity (as a fraction), and wind speed (m s^{-1}). Figure 1(a and b), gives the comparison of long term annual means over 24 years and annual means of air temperatures and precipitation during the experimental period (2005 and 2006).

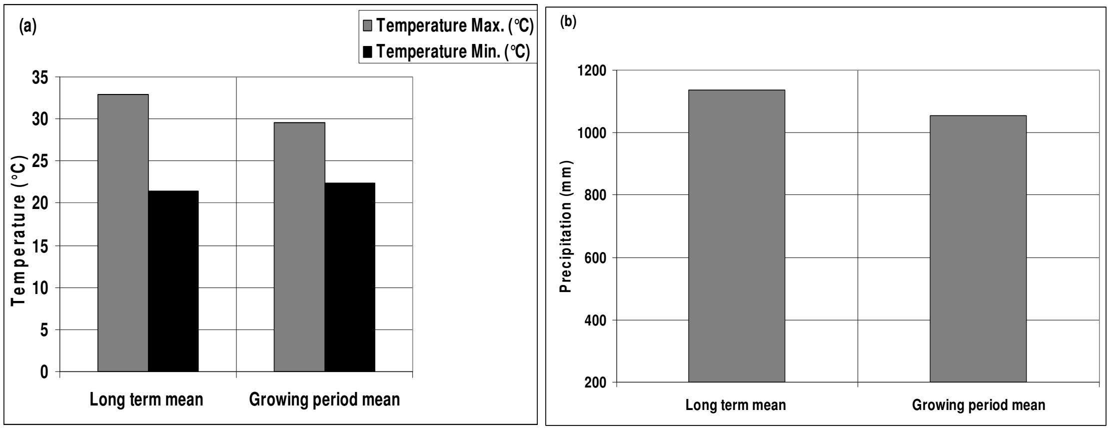

Figure 3(a & b): 24 years long term annual means at Parakou station (Benin Republic) and annual means of maximum and minimum temperatures as well as precipitation at Dogué (Benin Republic) during the experimental period.

The long term annual mean values of maximum and minimum temperatures were 32.9°C and 21.4°C, whereas the corresponding values for the experimental period (2005 and 2006) were 29.6 °C and 22.4 °C respectively, thus, comparatively, the weather conditions in the experiment period were fairly typical. The long term mean value of precipitation was 1137 mm, whereas for the experimental period it was 1054 mm.

4.3.2. SOIL

The texture of the top soil (~ 20 cm) was loamy sand with 3-10% of clay and 76-81% of sand. According to the FAO soil classification system, the soils of the experimental plots are characterized as Lixisols and Plinthosols.

4.3.3. FIELD MANAGEMENT

For each sub-plot, information from the six preceding years on crops, fertilization, tillage, planting, and harvesting, were available and grouped together to create a history of field operations input file for each of the two treatments (fertilized and non-fertilized). The amounts and dates of fertilizer applications in the model were carried out according to the field experiment described in Section 2.3. In 2005 and 2006, the two treatments had the same tillage operations, as well as planting and harvesting dates. Potential heat units were estimated at 1945°C using the average of a 2 year growing degree day period, accumulated during the normal growing season. The average start and end of the growing season were determined as the 20th May and 9th January, respectively, by averaging the planting and harvest dates of the 2 years. In both years, the same yam variety "Discovery" (popularly known as "Florido", introduced by Institut de Recherches Agronomiques Tropicales [IRAT] – Ivory Coast), was used; it is a short-cycle variety producing medium sized tubers, chosen mostly for frying. This variety is preferred among farmers for both the good stability and extended storage life of its tubers, as well as its resistance to most pests, wilting and diseases – especially the internal brown spot disease, which predominantly affects the production of *Dioscorea alata* varieties (Zannou *et al*., 2005).

4.4. Model calibration

The Cassava (*Manihot esculenta*) crop parameter dataset (provided with the EPIC model – version 3060), was used as a starting point to establish a new parameter set for yam (*Dioscorea alata*). It was chosen as a starting point because cassava can be regarded as the representative crop for yam on the basis of its agro-climatic requirements for growth and development. Subsequently, this data set was modified using data from the yam grown in the fertilized treatments in 2005 and 2006, together with other values from the literature. Table 1 lists the values using the original EPIC nomenclature (Kiniry *et al*., 1995).

Table 1: Crop parameter values of yam (*Dioscorea alata* var. Discovery) for the Environmental Policy Integrated Climate (EPIC) model used in the simulations.

Parameter		Values
BN1 (a)	Normal crop N concentration at emergence	0.06
BN2 (a)	Normal crop N concentration at mid-season	0.036
BN3 (a)	Normal crop N concentration at maturity	0.025
BP1 (a)	Normal crop P concentration at emergence	0.006
BP2 (a)	Normal crop P concentration at mid-season	0.003
BP3 (a)	Normal crop P concentration at maturity	0.002
CNY (a)	Normal fraction of N in yield	0.013
CPY (a)	Normal fraction of P in yield	0.003
DLAP1 (a)	Defines a point on the LAI development curve early in the season (% season, % max LAI)	30.01
DLAP2 (a)	Defines a point on the LAI development curve when LAI is near maximum (%season, % max LAI)	65.95
DLAI (b)	Fraction of the growing season when LAI begins to decline	0.8
DMLA (c)	Potential leaf area index (m^2 m^{-2})	8
GSI (b)	Maximum stomatal conductance (m s^{-1})	0.007
HI (a)	Harvest index (%)	0.95
HMX (a)	Maximum crop height	0.3
PPC1 (b)	1st point plant population for crops	1
PPC2 (b)	Fraction of maximum leaf area at 1st point	300
PPT1 (b)	1st point plant population for trees	3
PPT2 (b)	Fraction of maximum leaf area at 2nd point	980
RBMD (b)	Rate of decline in WA after LAI starts to decline	10
RDMX (b)	Maximum rooting depth (m)	2
RWPC1(b)	Fraction of root weight early in the season	0.4
RWPC2(b)	Fraction of root weight at maturity	0.95
RLAD (b)	Rate of LAI decline	2
TB (c)	Optimum temperature (°C)	30
TG (c)	Base temperature (°C)	15
VPTH (b)	Threshold value for sensitivity of leaf conductance to VPD (kPa)	1
VPD2 (b)	Rate of decline of leaf conductance with increasing VPD (kPa, fraction GSI)	4.3
WA (d)	Radiation use efficiency (kg ha^{-1} MJ^{-1} m^2)	10.5
WCY (b)	Fraction of water in yield	0.5
WAVPD(b)	Rate of decline in WA per unit increase in vapor pressure deficit (VPD) (kg ha^{-1} MJ^{-1} m^2 kPa^{-1}	10

Where,

(a) = Parameter values are derived from our experiments (Srivastava and Gaiser, 2008; Dagbenonbakin, 2005).
(b) = Parameter values are taken from cassava parameter file from EPIC (version 3060).
(c) = Parameter values taken from literature (Goenaga and Irizarry, 1994; Suja *et al*., 2000; FAO, 2005; Marcos *et al*., 2009).
(d) = Parameter value adjusted.

Yam yield simulations were sensitive to several parameters. Two parameters are critical to the calculations of yield: biomass energy ratio (WA) and the fraction of root weight at maturity (RWPC2). Biomass energy ratio is used in the model for converting energy to biomass. This parameter has been adjusted for yam (*Dioscorea alata*) to 10.5 kg ha^{-1} M J^{-1} m^{-2} in the final calibration step. The biomass energy value is slightly lower than the value of 15, as is indicated for Cassava (*Manihot esculenta*). Harvest index is defined as the ratio between crop yield and above ground biomass. The final HI used to calculate yield in the model was adjusted, based on the heat unit index (HUI), percentage of the growing season, and the fraction of HI. Harvest index is the main determinant of yield when the adjusted HI is larger than the water stress-yield factor (WSYF); otherwise, yield is determined by WSYF. The HI was calculated using observed data (range: 0.91-0.98), with the mean value of 0.95 used for the HI (Srivastava and Gaiser, 2008) and the minimum value of 0.2 for the WSYF. The value of 8.0 used for DMLA in the yam parameter set was based on the findings of field experiments at the Corozal Research Station of the University of Puerto Rico (Goenaga and Irizarry, 1994; Suja *et al.*, 2000). The values of DLAP1, DLAP2, DLAI, RLAD and RBMD, were determined through fitting the simulated values to the observations made in the field experiment (Srivastava and Gaiser, 2008). Base temperature (TG) 15°C and optimum temperature (TB) 30°C were fixed according to the ECOPORT database (FAO, 2005; Marcos *et al.*, 2009). Maximum rooting depth (RDMX) was set at 2.0 m, the same as used by EPIC for other tuber crops like potato or cassava, and maximum crop height (HMX) was set as per the findings in the field experiment (Srivastava and Gaiser, 2008). The values for the normal concentrations of N and P in the biomass and tubers were set according to the findings of field experiments with mineral and organic fertilization conducted in the Upper Ouémé Basin from 2001-2003 (Dagbenonbakin, 2005). The values concerning fractions of root weight at emergence and maturity were set according to the findings of Srivastava and Gaiser (2008). Values for the rate of decline in WA per unit increase in vapor pressure deficit (WAVP); the threshold for sensitivity of leaf conductance to vapor pressure deficit (VPTH); the rate of decline of leaf conductance with increasing vapor pressure deficit (VPD2); maximum stomatal conductance (GSI), and fraction of water in yield (WCY), were the same as used by EPIC for Cassava. The value of 300 for PPC2 and 980 for PPT2 was adopted to bring the values of observed and simulated LAI in congruence.

As a measure of precision to compare observed data and simulated values, the following parameters were used (Papula 1982):

a. The mean residual error *ME* as

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$$

b. The mean relative error *MR* as

$$MR = \frac{1}{n}\sum_{i=1}^{n}\frac{(y_i - x_i)}{x_i}$$

Where n is the sample number, x is the observed and y is the simulated value. The mean relative error (MR) gives an indication of the mean magnitude of the error in relation to the observed value. Small values indicate little difference between simulated and measured values. Regression analysis was performed with the MS EXCEL software program. The means of measured yield were regressed against simulated values to test if slopes and intercepts of linear regression were significantly different from 1.0 and 0.0 respectively.

4.5. Results and discussion

4.5.1. SIMULATION OF PLANT GROWTH AND YIELD

Yam (*Dioscorea alata*) yields, under fertilized and unfertilized conditions during 2005-2006, were simulated with the parameterized EPIC (version 3060) model. Observed yields were converted to dry matter yields (0% moisture) to enable comparisons against the simulated values. In 2005 and 2006, the means of simulated yields agree well with the observed means resulting in simulation errors ranging from 5.7 to 9.7 % (Table 2a). The model has adequately predicted the total biomass production (Table 2b) for both fertilized (Figure 4b) and unfertilized treatments (Figure 4a). The analysis of the models results reveal that mean simulated water stress days (number of days where water stress is the most serious constraint to biomass increase) over the two growing seasons were 12.0 in the unfertilized treatment and 14.7 in the fertilized treatment. Thus, water stress was not the major reason for the differences in biomass production between fertilized and unfertilized treatments. Simulated nitrogen stress days (number of days where nitrogen stress is the most serious constraint to biomass increase) in the unfertilized treatment was 55.4 days and 17.9 days in the fertilized treatment. This difference in stress days explains the overall lower biomass production in the unfertilized treatment.

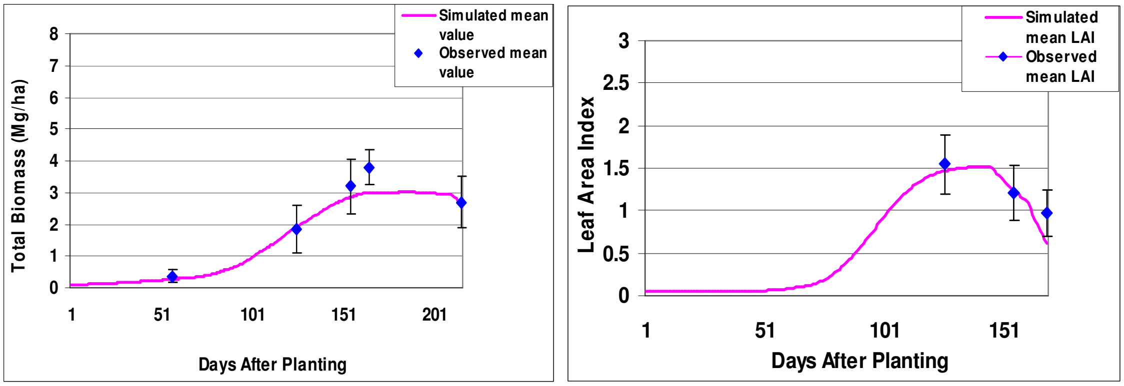

Figure 4a: Observed (means of three plots) and simulated values by the model of leaf area index (LAI) and biomass under unfertilized condition (Bars are values of standard deviation).

The model slightly underestimated the total biomass produced under fertilized conditions between 150-195 days after planting. In the fertilized treatments, simulated nitrogen stress was probably too high between 150 and 195 days after planting. This could be due to an overestimation of yam nitrogen demand during this period, which caused increased nitrogen stress and lowered biomass production in the model. The overestimation of nitrogen demand and nitrogen stress simultaneously affects both leaf area development and duration of maximum leaf area extension as shown in Figure 4b. When the model optimizes the dose of nitrogen fertilizer, an underestimation of roughly 6.1% in total biomass production is registered, which is well in agreement with the observed values compared to the simulated biomass production under non- optimized fertilization (an underestimation of about 11.3%). These observations suggest an overestimation of nitrogen demand at different growth stages of yam (*Dioscorea alata*) by the EPIC model. The same result was observed by He *et al.* (2006) in the case of corn yield, where EPIC underestimates the yield by 10%. Cabelguenne *et al.* (1990) also reported an underestimation of wheat yield and biomass by the EPIC model. In another study, simulations obtained with EPIC show an overall underestimation of maize biomass when compared with measurements averaged over all input levels; the mean production was 17.16 Mg ha^{-1}, instead of the 18.63 Mg ha^{-1} measured (Cabelguenne *et al.*, 1999).

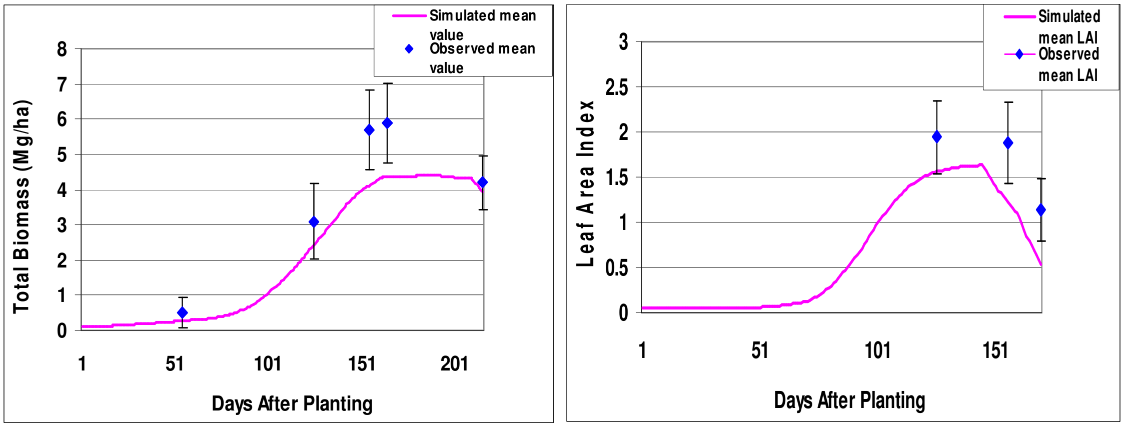

Figure 4b: Observed (means of three plots) and simulated values by the model of leaf area index (LAI), and biomass under fertilized condition (Bars are values of standard deviation).

Table 2a: Comparison of mean values of observed tuber yield (from field experiments) and simulated tuber yield (from model output), mean residual error (ME), and mean relative error (MR).

Treatment	Simulated (Mg ha^{-1})	Observed (Mg ha^{-1})	ME	MR (%)
Control	2.44	2.59	0.15	- 5.7
Fertilized	3.72	4.12	0.40	- 9.7
Optimum fertilization	3.94	4.12	0.18	- 4.3

Table 2b: Comparison of mean values of observed total biomass production (from field experiments) and simulated total biomass production (from model output), mean residual error (ME), and mean relative error (MR).

Treatment	Simulated (Mg ha^{-1})	Observed (Mg ha^{-1})	ME	MR (%)
Control	2.64	2.78	0.14	- 5.0
Fertilized	3.92	4.42	0.50	- 11.3
Optimum fertilization	4.15	4.42	0.27	- 6.1

When EPIC was used to simulate sunflower growth, LAI and yield, Kiniry *et al.* (1992) found that measured and simulated yields were very similar. The mean square error (Wallach and Goffinet, 1987) of prediction was 0.078, representing an absolute root mean squared error of 0.28 Mg ha^{-1}, which was equal to 10% of the observed yield. A similar study was conducted to evaluate EPIC's ability to simulate the growth and yield of corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* L.), Sunflower (*Helianthus annuus* L.), soybean (*Glysine max* L.) and wheat (*Triticum aestivum* L.). When grown in rotations at three levels of management inputs, including three levels each of fertilizer, irrigation and tillage over a 5-year period, the root mean square error of simulated model grain yield ranged from 0.4 Mg ha^{-1} for sunflower to 1.6 Mg ha^{-1} for corn. The conclusion rests in the proven capacity of EPIC in simulating yield for the above mentioned crops (Cabelguenne *et al.*, 1989).

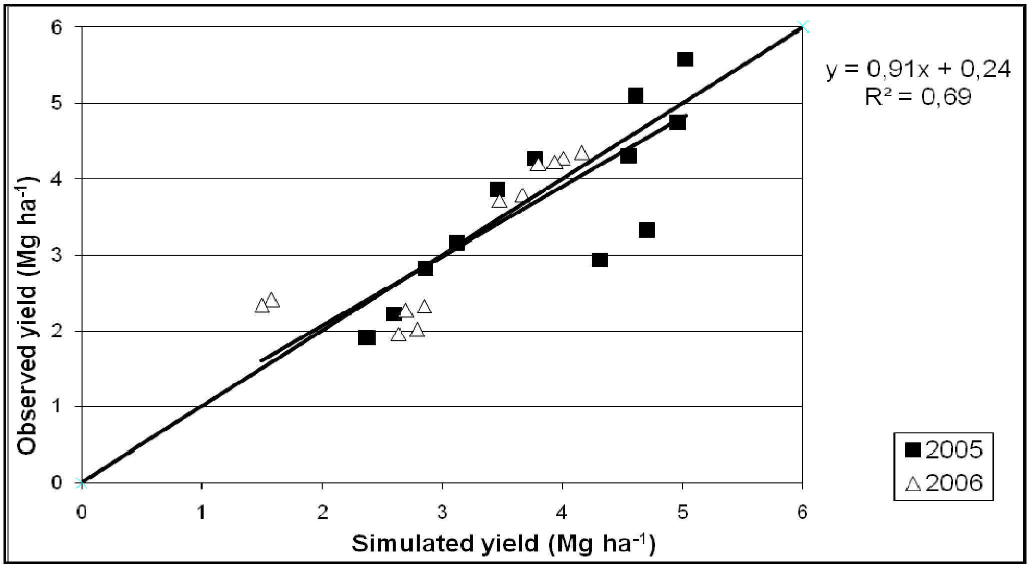

Figure 5: Determination of coefficient between observed and simulated yield of yam (data of fertilized and unfertilized yield together from year 2005 and 2006 have been plotted).

YAMSIM (a crop growth model) simulates dry matter accumulation by using the SUCROS (Spitter *et al.*, 1989) sub-model as EPIC does. Montero (1997) compared simulated yam yields with results from field trials in Costa Rica (with *Dioscorea alata*). The model overestimated LAI by 45-55%, as well as leaves and stems (mostly above 50%), whereas tuber DM was underestimated. However, general agreement between the pattern of the curves describing measured and simulated DM production was promising. It has been indicated that EPIC is best suited for long-term simulations and that it did not adequately simulate variability in yields between years (Williams *et al.*, 1989; Kiniry *et al.*, 1995). This is shown in Figure 5, which indicates some variance when simulated and observed yields from single plots and individual years are plotted. Bryant *et al*. (1992) pointed out that EPIC, and other simulation models, are best used to generate simulated yield distributions that are similar to measured yield distributions, rather than trying to match measured yields in each single year. The estimation of parameters is a complex approach in dynamic simulation models, because of the great number of sensitive parameters involved. Additional data sets are necessary for a complete and rigorous optimization of the model for the large range of yam varieties used in Africa and elsewhere. In crops receiving normally distributed rainfall and adequate fertilization, the variability between years in plant growth is usually not very high, provided that incidence of weeds, pests and diseases is minimal. Under such conditions, the model can provide adequate predictions.

CHAPTER 5

Estimating the availability of fallow for yam (*Dioscorea alata*) production using a crop model

Submitted to Field Crops Research

5.1. Introduction

Yam (*Dioscorea* spp.) is the third most important tropical root crop after cassava (*Manihot esculenta* Crantz.) and sweet potato (*Ipomoea batatas* L. Lam.) in West Africa, Central America, the Caribbean, Pacific Islands and Southeast Asia (Onyeka *et al*., 2006). Although, there has been a decline in yam production relative to cassava and rice in Africa, yam is a preferred staple food and, considering projected population increases, total production is likely to increase in the future (Srivastava and Gaiser, 2008).

Agriculture practices in the Republic of Benin (West Africa) are characterized by low input technologies and soil fertility is restored by fallowing the cropland for a number of years depending on the availability of land. Few attempts have been tried to incorporate fallow effects into crop modeling at the catchment or regional scale (Van Nordwijk, 2002). However, information about fallow duration and management across farms within a region is often not available but will affect simulation results. Fallow availability may be a way to consider fallow effects in regional modeling and assessment studies but has not been explored yet.

The objective of this study was to estimate the fallow availability for yam production using the crop growth model EPIC (Environmental Policy Integrated Climate). The EPIC (version 3060) model was calibrated at field scale for yam (Srivastava and Gaiser, 2009) and applied at the district scale in the sub-humid savannah zone in West Africa. Different scenarios of fallow availability and its effect on yield were explored and compared with yields obtained from regional statistics.

5.2. Material and methods

5.2.1. MODEL DESCRIPTION

The EPIC model consists of nine integrated sub-models: hydrology, weather, erosion, carbon and nutrient cycling (N, P, and K), plant growth, soil temperature, tillage, economics, and plant environment control. In its current form, EPIC is well suited for assessing the effects of soil erosion on crop productivity, predicting the effects of management decisions on soil, water, nutrient, and pesticide movements, and tracing the allocation and turnover of C and N in soil. The model operates on a daily time step and is capable of long-term simulations of up to 4000 years with soil profiles having up to 10 layers.

5.2.2. CROP GROWTH MODEL

A single plant growth model is used in EPIC to simulate biomass accumulation and crop yield of about 130 crops, each with a unique set of growth parameters (e.g., radiation use efficiency, RUE; potential harvest index, HI; optimal and minimum temperatures for growth; maximum leaf area index, LAI; and stomatal resistance). EPIC is capable of simulating growth for both annual and perennial crops. Annual crops grow from planting date to harvest date or until the accumulated heat units during the simulation equal the potential heat units for the crop (Williams, 1995). EPIC estimates crop yields by multiplying aboveground biomass at maturity by a harvest index. For non-stressed conditions, the harvest index is affected only by the heat unit index. The final HI is estimated based on the potential HI, minimum harvest index, and water use ratio. The model estimates potential biomass based on the interception of solar radiation and the RUE that is affected by vapor pressure deficit and by atmospheric carbon dioxide concentration. Water, nutrient, temperature, aeration, and radiation stresses restrict daily accumulation of biomass, root growth, and yield (Williams, 1995). Stress factors are calculated daily and range from 0.0 to 1.0. For plant biomass, the stress used on a given day is the minimum of the water, nutrient, temperature, and aeration stresses. For root growth, it is the minimum of the calculated soil strength, temperature, and Aluminum toxicity stresses. In addition, crop yield reductions are calculated through water stress-induced reductions of the HI.

A prerequisite to use a field scale model at the regional scale lies in the evaluation of the model performance at different areas in the target region. EPIC model has been applied for yam (Srivastava and Gaiser, 2009), cassava, millets, sorghum (Adejuwon, 2004) and maize with reasonable accuracy except for sites with highly acid soils (Gaiser *et al.,* 2008b). The same model version (EPIC 3060) has been used in the present study.

5.2.3. STUDY AREA AND SIMULATION UNITS

The Upper Ouémé basin covers an area of 14,500 km^2 within the Republic of Benin. The climate is tropical sub-humid with a mean annual temperature of 26.8℃ and mean annual precipitation of 1150 mm (Mulindabigwi *et al.,* 2008). According to the FAO soil classification, the predominant soils are Luvisols with variable depth and coarse fragment content. Soils with plinthic layers occur frequently (Giertz and Hiepe, 2008). Soil texture in most of the cases is sandy in the top layers and loamy to clayey in the subsoil. Soil pH is neutral to slightly acid.

The catchment has been subdivided into 121 sub-basins. Each sub-basin is composed of up to 15 response units of variable size which constitute the spatial simulation units (LUSAC= Land Use-Soil Association-Climate units). A total of 960 simulation units were identified. The LUSAC units have variable surface and represent an area with similar climate conditions, soil characteristics and a representative crop and soil management. All data were gathered in the database of the spatial decision support system PEDRO (Protection du sol Et Durabilité des Ressources agricoles dans le bassin versant de l'Ouémé), which combines the agro-ecosystem model EPIC with the hydrological model SWAT (Arnold *et al*., 1998). PEDRO provided representative soil profile data for the dominant soil type of each of the 38 mapping units of the soil association map. Topographical information for each sub-basin including average slope inclination and length were extracted from the DEM (Digital Elevation Model) provided by the global SRTM (Satellite Radar Topographic Mission).

5.2.4. SIMULATION OF TUBER YIELD

The simulation of tuber yield and upscaling of the simulation results to obtain regional estimations of mean tuber yield for each sub-basin was done according to the procedure described by Gaiser *et al*. (2008a). The procedure consists in the following steps (Figure 1).

- Preparation of EPIC input database file for each LUSAC unit
- Running the simulations for each LUSAC unit.
- Extracting the output files and transfer it to the database.
- Aggregation of the results at district level.

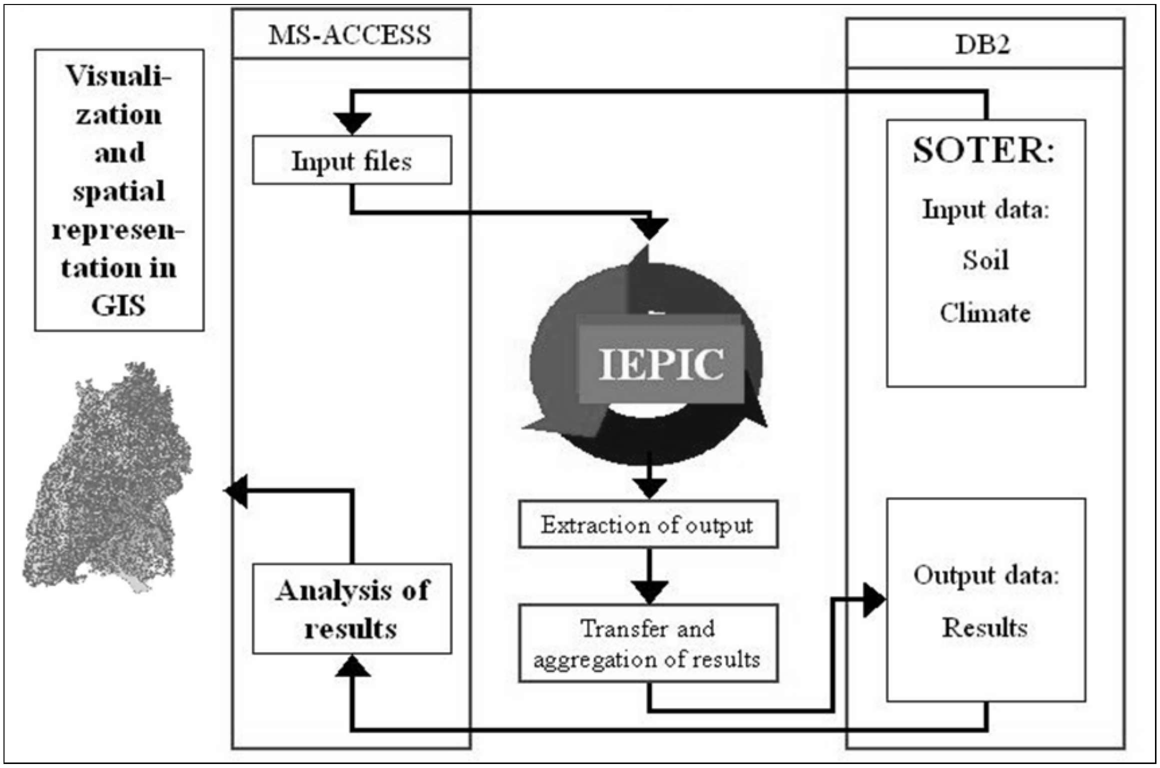

Figure 1: Workflow for the upscaling of EPIC simulation results to the sub-basin and district level.

Each sub-basin was linked to the nearest climate station. A total of 14 rain guage stations were available with daily rainfall measurements from 1960 to 2005. Daily minimum and maximum temperature for these 14 stations were generated by the REMO model which has been previously calibrated for the period 1960 to 2000 (Paeth and Thamm, 2007). For the calculation of the potential ET the approach given by Hargreaves and Samani (1985) was used. Cropping systems in the Upper Ouémé basin are characterized by low-input agriculture. In case of yam no fertilizer is applied and soil fertility restoration depends exclusively on the duration of the fallow period. Hence, the availability of fallow area, which is reflected in the duration of the fallow period is crucial for crop production.

5.2.5. AVAILABILITY OF FALLOW AREA AND FALLOW DISTRIBUTION PROCEDURE

In order to assess the availability of fallow in each of the 121 sub-basins, in the first step, the total cropland in the year 2000 as well as the non-cropped area excluding settlements were estimated from satellite images (Judex, 2008). The cropland had a proportion of 1745 km^2 or 12.1%. The non-cropped area was classified into “Bush savannah” and “Tree savannah (including forest)” with a total proportion of 58.2 and 29.7%, respectively. The major part of the land use class “Tree savannah” belongs to protected forest areas, where cropping is prohibited. Therefore, in a second step, the sub-basins which are located entirely or with a major proportion within these protected areas were excluded from the study, as well as sub-basins where the proportion of cropland was lower than 5%. Then, for the remaining 64 sub-basins, different scenarios of fallow availability were defined:

Scenario 1: Total savannah area is available as fallow land

Scenario 2: 50% of the bush savannah is available as fallow land

Scenario 3: 25 % of the bush savannah is available as fallow land

In the remaining sub-basins the percentage of cropland was on average 19.8% (Table 1), which corresponds to a fallow-crop ratio of 4:1 or a fallow-crop-cycle with 1 years cropping and 4 years of fallow. However, in some sub-basins the proportion of cropland was lower or higher. Therefore, for the simulations at the LUSAC level, fallow-crop cycles with 1 year of cropping and 5 years of fallowing and a crop rotation without fallow were also defined. Simulation duration was 18 years from 1988 to 2005.

Table 1: Proportion of land use classes and resulting fallow-cropland ratio within the Upper Ouémé basin.

	All sub-basins		**Sub-basins with cropland**	
	Km^2	**% of total area**	**Km^2**	**% of total area**
Cropland	**1745**	**12.1**	**1745**	**19.8**
Bush savannah	**8403**	**58.2**	**5324**	**60.4**
Tree savannah	**4284**	**29.7**	**1752**	**19.9**
Total	**14432**	**100.0**	**8821**	**100.0**
Average fallow-cropland ratio		**7.3**		**4.1**

In further step, each of the 64 sub-basins were classified according to their average fallow-cropland ratio in the three scenarios. Seven fallow-crop classes were defined with average percentage of cropland between 17% (Fallow-crop class 1) to 100% (Fallow-crop class 7). In fallow-cropland class 1 the average fallow-cropland ratio is 4.9 (Table 2) which means that 4.9 ha of fallow are available against 1 ha of cropland, whereas in fallow-crop class 7 no fallow land is available and all land is used for cropping. Thus, from class 1 to 7 the fallow-cropland ratio and hence fallow availability are decreasing. Each sub-basin was categorized into one of these seven classes.

Table 2: Definition of regional fallow-crop classes according to their average fallow-cropland ratio.

Fallow-cropland class	**Cropland area**	**Fallow-cropland ratio**	**Crop cycles without fallow**		**Fallow-crop cycles**	
			Area	**Cropland**	**Area**	**Cropland**
	(%)		(%)	(%)	(%)	(%)
1	**17**	**4.9**	**0**	**100**	**100**	**17**
2	**25**	**3.0**	**10**	**100**	**90**	**17**
3	**38**	**1.6**	**25**	**100**	**75**	**17**
4	**50**	**1.0**	**40**	**100**	**60**	**17**
5	**67**	**0.5**	**60**	**100**	**40**	**17**
6	**83**	**0.2**	**80**	**100**	**20**	**17**
7	**100**	**0.0**	**100**	**100**	**0**	**17**

Crop management was defined in the simulations according to the prevailing, traditional field activities.

5.2.6. DATA AGGREGATION AND STATISTICAL ANALYSIS

For the regional analysis, yield data are available at the district (French: commune) level in Benin (INRAB, 2005). Data series from 1988-2005 were available from the National

Agricultural Research Organization (INRAB). Therefore, tuber yield of yam was calculated within each LUSAC for the period 1988 to 2005. Then, tuber yields were aggregated from the LUSAC level to both the sub-basin and commune level taking into account the area share of the LUSACs within these larger spatial units in order to obtain the average tuber yield Y_s. as

$$Y_s = \sum_i^N Y_i * Area_i$$

with

Y_s is the average tuber yield per sub-basin/ district in t ha^{-1} a^{-1}

Y_i is the tuber yield in LUSAC unit i in t ha^{-1} a^{-1}

$Area_i$ is the decimal area percentage of LUSAC unit i in the respective sub-basin/ district. As a measure of precision to compare statistical data and simulated values the following parameters were used (Papula 1982):

a. The mean residual error *ME* as

$$\mathrm{ME} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - \mathrm{x_i})$$

b. The mean relative error *MR* as

$$\mathrm{MR} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{(\mathrm{y_i} - \mathrm{x_i})}{\mathrm{x_i}}$$

Where *n* is the sample number, *x* is the observed and *y* is the simulated value. The mean relative error (MR) gives an indication of the mean magnitude of the error in relation to the observed value. Small values indicate little difference between simulated and measured values. Regression analysis was performed with the MS EXCEL software program.

5.3. Results and discussion

5.3.1. DISTRIBUTION OF FALLOW CLASSES AND MODEL CALIBRATION

The frequency distribution of fallow-cropland classes obtained by the fallow distribution procedure is sensitive to the scenarios of fallow availability. In Scenario 1, where all non-cropped land is available for fallowing, 38 out of 64 sub-basins belong to the fallow-cropland class 2 with an average fallow-cropland ratio of 3.0, which means that 3 ha of fallow are available for one hectare of cropland (Figure 2).

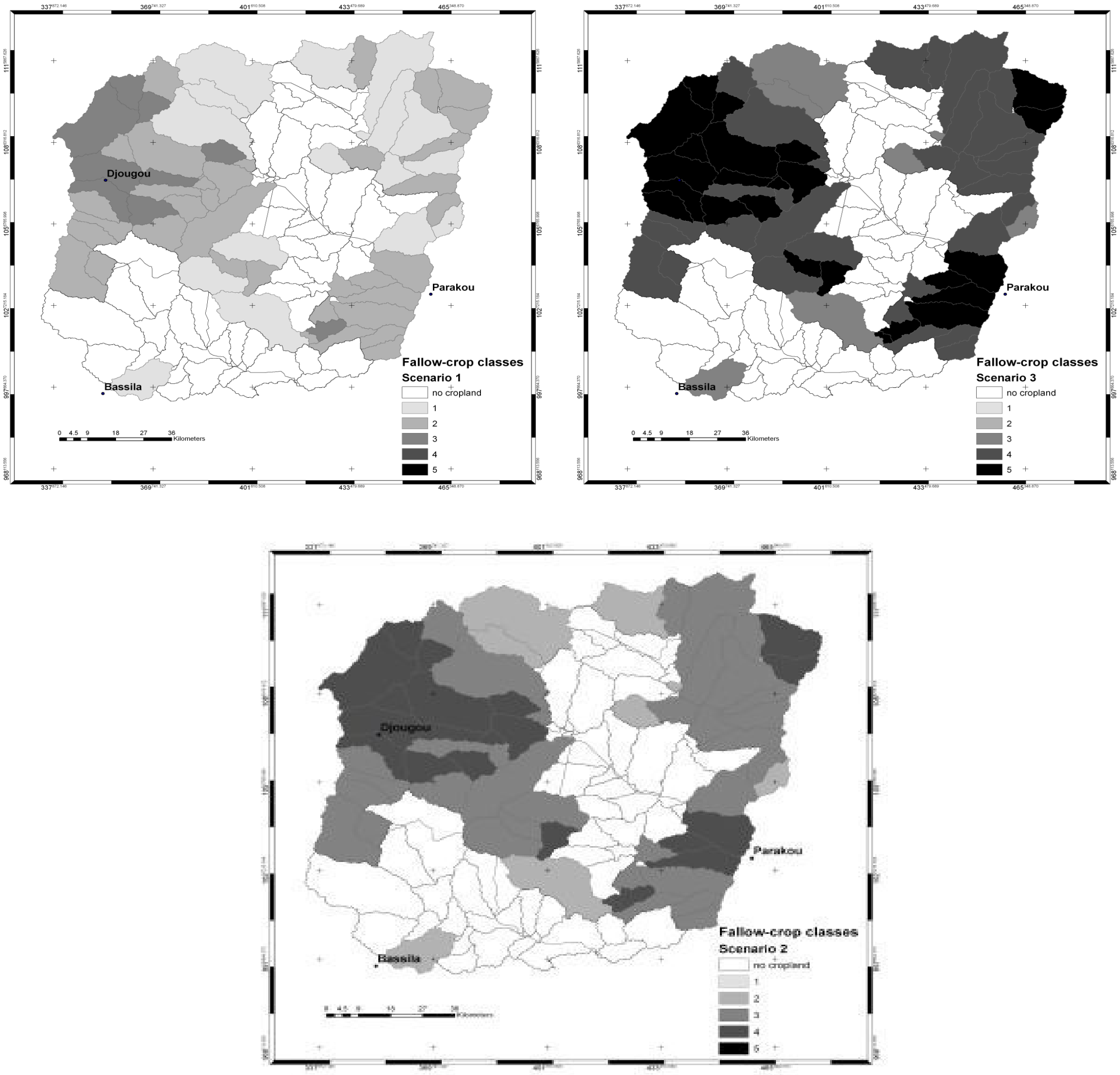

Figure 2: Spatial distribution of fallow-cropland classes in the Upper Ouémé catchment as affected by three different scenarios of fallow availability (left: 100% availability of fallow land; right: 25% availability of fallow land; down: 50% availability of fallow land). For description of fallow-cropland classes see text and Table 2.

On the other hand, in scenario 3, where it is assumed that only 25% of the bush savannah is available as fallow land, none of the sub-basins falls into this class, but 50% of the sub-basins fall into class 4 with a fallow-cropland ratio of 1.0.

Table 3: Mean observed and simulated tuber yields of the nine districts of the Upper Ouémé basin from 1988 to 2005 for three scenarios with different fallow availability (ME = Mean Residual Error and MR = Mean Relative Error).

	Weighted mean fallow area over all 64 sub-basins (%)	Observed (tons ha^{-1})	Simulated (tons ha^{-1})	ME (tons ha^{-1})	MR (%)
All rangeland as fallow	75.2	4.3	5.3	1.0	23
50% rangeland as fallow	59.5	4.3	4.6	0.3	8.0
25% rangeland as fallow	44.7	4.3	3.4	-0.9	-20

In the period 1988-2005, the mean annual observed tuber yield in the nine districts of the Upper Ouémé basin was 4.3 tons ha^{-1} according to the reports of the agricultural statistics (Table 3).

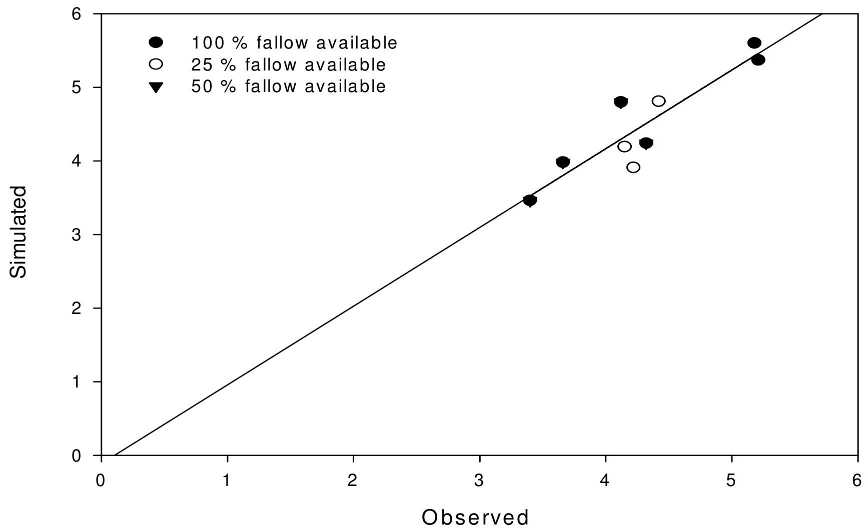

Figure 3: Simulated versus Observed average yam tuber yields (in tons ha^{-1}) of 9 districts belonging to the Upper Ouémé basin for three different scenarios with decreasing fallow availability.

Figure 3 shows that the correlation between the observed and simulated mean yam tuber yields for the nine districts, with coefficients of determination between 0.32 and 0.03 depending on the assumptions with respect to fallow availability. However, the mean yield over the nine districts, i.e., 4.3 tons ha^{-1} (INRAB 2005), is overestimated by 22 % if the entire not cropped area would be considered to be available as fallow land (Scenario 1). Gaiser *et al.* (2008b) reported from a multi-location validation in tropical regions, that maize yield predictions by the EPIC model at the field scale are overestimated on highly acid soils. However, this is not the case in the Central Benin, where mean soil pH ranges between 6.1 and 7.4 in the topsoil and 6.1 to 7.9 in the subsoil (Junge 2004, Igue 2000). However, a major factor determining yields at the farm and regional scale is the availability of fallow and to which extent it is included in the crop rotations. With decreasing availability of fallow land, the mean simulated crop yield at the district level decreases. When available fallow land is reduced to 50 or 25% (Scenario 2 and 3) the mean annual yam yield is 4.6 and 3.4 tons ha^{-1} over all districts (Table 3). For the scenarios 2 and 3 the mean errors between simulated and observed yields are 0.3 tons ha^{-1} a^{-1} and -0.9 tons ha^{-1} a^{-1}, with mean relative errors of 8 % and -20%, respectively. Therefore, the best agreement has been realized from the Scenario 2 (i.e., 50% of the bush savannah is available as fallow) that falls under fallow-cropland class 3 (Table 2) which suggests that 59.5 % of the land area fallowed are available for yam cultivation (Table 3) and also corresponds to an average fallow period of 1.6 years compared to 1 year of cropping (Table 2). This is in the concordance with the regional surveys done in farms and villages within the districts. The small overestimation in this scenario can be explained by the fact that in the present version of EPIC, allocation of assimilates is regulated only by the plant developmental stage and is based on observations from few experiments. Direct responses of the partitioning pattern to changing environmental conditions across fields in the regions are considered. Also, EPIC simulates except for weed competition only effects of abiotic stresses. Hence, yield losses due to pests, diseases and extreme events (storm, hail) which can be observed frequently on farmer fields in Benin, are not considered in the model.

CHAPTER 6

Discussion

6.1. Overall Discussion

The importance of yam (*Dioscorea* spp.) as a major staple food in the Republic of Benin (West Africa), together with its decreasing productivity, motivated this study which involved both investigating the effect of different management practices on yam production and combining the results within a crop growth model.

With the first experiment in this thesis (chapter 2), we tried to analyze the effect of different sources of fertilizer (i.e., N P K fertilizer, manure and crop residue) on yam (*Dioscorea rotundata* var. Kokoro), tuber and total biomass production, along with the partitioning pattern of photosynthetic assimilates among different plant parts from a 3 year (2001 to 2003) dataset. The same study was carried out for a different yam species (*Dioscorea alata* var. Discovery), which considered only the effect of mineral fertilizer in a 2 year (2005 and 2006) experiment. We concluded from the experiments that mineral fertilizer treatment had a significantly ($p<0.05$) positive effect on the total biomass production and tuber yield of both yam species. In 2001, the total biomass production and tuber yield of *D. rotundata* increased by 18% and 23% respectively in mineral fertilized plots, as compared to the unfertilized plots. Whereas greater effect of mineral fertilizer on total biomass production and tuber yield was observed in 2002 and 2003 (around 21% and 30% increase respectively), as compared to unfertilized plots. This observation could be attributed to the higher rate of fertilizer application (N42:P30:K60 kg ha^{-1} in 2002 and 2003 compared to N30:P30:K60 kg ha^{-1} in 2001) and a higher, well distributed rainfall registered in 2002 (1087 mm) and 2003 (1081 mm), compared to 935 mm rainfall in 2001. In year 2005 and 2006, yam (*D. alata)* was fertilized at the rate of (N88:P69:K42 kg ha^{-1}) and increases of about 44% in tuber yield and 42% in total biomass production, were registered. Whereas in 2006, the response to fertilizer treatment was more pronounced, with a highly significant increase ($p<0.001$) of about 85% and 84% in tuber yield and total biomass production respectively, as compared with unfertilized treatment. The stronger effect in 2006 could be explained by the better water use efficiency of the crop, as this year received well distributed rainfall throughout the growing period of yam; the same was observed in 2002 and 2003 (mentioned above). This may have enhanced the uptake of nutrients by the crop resulting in improved stomata regulation and the metabolic efficiency of the crop. We also know from earlier studies that leaf area index (LAI) generally increased with mineral fertilizer application in yam plants due to increased leaf production and leaf duration (Law-Ogbomo *et al.*, 2007). Law-Ogbomo and Remison (2008) have observed a significant correlation between yam growth rate and LAI ($r = 0.66$; $p<0.05$). They further demonstrated the effectiveness of higher LAI resulting from fertilizer application in influencing plant growth and vigor. These findings were in agreement with the findings of Nwinyi (1983), which showed significantly higher yields in fertilized than in unfertilized yam plants. Chapman (1965) also obtained a 30% increase in tuber yield of *D. alata*. However, Gbedolo (1986) reported that experimentation with mineral fertilizers in Benin has rarely produced positive results. *D. alata* responded more to mineral fertilization compared to *D. rotundata*, which was also observed in the 2005 and 2006 experiment. A recent study conducted in International Institute of Tropical Agriculture (IITA), Yam Research Coordination Unit, Benin Republic (Personal communication) showed that among all the types of fertilization used, *D. alata* seems to respond more frequently to mineral fertilizer (67% positive response), as compared to the species *D. rotundata* (45% positive response). This difference in response between species has already been shown for *D. alata* and *D. rotundata* (Obigbesan *et al*., 1977; Ferguson and Haynes, 1971). In the experiment from 2001 to 2003, the effect of organic fertilizer on yam (*D. rotundata*) yield was positive, but not significantly different from the yield under unfertilized conditions. We observed an increase of 16 % and 13 % yield under manure and crop residue application respectively. Regarding partitioning pattern of photosynthetic assimilates to different plant parts of *D. rotundata* and *D. alata*, there was no significant difference observed in the partitioning rate between fertilized and unfertilized conditions, but a positive correlation between harvest index and fertilizer application rate was noticed in *D. rotundata* (Figure 1). This observation is in accordance with the reports of Anon (1980) and Law-Ogbomo and Remison (2008), who also reported a consistent positive correlation between harvest index and fertilizer application rate. The positive correlation between HI and fertilizer rate is an indication of the enhanced efficiency of translocation of photosynthetic assimilates to the tuber, resulting in a higher HI due to increasing fertilizer rate.

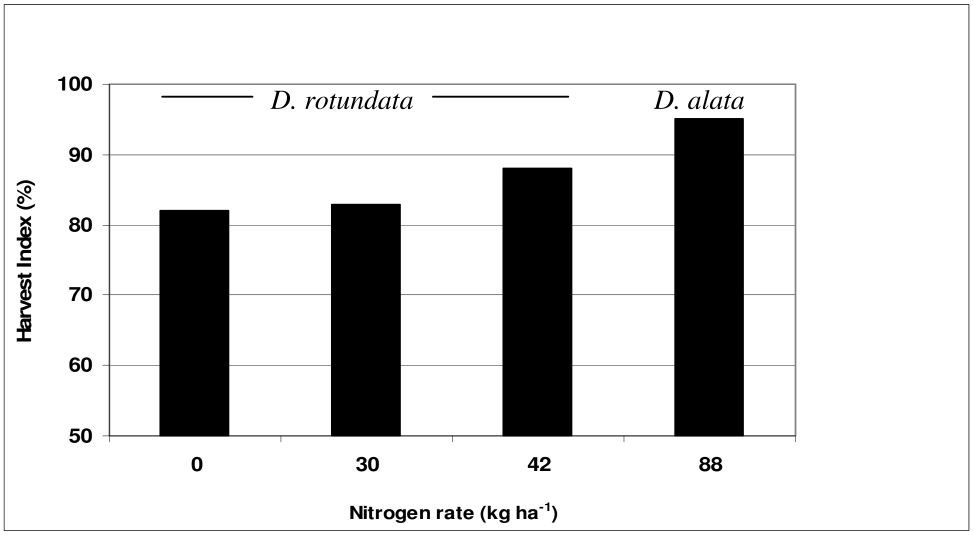

Figure 1: Effect of different rate of fertilizer application (kg ha^{-1}) on the harvest index of *D. alata and D. rotundata.*

From the experiments above, we derived some values of the growth parameters required for the modeling of yam growth and development in the next stage of the research work, which deals with the parameterization and calibration of the EPIC model (version 3060), at field scale, for simulating the yield and biomass production of yam (*Dioscorea alata* var. Florido). We developed a new crop parameter file for yam (*D. alata*) and evaluated the performance of the EPIC model by comparing simulations of two years of yam yields with the experiment conducted in Chapter 3. The model accurately simulated the effect of fertilizer on yam yield, as indicated by relatively low mean residual errors of the calculated values ranging from 0.15 to 0.40 Mg ha^{-1} with mean relative errors ranging from 4.3 to 9.7 %. There was a good correlation between simulated and observed mean yields during 2005 and 2006 ($R^2 = 0.69$, $p < 0.01$). The model could be used for improving the fertilizer management in *Dioscorea alata* production. Figure 2 clearly demonstrates that yam yield could be increased to about 74%, by applying nitrogen fertilizer at the rate of 200 kg ha^{-1} with a planting density of 0.88 plants m^{-2}. Whereas, a profound increase of about 160% in yam yield could be achieved with the same rate of nitrogen fertilizer application, by setting the planting density at 2 plants m^{-2}. As the model has been calibrated for the growing conditions of yam (*Dioscorea alata* var. Florido), in sub-humid tropical savannah regions, care should be taken when using the model to simulate production quantities, if yam varieties and climatic conditions differ.

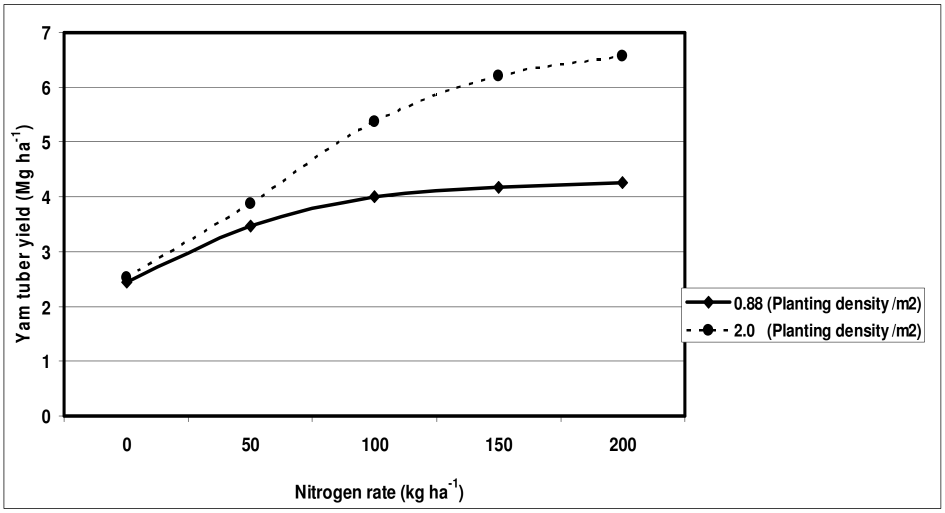

Figure 2: Yam yield under different nitrogen fertilizer application rate (kg ha^{-1}) at two levels of planting density (plants m^{-2}).

Finally, the calibrated EPIC model was used for estimating the fallow availability for yam cultivation at the regional scale, which is particularly important for yam production because of its high nutrient requirements. The model was incorporated into the spatial decision support system (SDSS) PEDRO (Protection du sol Et Durabilité des Ressources agricoles dans le bassin versant de l'Ouémé). Different scenarios of fallow availability were explored in a typical catchment within the sub-humid Savannah zone of West Africa. Yam-fallow rotations were simulated within 960 quasi-homogenous spatial units (LUSAC) and then aggregated to the 121 sub-basins within the catchment under three different scenarios of fallow availability: (S1) Total savannah area is available as fallow land; (S2) 50% of the bush savannah is available as fallow land, and (S3) 25% of the bush savannah is available as fallow land. A new aggregation procedure was developed based on changes in the frequency of fallow-cropland classes within the sub-basins to render the SDSS PEDRO sensitive to changes in fallow availability. Comparison of the average simulated tuber yield with the observed mean yield over the catchment shows that the simulations overestimated yam tuber yields by 23% and 8% for scenario S1 and S2 respectively, but underestimated the yield by about 20% under scenario S3. The best agreement between simulated and observed crop yields over the whole catchment was found when using the assumption that 50% of the bush savannah is available as fallow land under the prevailing cropping pattern. If we compare the decrease of 20% in yam tuber yield under scenario S3 (which would be the most likely situation in the days ahead for Benin Republic because of increasing demographic pressure), with the yield obtained under fertilized conditions (mean value over 3 yrs. experiment, from 2001 to 2003), an increase of about 0.6 t ha^{-1} (about 22 % increase) dry matter equivalent to 1.8 t ha^{-1} fresh matter has been registered by applying nitrogen at the rate of 38 kg ha^{-1} (mean value over 3yrs. experiment, from 2001 to 2003). We can conclude from this that by applying nitrogen at the rate of 38 kg ha^{-1}, current level of yam productivity (i.e., 4.3 t ha^{-1}, Source: INRAB, 2005) could be maintained.

The results show the sensitivity of regional yields of yam to fallowing and how a crop model can be used to analyze fallow practices in a region. However, the results obtained from the EPIC applications stress the need for more research to better understand and model fallow duration and fallow management practices (at the regional scale) and to consider these effects in regional assessments of cropping systems in which fallowing is an important soil fertility restoration measure.

6.2. Cost-Benefit Ratio

Based on the fertilizer rate required to maintain the current yam productivity in the Upper Ouémé basin derived from the field experiments, here we have tried to analyze whether the application of fertilizer is a profitable venture to the farmers or not.

Additional Cost	
- Urea (kg^{-1})	300 CFA
- Total urea required to maintain the current yam productivity (kg ha^{-1})	83
- Total urea cost (ha^{-1} yr^{-1})	**24900 CFA**
Additional Revenue	
- Current market price of yam in Benin Republic (kg^{-1})	300 CFA
- Increase in yam tuber productivity (kg ha^{-1})	1800
- Additional revenue generated per year	**540,000 CFA**
Net benefit [(Additional Revenue) - (Additional Cost)]	**515100 CFA = 860 €**

On calculating the cost-benefit ratio, application of nitrogen fertilizer is a profitable option to the farmers.

CHAPTER 7

Conclusions at a Glance

7. Conclusions at a Glance

Motivated by the problem of declining productivity of yam species in Benin Republic, the effect of organic and inorganic fertilizers on yam yield and biomass production were analyzed. We also modeled the growth and development of yam by using a process based biophysical crop model. From this work, the following conclusions can be drawn:

- Application of mineral fertilizer significantly increases the yield of both species of yam (*Dioscorea alata* and *Dioscorea rotundata*), in the Upper Ouémé basin (Benin Republic). Whereas, the effect of organic fertilizer was positive but not significant. The magnitude of effect depends on the species of yam, and rainfall amount and distribution.
- With the newly developed crop file for yam (*Dioscorea alata* var. Discovery), the EPIC (Environmental Policy Integrated Climate) model (version 3060) is able to simulate the mean biomass production and tuber yield of yam over two years under fertilized and unfertilized conditions with acceptable accuracy at field scale. However, validation of the model performance is still required.
- The EPIC (Environmental Policy Integrated Climate) model was successfully applied to analyze the sensitivity of yam productivity to fallow periods at the sub-basin scale in Benin Republic. The results show that on an average 59.5 % of the total available land must be under fallow for maintaining the current yam productivity in the study area. This corresponds to an average fallow period of 1.6 years compared to 1 year of cropping.
- Yam productivity could be increased by maintaining soil fertility via fallowing the crop land and applying mineral fertilizer. Nitrogen fertilizer application is a profitable venture. However, its accessibility to the farmers holds the key.

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